Asian Nuclear Prospects 2010

Laser Applications in Indian Nuclear Power Programme

P. D. Gupta
Raja Ramanna Centre for Advanced Technology, Indore 452 013, India

Abstract

High power lasers are remarkable tools which can be used for a wide spectrum of material processing applications in nuclear reactors. Unique properties of lasers, like high spatial coherence and spectral purity, can be used for remote diagnostics and precision metrology. Use of optical fibers for laser beam delivery adds a new dimension to their use in rather inaccessible areas and highly radioactive environment. In this paper, a brief description of R&D work on high power solid state lasers and laser-based systems carried out at Raja Ramanna Centre for Advanced Technology, Indore, for applications in various aspects of Indian nuclear power programme is presented.

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license. Selection and/or peer-review under responsibility of Indra Gandhi Centre of Atomic Research

Keywords: Nd:YAG laser; fiber optic beam delivery; nuclear reactor; coolant channel; pressure tube

1. Introduction

Lasers are increasingly finding applications in several different aspects of nuclear reactors and fuel cycle [1]. Solid-state lasers with fiber optic beam delivery have been found to be extremely useful tools for material processing applications such as cutting, welding and drilling in radioactive environment due to ease in tool handling, flexibility, non-contact nature, longer tool life, low MANREM consumption with enormous time and cost savings. Laser material processing in nuclear field is mainly concerned with maintenance of nuclear power reactor parts by laser cutting/welding, fabrication of new components, and nuclear power reactor decontamination and decommissioning. In addition, lasers are also being increasingly used for remote diagnostics for nuclear operation and precision metrology in nuclear fuel cycle.

*Corresponding author. Tel.: +91-731-2321341; fax: +91-731-2321343
E-mail address: pdgupta@rrcat.gov.in
Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, with its innovative research and indigenous technology base, has developed and deployed a large number of laser-based systems for applications in Indian nuclear power programme. Several high power Nd: YAG lasers along with fiber optic beam delivery systems have been developed which serve as robust industrial tools with remote control operation. About 20 such laser systems have been commissioned in different DAE units for various cutting and welding applications. Some of these are: a) Laser cutting of bellow lips during en-masse coolant channel replacement (EMCCR) in pressurized heavy water reactors, b) Laser cutting of single coolant channel, c) Laser cutting of irradiated fuel sub-assembly of fast breeder test reactor, d) Laser cutting of pressure tubes removed from reactors during EMCCR for easy storage, e) Underwater cutting of spent fuel with lasers, f) Decanning of rejected fuel bundles, g) Repair of leaking weld-joint inside calandria, h) Laser micro-welding of high dose rate brachytherapy capsules etc. A high stability CW Nd: YAG laser has also been developed for laser rapid manufacturing for fabrication of component of dissimilar metals and directly from CAD model. This should find applications in the manufacture of compositionally graded components for use in nuclear reactors. In addition, to meet future requirements, development of laser systems and technique for nuclear decontamination and decommissioning is also underway. Next, several laser-based diagnostics and metrology systems have been developed which include a) Laser uranium analyzer, b) Optical dip-type probes for remote plutonium measurement, c) Laser scan gauge for mixed carbide fuel metrology, d) Fuel pellets inspection system, e) Laser non-destructive testing systems for structural components of reactors, f) Underwater inspection head for metrology of FBTR spent fuel bundles etc. In this paper, we present a brief description of high power solid state laser development at RRCAT and laser-based systems for material processing and diagnostic applications in various aspects of reactor operation, and metrology applications in fuel cycle for the Indian nuclear power programme.

1.1. Solid-state laser development at RRCAT

Over the last two decades, lamp pumped Nd:YAG lasers have proven to be the workhorse in industrial environment. High power Nd:YAG lasers with fiber optic beam delivery have been exploited commercially for various material processing applications such as cutting, welding, drilling etc. in harsh environments. In order to enhance the quality and range of material processing applications, it is desirable to deliver the beam through an optical fiber with core diameter and numerical aperture as small as possible. Thus, to cope up with the demands of material processing applications, higher and higher power Nd:YAG lasers with improved beam quality are being developed worldwide. The basic configuration of a lamp pumped Nd:YAG laser consists of a pump cavity containing a flash lamp and a Nd:YAG rod within a gold coated elliptical reflector or a close coupled diffuse reflector and an optical resonator suitably designed to achieve high output power and better beam quality. Assessing the advantages of fiber coupled Nd:YAG lasers in applications related to Department of Atomic Energy, an industrial laser system of 250 W average power, 2-20ms pulse duration and 1-100Hz repetition rate having 5 kW peak power and 100 J maximum pulse energy was developed [2]. This system is pumped with 5 kW input electrical power and provides an electrical to laser conversion efficiency of about 5%, which, to the best of our knowledge is the highest as compared to any commercially available lamp pumped Nd:YAG laser. This fiber-coupled Nd:YAG laser system has four time-shared fiber ports, each of them has a fiber of 400 μm core diameter, 0.2 numerical aperture (NA) and 150 m length. Specially designed material processing nozzles of diameter in the range of 12 mm to 25 mm with gas flow through the same tube containing optical fiber were developed for applications having space restrictions in nuclear power installations. Using this, cutting of stainless steel sheets up to 14 mm and welding up to depth of 2 mm were established. This remotely operable laser system has been engineered for its robustness with proper fixtures and toolings for various material processing operations on industrial scale. Now, it has been scaled to 500W average power with 2-40 ms pulse duration and 1-100 Hz rep. rate with ~10kW peak power, 300J pulse energy and 400μm fiber optic beam delivery for laser cutting of up to one inch thick SS and weld depths in SS up to 6 mm [3].
Fig. 1 shows a view of the 250 W average power industrial Nd:YAG laser and Fig. 2 shows a view of 500 W average power industrial Nd:YAG laser developed in-house at RRCAT. High power CW lasers have also been developed with an output power of 880 W having 4.4% electrical to laser conversion efficiency [4]. CW laser with power scaling using multi-cavity design and modulation is useful in deep penetration welding and laser rapid manufacturing. One such CW laser system has been developed and commissioned at MSD, BARC for laser rapid manufacturing. Fig. 3 shows a view of this CW Nd:YAG laser.

Development of high-performance materials is often needed in nuclear applications, which requires measurement of thermal conductivity variation with temperature. It is very difficult and time-consuming to measure thermal conductivity at high temperatures and it also requires large specimens for conventional methods. The method of laser flash to measure thermal diffusivity is relatively fast and
requires very small amount of material, which is an important consideration in research on new experimental materials. A high energy short pulse Nd:YAG laser has also been developed for thermal diffusivity measurement of high-performance materials [5]. This lamp pumped Nd:YAG laser system provides a short duration (1 ms) laser pulse with variable laser energy from 1 J to 18.5 J. Four such laser systems for thermal diffusivity measurement have been commissioned in IGCAR and BARC for regular use.

2. Laser material processing applications in nuclear power programme

To introduce laser material processing applications in nuclear power programme, we begin with the design of pressurized heavy water reactors (PHWR), which is characterized by natural uranium fuel, heavy water as moderator, pressure tube containment of primary coolant, fuel bundles and ON POWER refueling. PHWR reactors of 220 MWe have typically 306 coolant channels, which are mounted horizontally within a horizontal cylindrical vessel, called Calandria and is surrounded by low pressure, low temperature heavy water moderator. A single coolant channel is a composite structure of end fittings, liner tube and a pressure tube. These pressure tubes, which contains fuel bundles, is made up of Zr-2 or Zr-2.5% Nb alloy and is attached with SS-403 liner tube and end fitting by means of rolled joints. Further, each end fitting is connected to a coolant pipe (feeder) by hub joint with a seal ring and high-pressure feeder coupling (HPFC) studs. Annular space around the coolant channel is sealed by a metallic bellow and CO₂ is circulated in it. It is essential to replace the pressure tubes in PHWR type of nuclear reactors after a period of 10-15 years and this replacement is performed during en-masse coolant channel replacement (EMCCR) campaign of such reactors. This is a complicated process due to space restrictions and high MANREM involvement. The 306 coolant channels placed in a matrix are very close to each other and bounded to the core of the reactor by means of two shrink fit welded bellow attachment rings, made up of carbon steel, one on each face of reactor core located at a distance of about 945 mm from E-face of end fittings i.e., from end point of coolant channel. These coolant channels can be replaced, if the welded bellow rings are detached at the welding point on each end. This requires grooving at the welding point up to the depth of welding (~3-4 mm) and then pulling the channel. Although, single point mechanical cutters can be utilized for this operation, but these mechanical cutters are bulky, require their frequent replacement and take long time to cut, which results in higher MANREM involvement. In the following a brief description of a few massive laser material processing applications in nuclear power programme carried out during past few years is presented.

2.1. Laser cutting of bellow lips during EMCCR

The mechanism for laser cutting of bellow lips developed at RRCAT consists of a motorized circumferential rotary arrangement, which can be mounted on the E-face of coolant channel and can be fixed on it just by tightening of a single bolt. The tool is designed to fit on E-face of end fitting using bore of the end fitting [6]. The locking of this tool is based on tapered ball locking grip at sealing plug position of end fitting. Specially designed material processing nozzles of 1/2 inch diameter with gas flow through the same tube containing optical fiber were developed for applications having space restrictions in nuclear power installations. Using this system, laser cutting of 612 bellow lips during EMCCR of NAPS#1, NAPS#2 and KAPS#1 reactors have been performed successfully in May 2006, Nov. 2008 and Feb. 2009 respectively. It is desired to separate the bellow rings in such a way that the outer ring can be reused for welding at the time of recommissioning. This required grooving of the ring at weld location up to a depth of ~4 mm. It is easy to cut through and through using laser beam while it is very difficult to make grooves in a material. The laser grooving technique for carbon steel was established specially for this purpose.

Two industrial Nd:YAG lasers with four port time shared fiber optic beam delivery and 150 m long fiber optic cable were deployed for cutting of bellow lip, one on each north and south vaults of these 220 MWe reactors and in-situ bellow lip cutting was performed and separation was ensured for all the 612 bellow lips. The fixing of tool on any of the coolant channels required about one minute and the cutting process took ten minutes for each bellow lip, and total operation was completed within a few days of laser operation. Laser cutting of 18 numbers of shock absorber yoke studs was also performed during EMCCR activity to access bellow lip weld for laser cutting. These studs were jammed and could not be opened by any mechanical means. This resulted in a large MANREM saving as compared to
conventional technique and also time saving of at least six months with enormous cost saving. As compared to previous campaign of laser cutting of bellow lip during EMCCR of NAPS#1 reactor, about 30% less MANREM was consumed and bellow lip cut quality was improved, which resulted in much safe separation of bellow rings. Fig. 4 shows the fixture mounted on a coolant channel performing the cutting process in mock-up. Fig. 5 shows the laser cut and separated bellow lip. Fig. 6 & 7 show the fixture mounted on E-face of one of the coolant channels in NAPS#1 and NAPS#2 reactors, respectively. Fig. 8 shows welded bellow lip. The same fixture was utilized for re-welding of bellow lip during re-installation of coolant channels. This fixture is able to hold laser welding nozzle as well as TIG welding torch. Fig. 9 shows fixture mounted on end face of coolant channel for cutting of HPFC stud in mock up and Fig. 10 shows laser cutting of HPFC stud. Fig. 11 shows laser cut shock absorber studs from NAPS#2.

Prior to bellow lip weld cutting, it is necessary to remove obstruction of all the 612 shock absorber yoke assembly and its 1224 studs. In previous EMCCR campaign at NAPS#1, it was found that in serious attempts to open a few jammed shock absorber studs, shock absorber yoke assembly studs were broken from end shield. This required a lot of effort to make threads at proper location in end shield during re-commissioning process of reactor coolant channels. To avoid this difficulty, laser cutting technique and fixture for 18 mm diameter shock absorber yoke assembly studs was also developed at KAPS site (in a similar fashion as at NAPS#2) to cut these studs near the bellow lip weld joint to remove obstruction for bellow lip weld cutting and also to avoid damage of stud threads in end shield. Out of 1224 studs, a total of 78 were found jammed and using laser technique, these studs were cut successfully and safely near the bellow lip weld joint during EMCCR campaign at KAPS#1. Now, the laser based cutting technique for EMCCR of PHWRs has been established and can be exploited in future EMCCR campaigns.

Fig. 4. Bellow lip cutting mock-up.

Fig. 5. Separated bellow lip.

Fig. 6. A site view of laser based bellow lip cutting in NAPS#1 reactor.
Fig. 7. A site view of laser based bellow lip cutting in NAPS#2 reactor.

Fig. 8. Welded bellow lip.

Fig. 9. Fixture mounted on coolant channel for laser cutting of HPFC studs.

Fig. 10. Laser cutting mock-up of HPFC studs.
2.2. In-situ laser cutting of a single coolant channel at KAPS#2 reactor

Laser cutting technique along with fixture was developed and deployed successfully in January 2005 for in-situ cutting of single coolant channel S-7 from inside of the channel, which includes cutting of 4mm thick liner tube and 12mm thick end fitting made up of SS. Total cutting time was 12 min. This was cut to generate data on Zr-2.5%Nb pressure tubes used for the first time in KAPS#2 reactor after a life of 8 years.

Kakrapar Atomic Power Station#2 is the first reactor in which Zr-2.5%Nb pressure tubes were used and it was required to generate data on these kind of pressure tubes. It was decided to take out one of the pressure tubes after about eight years of reactor operation. To extract pressure tube, it was required to cut liner tube and end fitting from inside due to space restrictions. This cutting was performed remotely by laser cutting fixture specially designed with several innovative ideas. The coolant tube cutting fixture developed is described briefly here. The tool fixing mechanism consisted of two disks made up of Aluminium, one of them gets attached at E-face and the other disk is inserted inside end fitting through a dual rod handle which comes out from two diametrically opposite holes in the first disk and holds the two disks together and can also fix the separation of the two disks.

There is a third long screw, which passes through the first disk and is attached to the second disk. Tightening of this third screw pushes movement of a button out of the disk diameter and helps in locking this disk with the inner diameter of the end fitting and the whole fixture. The motion of nozzle for circumferential cutting from inside of the tubes has been motorized by means of a DC motor and a geared coupling of fixture with the motor. Tool fixing time was about one minute and total cutting time was four minutes for linear tube and ten minutes for end fitting with enormous MANREM, time and cost savings. Fig.13 shows a mock-up of coolant channel cutting [7].
2.3. Laser cutting of FBTR spent fuel subassembly

Laser cutting for dismantling of highly radioactive fuel subassemblies of FBTR was successfully carried out in hot cell at IGCAR, Kalpakkam using a fiber coupled industrial Nd:YAG laser (250 W average power and 5 kW peak power). The Pu-U carbide fuel rods had undergone a burn-up of 154 GWd/t and had a radiation level of $10^7$ rad/hour. This fuel assembly was precisely cut at a gap of 5 mm from the position of the fuel pins for Post-Irradiation Examination (PIE) of burnt fuel. The following were cutting parameters: total cutting time of the subassembly ~2 minutes, cutting speed ~120 mm/minute, cut width of 400 μm. Compared to the conventional mechanical methods there are several advantages in laser cutting like: it is fast, does not lead to contamination and secondary waste generation, does not create shape deformation and stress on surface, which is important for measuring swelling, cracks, and stress of a burnt subassembly at different locations [8].

The laser beam was delivered through a 400μm optical fiber with a focused spot size of 400μm on the job to minimize waste generation. The laser system has a dual port time shared fiber optic beam delivery, with one fiber port for optimization of cutting process outside the hot cell, and another for cutting inside the hot cell. A compact, shielded cutting nozzle assembly of 20 mm outer diameter containing beam delivery fiber and coaxial flow of the assist gas was specially developed for insertion through the S-bend in hot cells. Due to the presence of highly radioactive sodium, cutting was carried out with nitrogen as an assist gas at a pressure of 8 kg/cm². Now, this technique of laser cutting of FBTR spent fuel subassembly is in regular use at IGCAR since past three years for PIE data. Fig. 14 (a), (b) and (c) show laser cutting of hexagonal FBTR spent fuel during mock up, cut sample and actual cutting in hot cell.

This industrial Nd:YAG laser was also deployed at Nuclear Fuel Complex (NFC) to extract fuel from rejected fuel pins of PHWRs and fuel from about 65 tons of rejected storage was extracted within a period of one year.
2.4. Laser cutting for easy storage of pressure tubes removed from reactors during EMCCR

Laser cutting technique was developed and successfully deployed for cutting of 7 pressure tubes made up of zircaloy material, which were removed from MAPS#1 reactor. These tubes of 5m length were cut in two pieces to establish laser cutting technique for reduction in storage space with a radiation level of 700 Rad/h [9].

Pressure tubes in PHWRs are about 5m in length and are highly radioactive. After EMCCR operations, these tubes are stored as such and require a large space. For initial study, a laser based cutting fixture was designed and deployed for cutting of seven pressure tubes removed from MAPS#1 in two halves to reduce storage space. This will be further deployed in mass cutting of pressure tubes by slotting the pressure tube linearly in three pieces using three nozzles simultaneously at 120° with each other and then cutting it circumferentially after a certain length. Fig. 15(a) shows pressure tube cutting fixture and cutting mock up and Fig. 15(b) shows a cut samples from pressure tube.

2.5. Under water cutting of spent fuel with lasers

There are several requirements from NPCIL to cut nuclear components underwater in water pool at a depth of about 8-10 m. In Dhruva reactor also, it is required to cut Aluminium racks of 3 mm thick. In this regard laser cutting technique using fiber optic beam delivery has been developed for cutting of SS
up to a thickness of 12mm and aluminium of thickness 4 mm. Development of fixture for underwater cutting of Aluminium rack of irregular orientation is under progress. Fig. 16 shows underwater cutting of 4.2 mm thick zircaloy [10 – 12].

2.6. Repair of water leak from weld joint inside calendria at KAPS#1 reactor

There was leak from a few weld joints inside calendria of KAPS#1 reactor since its commissioning. It was decided to repair this leak during EMCCR campaign. Due to high radiation field near the leak position, laser welding technique with remote operation was decided as an option. Development of required fixture for remote laser welding operation and nozzle for welding along with laser weld qualification has been carried out and its implementation at site is under progress. Fig. 17 shows a view of wire rope based three axis remotely operable fixture developed for welding in high radiation field.

2.7. Decanning of rejected fuel bundles

Using laser cutting technique, extraction of fuel pellets from rejected fuel bundles was also carried out at NFC by cutting the fuel pin linearly and giving a thrust on fuel pin. Using laser cutting technique about 65 tonnes of fuel pellets were decanned, which were piled up due to rejection during fabrication process. Dismantling of spent fuel bundles from PHWRs by cutting end plates is also being carried out regularly in hot cell at BARC by using laser from RRCAT. Figure 18 (a) shows a view of laser cutting of end plate of fuel bundle in hot cell. Fig. 18 (b) & (c) shows intact fuel bundle and dismantled fuel bundle.
2.8. Laser welding of high dose rate brachytherapy assembly

Treatment of cancer by using radiation emitted from the radio-isotopes is in practice for decades. Teletherapy and Brachytherapy are widely used for this purpose. In teletherapy, the cancerous volume is irradiated by gamma rays emitted by radio-isotopes. Brachytherapy is one of the most efficient ways of treating cancers such as localized uterus cancer and cancers of the head and neck. Brachy is from the Greek word for "short", hence, brachytherapy approximately means short distance therapy. This is essentially a supplementary radiotherapy, where a radioactive source is placed inside or next to the area requiring treatment. High Dose Rate (HDR) Brachytherapy is a common brachytherapy method used for treatment of a large number of cancer patients. Applicators in the form of catheters are arranged on the patient. A high dose rate source (often Iridium-192) is then driven along the catheters on the end of a wire by a machine while the patient is isolated in a room. The source remains in a preplanned position for a preset time to allow controlled doses of radiation to be delivered to the cancerous tissues, without damaging the healthy tissues. The capsules that hold the radioactive 'seed' are only a few millimetres long, and about a millimeter in diameter and have a wall thickness of less than 150 μm.

The welds that join the capsules together (five weld joints) need to produce a hermetic seal, with a smooth weld bead. Presently, hospitals in India engaged in providing Brachytherapy, use imported HDR source assembly, which consists of radioactive material, miniature housing with cover and metallic wire ropes [13]. BARC with the help of RRCAT is developing indigenous HDR source assembly for BRIT. The quality of the indigenously developed HDR source assembly is matching with the imported ones, and will be considerably less expensive. This assembly has been tested in accordance with the AERB (Atomic Energy Regulatory Board) and IAEA (International Atomic Energy Agency) stipulated test procedures and guidelines. Based on the literature survey and after giving due consideration to various joining methods like friction welding, micro-TIG welding etc., laser welding has been chosen as the mode of joining the miniature SS components with the SS wire ropes. As compared to other welding techniques, laser welding is advantageous in terms of heat affected zone (HAZ), pointed and localized heating with better bead quality. A typical HDR source assembly, has four miniature SS micro machined components viz.; machine end terminal, rope joining sleeve, source retaining capsule and cover and two SS wire ropes (dia 0.91 and 0.73 mm). There are five laser welded joints between SS wire ropes and miniature components. Laser welding of miniature components has been performed without any damage. A laser welding system with 200μm fiber optic
beam delivery and required arrangement has been developed at RRCAT, which will be commissioned at BRIT for regular production of HDR brachytherapy assembly. Fig. 19(a) and (b) show the brachytherapy assembly and laser welded sample of this assembly.

![Diagram of brachytherapy assembly](image)

Fig. 19. (a) Brachytherapy assembly having HDR Source (b) Welded Brachytherapy assembly.

3. Laser-based diagnostic and metrology systems

Lasers are increasingly being used for measurement, inspection and metrology in industrial applications. Laser-based techniques have the advantage of being non-contact in nature, which enable development of many instruments for nuclear application that are not realizable using conventional gauging techniques. Moreover the non-contact nature of laser-based measurement ensures minimal contamination, low wear & tear and good repeatability. Since metrology and inspection can be done in an automated process, radiation dosages to operators and work personnel is also minimized. Keeping these points in mind development of laser-based measurement techniques and instruments were taken up at RRCAT. Based on the end-use requirement, laser-based instruments have been designed, developed and delivered to end users in various units of DAE. Some of the instruments developed are briefly described in this section.

3.1. Laser uranium analyzer

Measurement of uranyl salt concentration in ground water is used to locate uranium deposits. This requires measurement of uranium in water at ppb level concentrations. Since uranium salts fluoresce when irradiated with ultraviolet light, the fluorescence can be used for measuring concentration of uranium in water samples. In order to be able to measure uranium concentration to level of ppb it is necessary that the fluorescence arising from uranyl salts be separated from that arising from the organic impurities present in the ground water. Since the organic fluorescence decays much faster (decay time ~ few ns) compared to the fluorescence from uranyl salts (few hundred μs) a convenient approach is to excite fluorescence with a ns duration pulsed source of light (337 nm N2 laser) and use a gated detector that can be switched on after a delay of few tens of μs from the excitation pulse. This way, one can filter out the organic fluorescence and measure uranium fluorescence with high sensitivity. Development of a miniature metal-ceramic sealed-off nitrogen laser rugged enough for field use was taken up as a light source for this application. The compact Laser Uranium Analyzer developed using the miniature nitrogen laser system measures only 150mm x 110mm x 90mm and operates from a 12V power supply making it suitable for field use. This instrument can measure uranium in water with a resolution of 0.05 ppb and has a range of up to 20 ppb. The laser uranium analyzer, apart from being used in uranium exploration is also useful for uranium measurement in reactor chemistry, health physics, effluent
monitoring and environmental survey. Several of these instruments (Fig. 20) have been supplied to various users in AMD, IGCAR and HWPs. The technology for this instrument has been transferred to Quantalase Enterprises Pvt. Ltd., Indore, for production.

![The compact laser uranium analyzer](image)

The uranium analyzer is based on a miniature sealed-off nitrogen laser which needs to be re-filled after a year. The Reprocessing Development Lab (RDL) of IGCAR was interested in using the system for measuring uranium in the re-processing raffinate which would require putting the uranium analyzer inside a glove box precluding any kind of service/maintenance or re-filling of the tube. To solve this issue a system based on a high power UV LED (200mW at 385nm) was developed and has been delivered to RDL of IGCAR for use in the measurement of uranium in active samples. The developed LED based system achieves the sensitivities comparable to the laser based system. Field trial of this version of the laser Uranium analyzer is in progress.

A micro-fluidic version of the Laser Uranium Analyzer is being developed for measurement of Uranium in active samples. Use of miniscule quantities for measurement should reduce the radiation dose to personal as well as minimize the radioactive waste generated due to analytical measurements during the reprocessing cycle.

### 3.2. Remote Pu measurement

Fiber optic absorption probes of different path lengths from 5mm to 100mm have been designed and developed for remote Pu Spectroscopy for use at Reprocessing Development Lab (RDL) of IGCAR. The probes (Fig. 21) are used in conjunction with a fiber coupled spectrophotometer to acquire absorption spectra of samples remotely. A detection limit of 12μg/ml for Pu has been achieved. Patents for the probes and the remote Pu measurement technique have been applied for jointly with RDL of IGCAR.
3.3. Nuclear fuel pellet metrology

Most nuclear fuel pellets are made from ceramic powders by sintering. These have to meet stringent
criteria in regards to its diameter, length, weight and density before acceptance for loading in a
fuel pin. Instruments required for this purpose have also been developed taking into account the nature
of the fuel.

3.3.1. Uranium oxide fuel:

Uranium oxide fuel pellet dimensions need to be within a tolerance of ± 25μm and the density needs
to be estimated to second decimal digit accuracy. The diameter of pellet is measured at three cross-
sections and length is measured along one cross-section. We have developed an instrument, which
makes use of laser scanning technique to measure diameter and length with the desired resolution and
minimizes handling of the pellet. In this approach, the pellet is scanned with a laser beam and the time
duration for which it obstructs the scanned laser beam is measured. The laser-gauging unit, a schematic
of which is shown in Fig. 22 consists of an optical polygon mounted on a brushless dc motor that scans
the laser beam and a collimating lens that generates the line scan. The pellet to be measured is placed in
the collimated scan region.

Fig. 21. Fiber optic dip-type probes with different optical path-length tips

Fig. 22. Schematic of the laser scan gauge.
Three laser gauging units were used to measure the diameter of the pellets at three equally spaced cross-sections and to measure length of the pellet across one cross-section. The measured diameter and length of the pellet are used to calculate the geometric volume of the fuel pellet. With an accuracy of $\pm 2\mu m$ for the laser scan gauges and an accuracy of $1mg$ for the weighing machine, the density of the pellet could be calculated to second decimal digit accuracy. This system was developed for NFC, for their UO2 fuel fabrication line.

3.3.2. Mixed carbide fuel

Mixed carbide fuels are alpha-active and have to be handled in a glove box. The laser scan gauges developed for this application are of a retro-reflective design so that the transmitting and receiving optics sit in the same unit and the pellet can be measured through a single window in the glove box. The pellet sits on a precision machined V-block mounted inside the glove box on the load cell of the weighing machine. The retro-reflective optics is mounted on the V-block assembly. The transmitting optics with the scanner elements, the receiving optics with the associated electronics for diameter and length measurement and the electronics of the weighing machine are located outside the glove box in a single unit. This design ensures that only passive components are inside the glove box and all items that need maintenance are outside the glove-box. The prototype system developed for the metrology of mixed carbide fuel is shown in Figure 23. The developed system has a resolution of $1\mu m$ and can measure the fuel pellets with an accuracy of $\pm 2\mu m$. This system has been developed for Radio Metallurgy Division, BARC for their FBTR fuel fabrication line.

![Fig. 23. Nuclear fuel metrology system for mixed carbide fuel](image)

3.4. Laser NDT systems for mechanical component testing

Structural components of reactors are designed and analysed for mechanical stability and deformation using finite element codes. To validate these designs, scaled down models of these components are tested by loading with the required stress and measuring the generated strain. Conventional techniques using strain gauges take a long time to setup; are manpower intensive and are complicated by the large number of data acquisition channels that need to be used simultaneously to measure the strain field. Laser based techniques such as shearing speckle interferometry can greatly simplify the strain analysis of loaded structures. Moreover these techniques are more sensitive and can generate a larger density of data than what are possible using strain gauges. A speckle shear interferometer (Fig. 24) has been designed and developed to do strain measurements on scale models. Shearing speckle interferometry is an optical method based on the principle of speckle correlation where an interferometer is used in shearing mode. This and other laser based systems are being developed for inspection and non-destructive testing of structural components for reactors, at the Structural Mechanics Lab of IGCAR.
Fig. 24. The speckle shear interferometer developed for NDT of structural components

3.5. Under water inspection system for metrology of FBTR spent fuel bundles

The spent FBTR Fuel at IGCAR is kept under water for cooling and shielding. These spent fuel need to be inspected as part of the post-irradiated examination to generate data about the fuel integrity and projected life. One of the first measurements that need to be done is the dimensional gauging of the whole fuel bundle assembly. RRCAT was requested by the MMG group of IGCAR to explore the possibility of developing optical techniques that can be used for inspection under water in a non contact way. A triangulation sensor based optical probe head has been developed for the under water inspection of the spent fuel. The laser triangulation sensor comprises of a laser diode module, an imaging lens and a linear position sensitive detector. The probe is positioned in such a way that the laser beam falls normally to the surface to be detected. The light scattered from the object is imaged onto the linear position sensitive detector by the lens system. A change in the surface contour of the object leads to a change in the position of the image spot on the linear position sensitive detector. The Fig. 25 shows the developed triangulation head on a calibration setup.

Fig. 25. Triangulation head for underwater inspection

This triangulation head would be used in conjunction with a robotic system built by IGCAR, for moving the optical probe underwater. After successful trials are completed similar systems would be developed for use in underwater inspection of spent PFBR fuel in the future.
4. Conclusion

In conclusion, RRCAT has developed high power industrial Nd:YAG lasers and deployed them successfully on industrial scale for refurbishing and maintenance operations in nuclear power reactors with significant savings on MANREM, time and cost. A number of laser-based diagnostic systems for nuclear operations and mineral exploration and metrology of nuclear fuel have been developed and deployed. RRCAT is also working on development of short pulse Nd:YAG lasers with fiber optic beam delivery for decontamination purposes and kW-level power Nd:YAG lasers for decommissioning of nuclear power plants in future.

Acknowledgement

This paper is based on work carried out in the Solid State Laser Division and Laser Biomedical Applications and Instrumentation Division of Raja Raman Centre for Advanced Technology, Indore. Thanks are due to B. N. Upadhyay and Sendhil Raja for their help in preparation of this article.

References