Theme Article-1

T.1 : Laser based instruments for the nuclear fuel cycle

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Introduction: The nuclear fuel cycle involves various stages right from uranium prospecting, to spent fuel inspection and reprocessing. At each stage of the fuel cycle, instruments are required for monitoring different parameters with high sensitivity and accuracy. For example, uranium prospecting demands measurement of the concentration of uranium salts in ground water to an accuracy of 0.1 ppb and for reprocessing the spent fuel, it is necessary to regularly monitor the integrity of the reprocessing vessel used, to avoid accidental leakage of radioactivity. In many of these measurements, in order to avoid possible radiation exposure to personnel, remote measurements are needed. At RRCAT, several laser-based instruments have been developed to meet the requirements of the different stages of nuclear fuel cycle. In this article we provide a brief overview of some of these developments.

1. Prospecting of Uranium:

In regions close to uranium deposits, the concentration of uranyl salts in ground water is expected to be higher. Since uranium salts fluoresce when irradiated with ultraviolet light, the fluorescence can be used for measuring concentration of uranium and thus locate uranium deposits. However, the concentration of uranium in water is expected at ppb level and for measurements at these low concentrations it is necessary that the fluorescence arising from uranyl salts be separated from that arising from the organic impurities present in the ground water. For this purpose one convenient approach is to exploit the fact that the organic fluorescence decays much faster (decay time ~ few ns) compared to the fluorescence from uranyl salts (few hundred μs). Therefore, one can filter out the organic fluorescence and measure uranium fluorescence with high sensitivity by using a ns duration pulsed source of light (337 nm N_2 laser) to excite fluorescence and measure fluorescence after a delay of few tens of μs from the excitation pulse by use of a gated detector. Indeed, the instruments procured by Atomic Minerals Directorate (AMD), DAE, from Scintrex, Canada, for U prospecting work were based on this approach. At RRCAT, the development of a uranium measurement system to meet the requirements of DAE units was initiated in 1992. Although the technology for the flowing gas nitrogen laser was available at RRCAT, fabrication of a table-top uranium analyzer system necessitated the development of a compact nitrogen laser using a sealed nitrogen laser tube. The glass-to-metal joint and sealed spark-gap required for this purpose were developed at RRCAT and the table-top system made using the sealed laser system is shown in Fig.T.1.1. The resolution of the system was measured to be ~ 0.1 ppb and its measurement range was up to 10 ppb. It is pertinent to note that in the system developed at RRCAT we used a spark gap to switch the discharge instead of a thyratron used in the Scintrex instruments. This not only made the system compact and cheaper, but also led to the advantage that the instrument could be used immediately after switching on and entailed no warm-up time, which was the case with the Scintrex instrument. The instrument was also provided with a digital data acquisition system with a RS232 interface for connecting to a computer for data logging. This made recording and analysis of the data very convenient.

Fig.T.1.1: Tabletop system developed for Uranium analysis.

Fifteen of these instruments have been given to various end users in AMD. As AMD uses some of the uranium analyzers in the field and in mobile geological survey vans, there was requirement for a portable instrument suitable for field use. The attempts to scale down the glass laser tube used in the table-top instrument were not very successful because the inductance of the feed-through pins limited the laser efficiency. Therefore, development of a miniature metal-ceramic sealed-off nitrogen laser tube, rugged enough for field use was taken up. Since a reduction in active gas volume also puts greater demands on the cleanliness of the tube and the quality of sealing, to ensure high tube life and efficient laser operation strategies to address these aspects were also worked out. The power supply of the laser system has also been made more compact by miniaturizing the spark gap switch and evolving the processing parameters required to ensure repeatable switching characteristics of the spark gap. The developed miniature nitrogen laser system is shown in Fig.T.1.2. Surface mount technology was used to miniaturize the electronics and data acquisition boards. The compact "Laser Uranium Analyzer" developed using this miniature nitrogen laser system is shown in Fig.T.1.3. Its small dimensions (150mm x 110mm x 90mm) and the fact that it can operate from a 12V power supply makes well suited for field use.

Fig.T.1. 2: Miniature nitrogen laser system.

Due to the improvement in fluorescence collection and detection system, this instrument has a resolution of 0.05 ppb and a range of 20 ppb. The technology for this instrument has recently been transferred to Quantalase Enterprises Pvt. Ltd., Indore.

Seven of the laser uranium analyzer units, have been supplied to end users in Nuclear Fuels Complex, Heavy Water Plants, Environment Assessment Division of BARC and Fuel Chemistry Division of IGCAR, where these are being used for uranium measurement in reactor chemistry, health physics, effluent monitoring and environmental survey.

Fig.T.1. 3: Laser Uranium Analyzer.

2. Quality assurance of nuclear fuels :

Most nuclear fuel pellets are made form ceramic powders by sintering. These have to meet stringent specifications 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 keeping into account the nature of the fuel.

i. Uranium oxide fuel: For the preparation of Uranium oxide fuel used in PHWR, the natural uranium oxide powder is pressed in a die and the pressed "green" pellets are sintered in a furnace. Subsequent to sintering, the pellets are ground on a centreless grinder to tight tolerance. The pellet dimensions need to be within a tolerance of ± 25µm and the density needs to be estimated to second decimal digit accuracy. Usually diameter of pellet is measured at three cross-sections and length is measured along one cross-section. With conventional mechanical instruments such as vernier-calipers, not only it is difficult to ensure accurate repetitive measurement but the pellet needs to be handled multiple times. We have therefore developed an instrument that 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.T.1.4 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.

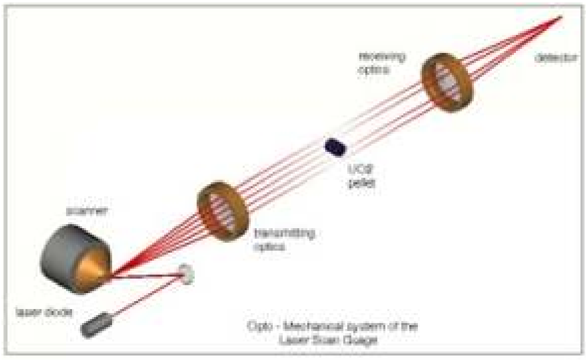

Fig.T.1. 4. Schematic of the laser scan gauge.

In the first prototype unit developed for the metrology and density estimation of UO_2 fuel pellet we had four laser gauging units and an electronic weighing machine integrated together to measure the dimensions and the weight of the pellet simultaneously. Three laser gauging units were used to measure the diameter of the pellets at three equally spaced cross-sections and the fourth was used to measure length of the pellet across one cross-section. The measured diameter and length of the pellet was used to calculate the geometric volume of the fuel pellet. Given an accuracy of ± 2µm for the laser scan gauges and the accuracy of 1mg of the weighing machine, the density of the pellet could be worked out to second decimal digit accuracy. Subsequent to the trials of the prototype system at NFC, a second version of the Density Measurement Station (DMS) has been developed using a multiplexed optical system to reduce the electronic complexity. In this improved version, a single scanner is used to generate the four scans using an optical multiplexing prism resulting in a more robust instrument. The electronics has been implemented in Field Programmable Gate Arrays (FPGA) to make the electronic sub-system reliable and compact. This version of the instrument is shown in Fig.T.1.5.

Fig.T.1.5: Density measurement station.

Another significant advancement made in this version was that the opto-mechanical system was redesigned to reduce the total length of the system and thus reduce the thermal sensitivity of the system. Three of these systems have been supplied to NFC for field-testing on the shop floor. Subsequent to the testing of these systems in the field, transfer of technology for this instrument would be taken up. These systems should also find use in other manufacturing industry.

ii. 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 an optical (fused silica) window mounted on 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. This design ensures that only passive components are inside the glove box and all items that need maintenance are outside. The prototype system developed for the metrology of mixed carbide fuel is shown in Fig.T.1.6. The developed system has a resolution of 1µm and can measure the dimensions of the fuel pellets (few mm in size) with an accuracy of ± 2µm. This system has been developed for Radio Metallurgy Division, BARC for their FBTR fuel fabrication line.

Fig.T.1.6: Nuclear fuel metrology system for mixed carbide fuel.

3. Inspection of spent fuel:

Spent fuel after being taken out of the reactor needs to be inspected for defects, failure and swelling. Conventionally LVDT (linear voltage differential transformer) based contact systems have been used for the profiling of the spent fuel for post irradiative inspection. As the radiation levels near these fuel elements are very high, optical systems are better suited for this purpose as these can provide non-contact measurements and are also easier to radiation hardened than electronic systems. Keeping in view this objective a laser triangulation sensor has been developed to meet this requirement. The laser triangulation sensor comprises of a laser diode module, an imaging lens and a linear position sensitive detector. In Fig.T.1.7 we show the optical probe and a schematic of the optical design. The probe is positioned such 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 position sensitive detector has an accuracy of 0.2% of the spot size. The developed sensor has a range of ± 5mm and a resolution of 5µm. This sensor can be used for point-wise profiling of objects for inspection and metrology. A fiber-coupled radiation hardened version of this laser triangulation probe is being developed for the remote profiling and inspection of spent fuel bundles of FBTR. The sensor apart from being radiation-hard will also have to be water tight and designed for underwater operation, as the spent fuel bundles will be inspected under water.

Spent fuel of FBTR is reprocessed by using an electrolysis process wherein the fuel is dissolved in nitric acid in a dissolver vessel made of titanium. Due to the use of high concentration of nitric acid at high temperature, the vessel gets corroded fast and hence periodic monitoring to assess the extent of corrosion is desirable using non-destructive examination (NDE) techniques. A laser triangulation based ID scanning system has been developed for this application for use at IGCAR. The inspection system consists of a radially measuring laser triangulation sensor and a Z-θ robot for the 3D profiling of the inner surface of the dissolver vessel. The inner surface of the vessel to be scanned is 540 mm long seamless Ti pipe of 100 mm internal diameter. For the introduction of the system into the dissolver vessel, it should fit in the bag-in and bag-out facility for lead-mini-cell, the dimensions of which were 250 x 250 x 250 mm. Since a fixed system with rotating laser head was too large to get bagged in, a Z-θ robot based on a lowering mechanism was developed. The system has a scanning resolution of 100 micron in Z and θ direction and 15 micron in depth. A Graphical User Interface (GUI) has been developed for the control and automation of the inspection system. Fig.T.1.8 shows a close-up of the inspection head and a screen shot of the GUI. Mock studies have been carried out using a 'Ti test bed' and pickled vessel at IGCAR. A radiation-hardened version of this system is under development.

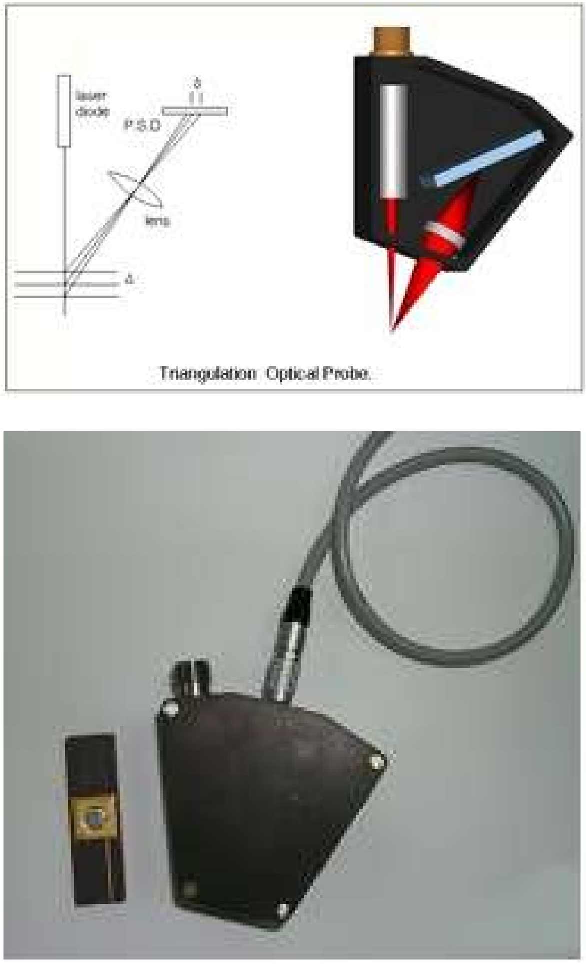

Fig.T.1.7: The laser triangulation sensor developed for position sensing applications.

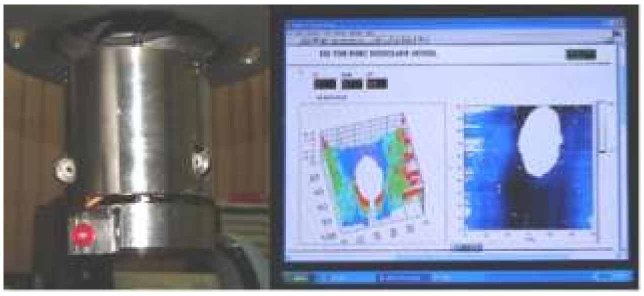

Fig.T.1.8: Picture of the scan head and the screen shot of the GUI.

4. Laser NDT for reactor components:

Validation of the design of the reactor components requires extensive tests on scaled down models by loading with the required stress and measuring the generated strain The use of conventional techniques like the use of strain gauges is not only time and manpower intensive but is also rather complicated by the need for a large number of data acquisition channels that need to be used simultaneously. Shearing speckle interferometry that makes use of speckle correlation is a very sensitive technique for monitoring deformations and can generate a much larger density of data than that can be obtained using strain gauges. We have therefore set up an experimental arrangement for shearing speckle interferometry and initiated experiments to explore its potential for structural testing and safety tolerancing of reactor components.

In our set up the object to be inspected is illuminated with an expanded laser beam. A speckle pattern of the unstressed object is initially captured and stored in a computer as a reference image. The speckle image of the object deformed by subjecting it to some stress (mechanical, pressure or thermal) is acquired and stored as deformed image. By subtracting the image of the undeformed object from that of the deformed object, correlation fringes are produced that correspond to the gradient of the deformation. The deformation of the object is derived by integrating the fringes. Fig.T.1.9 shows sample specklegrams of aluminum diaphragms subjected to pressure loading. The specklegram on the left is that of a uniform thickness plate and the one on the left is that of a "defective" plate that was thinned in a small region by machining. The surface bulging is not uniform anymore and is reflected in the specklegram as higher spatial frequency of fringes near the "defect".

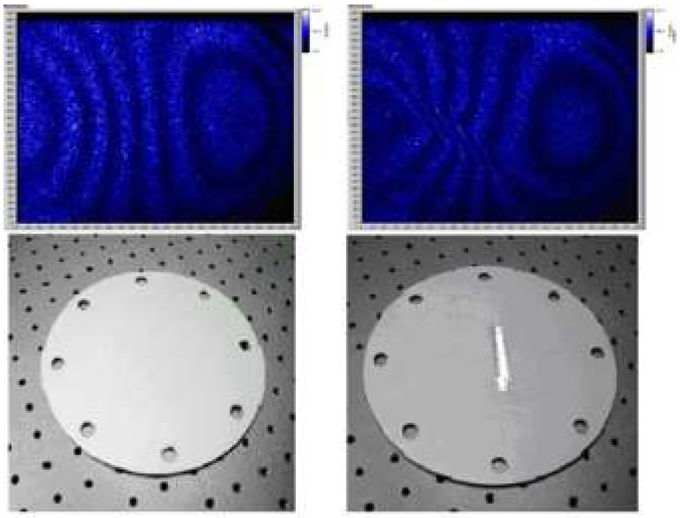

Fig.T.1.9: Specklegrams of a good and a defective plate and their corresponding pictures.

Conclusion:

We have provided an overview of some of the laser-based instruments that have been successfully deployed or are at an advanced stage of commissioning/deployment at different units of DAE for use in nuclear fuel cycle. Each of these developments have required proof-of-principle design, table-top experimental testing, prototype development, field testing, engineered system design, production prototyping and finally delivery to end user. Over the years, conscious effort has also been made to augment the required in-house facilities so that the time required for development and prototyping of an instrument is made as small as possible. The experience gained in successful deployment of several systems makes us confident of taking up even more challenging requirements.