Evaluation of the feasibility of the New Measurement Methodology for Reactor Control and Shutdown Rod Drop Time Measurement After Introduction of Digital Systems

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ABSTRACT

Nuclear power plants use neutron absorbers to control the magnitude of neutron flux in an operating nuclear reactor. Essential part of that control mechanism are Control and Shutdown Rods, which control the neutron flux by changing the length of the neutron absorber presented inside the reactor core. This is commonly referred to as Control Rod Height. Naturally, power plant manufacturers devised a system to indicate actual rod height to the control room operators, called Rod Position Indication system (RPI). Same system is used to measure the time required for Control and Shutdown rods to go from fully withdrawn to fully inserted position (Rod Drop), ensuring swift and proper shutdown of the nuclear reactor. As such, this Rod Drop Time measurement is required on a plant cycle basis to certify the plant for power operation. As the digital age progresses, innovation and introduction of digital systems has made alternative methods of Rod Drop Time measurement feasible. This paper evaluates the feasibility of the new measurement methodology and compares it with the legacy Rod Drop Time measurement, still widely used in nuclear power plants.

Keywords: *nuclear, rod drop, control rods, rod position indication, RPI*

1 INTRODUCTION

Pressurized water nuclear reactor operates in a delicate balance between thermal power generated inside the nuclear core and the amount of thermal power being transferred to a secondary loop via steam generators. Generated thermal power is maintained and precisely controlled using Shutdown and Control Rods which control the neutron flux by changing the length of the neutron absorber presented inside the reactor core. This is commonly referred to as Control Rod Height.

Additionally, Shutdown and Control Rods are essential to ensuring that the reactor can be safely shut down from any power level and maintained in shut down state, by inserting the rods completely into the core. In pressurized water reactors that essential safety function is achieved by interrupting power to Shutdown and Control Rod Drive Mechanisms (CRDMs), therefore letting the rods fall into the core using gravity. Interrupting power to CRDMs is achieved by opening the Reactor Trip Breakers, which can be opened manually or by initiated automatic action if certain combinations of plant parameters are reached and exceeded.

The time it takes for the rods to fall from fully withdrawn to fully inserted position is called Rod Drop Time. Rod Drop Times are used in plant Safety Analyses and as such are part of NEK's Technical Specifications. To ensure that Safety Analyses are valid, Rod Drop Times are strictly limited and must be measured before each power operation cycle or whenever Reactor Vessel Head is dismantled and removed.

Indicating actual position of Shutdown and Control Rods inside operating reactor is a function of a Digital Rod Position Indication System (DRPI). DRPI is used during power operation to provide rod position indication to Main Control Room operators as well as to confirm complete rod insertion in the event of a reactor shut down and/or emergency procedures. Additionally, an essential function of DRPI system is facilitating the measurement of Rod Drop Timing.

2 DIGITAL ROD POSITION INDICATION SYSTEM

2.1 System Description

During 1970s engineers developed a digital system that can passively detect the actual position of Shutdown and Control Rods. Passively means that no part of the DRPI system is located inside the Reactor Coolant pressure boundary. As shown in Figure 1, DRPI system consists of three distinct parts:

1. DRPI Detector for each Shutdown and Control Rod, located on Reactor Vessel Head,
2. DRPI Data cabinets, train A and B, located inside Containment,
3. DRPI Display unit, located on the Main Control Board (MCB).

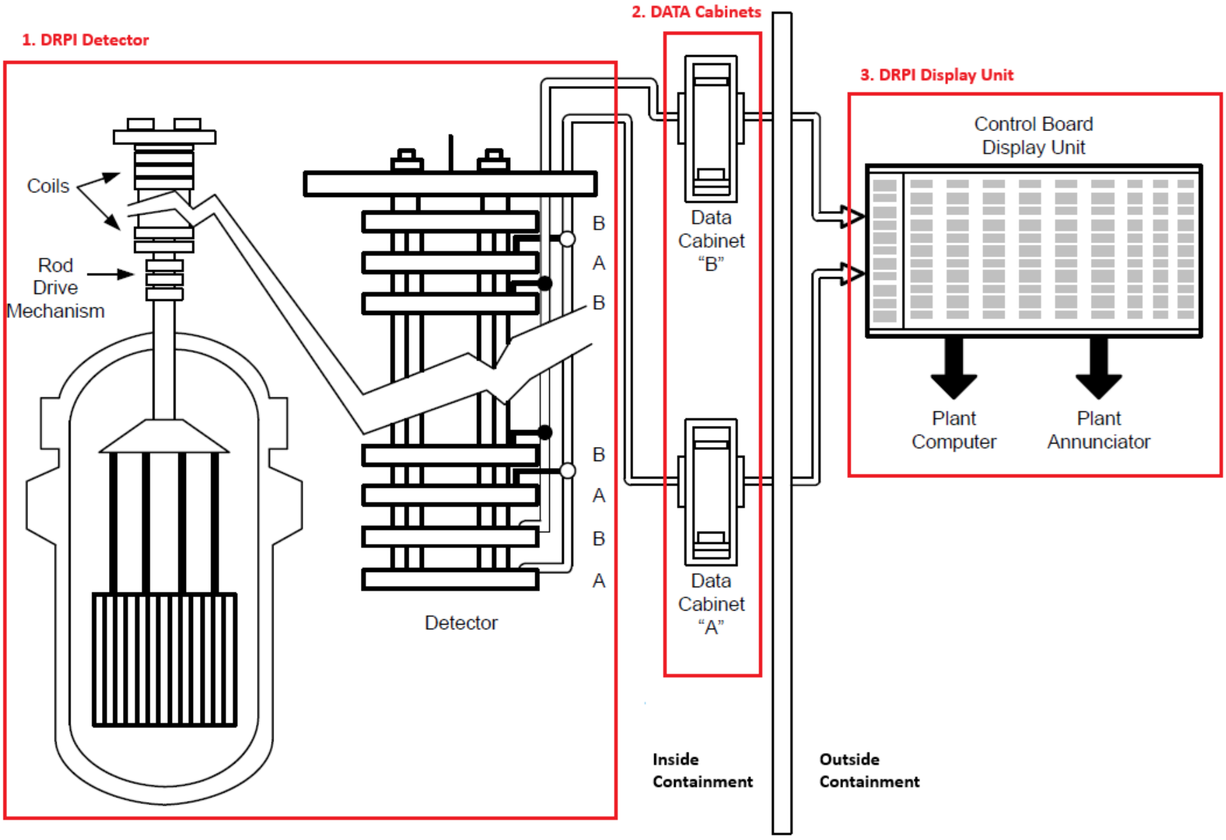

Figure 1: Digital Rod Position Indication System

DRPI Detector, also called DRPI coil stack is placed on top of a Control Rod Drive Mechanism (CRDM) for each Shutdown and Control rod. In NEK there are 33 Shutdown and Control rods, so there are 33 DRPI Detectors located on the Reactor Vessel Head.

Each DRPI Detector consists of 42 coils, arranged in a vertical sequence of 21 coils per train. Coils corresponding to each train alternate through the length of the detector, so in an event of failure in one train, rod position is still available from data from the alternate train, although achieving reduced accuracy.

Figure 2: DRPI Detector

DRPI Data cabinets are located inside containment, just outside of reactor compartment, to shield electronics from harmful neutron radiation. There are two DRPI Data cabinets, one per train. Each Data Cabinet receives data from every detector (33 detectors, one per rod). Data cabinets compound the information, generating rod position for each rod and encode the data to be sent to DRPI Display unit, located in Main Control Room.

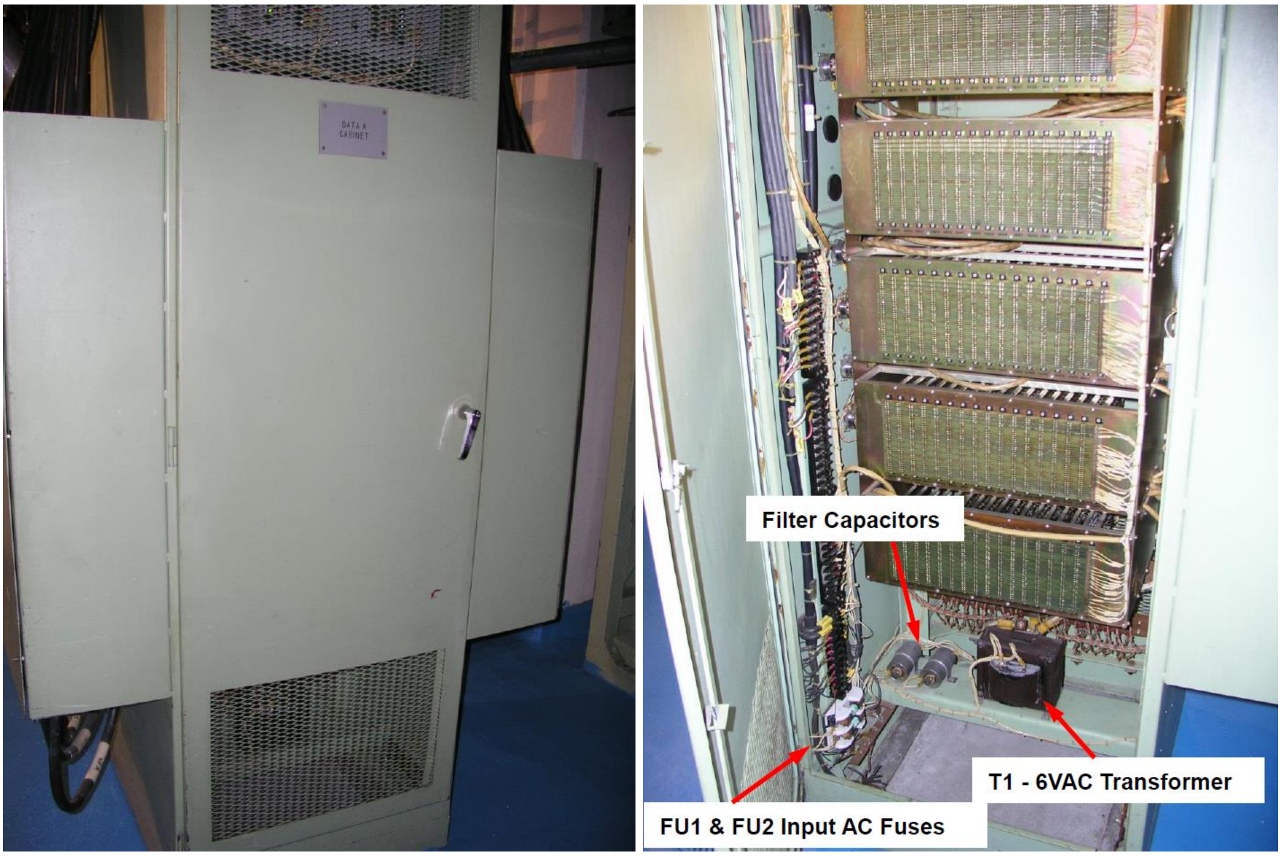

Figure 3: DRPI Data Cabinet (left: doors closed, right: doors open)

The DRPI Display unit combines the information from both Data Cabinets and creates a digital position signal for each rod that is then displayed on the Main Control Board and provide Control Room operators with indication of actual position of all rods in the reactor. Additionally, DRPI Display unit sends information to Plan Computer, so each intentional or nonintentional rod movement is recorded.

Figure 4: DRPI Advanced Display System (DADS)

2.2 Principle of Operation

When Shutdown or Control Rod is in motion, Rod Drive Shaft moves through the coils of a DRPI detector. The coils of DRPI Detector are energized with AC current from a constant voltage source and a ferromagnetic material of the Rod Drive Shaft changes the impedance to the flow of AC current through specific coil on the detector. Sequential changes of impedance of detector coils are then converted into rod position in each DRPI Data cabinet. Data cabinets compound the data for each train and the rod data is then sent from Containment to DRPI Display Unit, located in the Main Control Room.

To minimize cabling from Containment to the Main Control Room and reduce the number of cable penetrations going through Containment Vessel, data from DRPI Data Cabinets is multiplexed. Connections from Data Cabinets to Display Unit consist of 7 address lines and 5 data lines. Each individual Shutdown and Control Rod is coded with a unique 7-bit address. DRPI Display Unit generates address bits sequentially in regular time intervals. When Display Unit places the specific address on DRPI Address Lines, DRPI Data Cabinets place 5-bit encoded rod position data on DRPI Data Lines. Display Unit reads encoded rod position from each train, combines them in a full accuracy position and displays it in a way that is apparent to Control Room operators.

DRPI system uses Gray Code to multiplex and reliably transmit rod positions from Containment to Main Control Room. Gray Code is a specific encoding mechanism that uses predefined binary sequences for each possible rod position. Every position code is different from previous one by one bit only. This simplifies error checking and significantly reduces the possibility that a failure in a single data line corrupts position data.

Gray Code is generated on Detector/Encoder (DET/ENC) cards located in DRPI Data Cabinets. Each Data Cabinet (one Data Cabinet per train) consist of 33 DET/ENC cards, one for each Shutdown and Control Rod present in NEK. Corresponding DET/ENC cards in both trains are hard-wired with unique 7-bit rod address. DET/ENC card compares impedance of adjacent coils on accompanied DRPI Detector, identifies penetrated and unpenetrated coils and combines that data to generate the Gray Code representing the actual position of the rod in question.

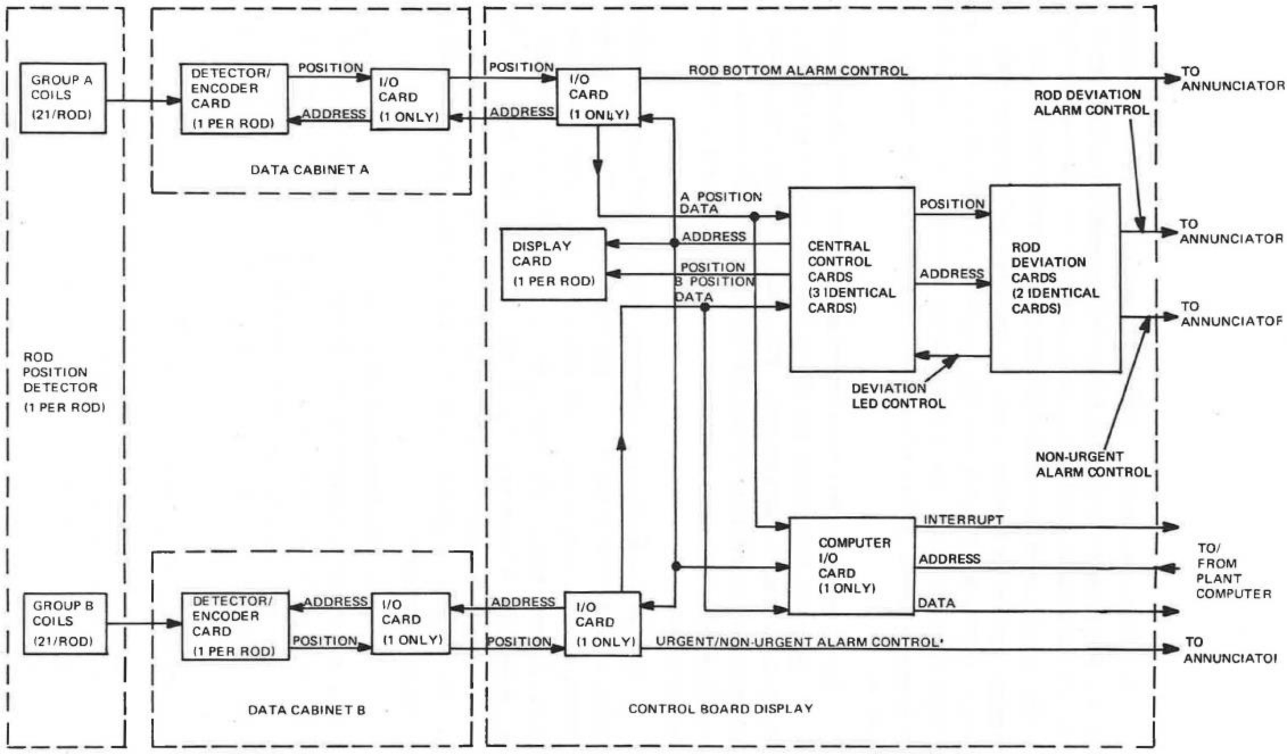

Figure 5: Simplified DRPI block diagram

3 ROD DROP TIME MEASUREMENT

3.1 Rod Drop Time Measurement using Induced DC Voltage Method

Common method of acquiring Rod Drop Times is using induced DC voltage while Shutdown or Control Rod is moving through DRPI Detector coils. Test is performed by withdrawing one or more banks of Shutdown or Control Rods to its fully withdrawn position, arming the Rod Drop measurement system and opening the Reactor Trip breakers. This simulates reactor shutdown from full power condition. The moment Reactor Trip breakers open, CRDM stationary gripper coil current is interrupted and rods free fall from fully withdrawn position to fully inserted position using gravity.

Detector/Encoder cards, described in previous section, are equipped with a test point for measuring 6 VAC voltage that is energizing all the coils on a DRPI Detector. When Shutdown or Control Rod is free-falling from top to bottom position in the core, additional DC voltage is induced in the coils that can be measured on the test point on DET/ENC card. DC voltage is superimposed on existing 6 VAC alternating voltage and is directly proportional to the speed of the falling rod.

Using filters, Rod Drop Measurement system can filter out 6 VAC voltage to isolate just the induced DC voltage component. Additional way of obtaining only the induced DC voltage component is by powering down DRPI Data Cabinets in the Containment, therefore eliminating 6 VAC component. Even with DET/ENC cards in powered down state, DC voltage induced in the Detector coils can be directly measured on the test point of the DET/ENC card. Currently, NEK is using a Rod Drop Measurement System that requires powering down Data Cabinets. During this short time frame, Control Room operators do not have a valid indication of the rod positions in the core, so they have to rely on additional indications to confirm that reactor is in a safe shutdown state.

Rod Drop Time Measurement system consists of a multi-channel voltage measuring device, that is connected to each Data Cabinet. Inside each Data Cabinet, voltage measurement channels are connected to every DET/ENC card's test point. NEK has 33 Shutdown and Control Rods, so 66 channels are required to capture full Rod Drop. Additionally, one channel is connected either to Reactor Trip Breaker auxiliary contacts, or a sample of a CRDM stationary coil current that is interrupted when Reactor Trip Breaker is opened. In each case, that signal is used as a trigger point T0 for calculating Rod Drop times.

On Figure 6, we can see a typical Rod Drop trace, in this case acquired for Shutdown rod E-03, during NEK's outage in December 2025. Trace consists of four distinct channels, each represented by a different colour:

1. Blue – CRDM Stationary coil current,
2. Purple – DC voltage component induced in DRPI Detector coils corresponding to train A,
3. Lime – DC voltage component induced in DRPI Detector coils corresponding to train B,
4. Red – Represents combined trace of induced DC voltages from both DRPI trains.

Such traces are acquired for every Shutdown and Control Rod in NEK's reactor. Traces are then analysed and Rod Drop Times are measured and verified against Technical Specification limit.

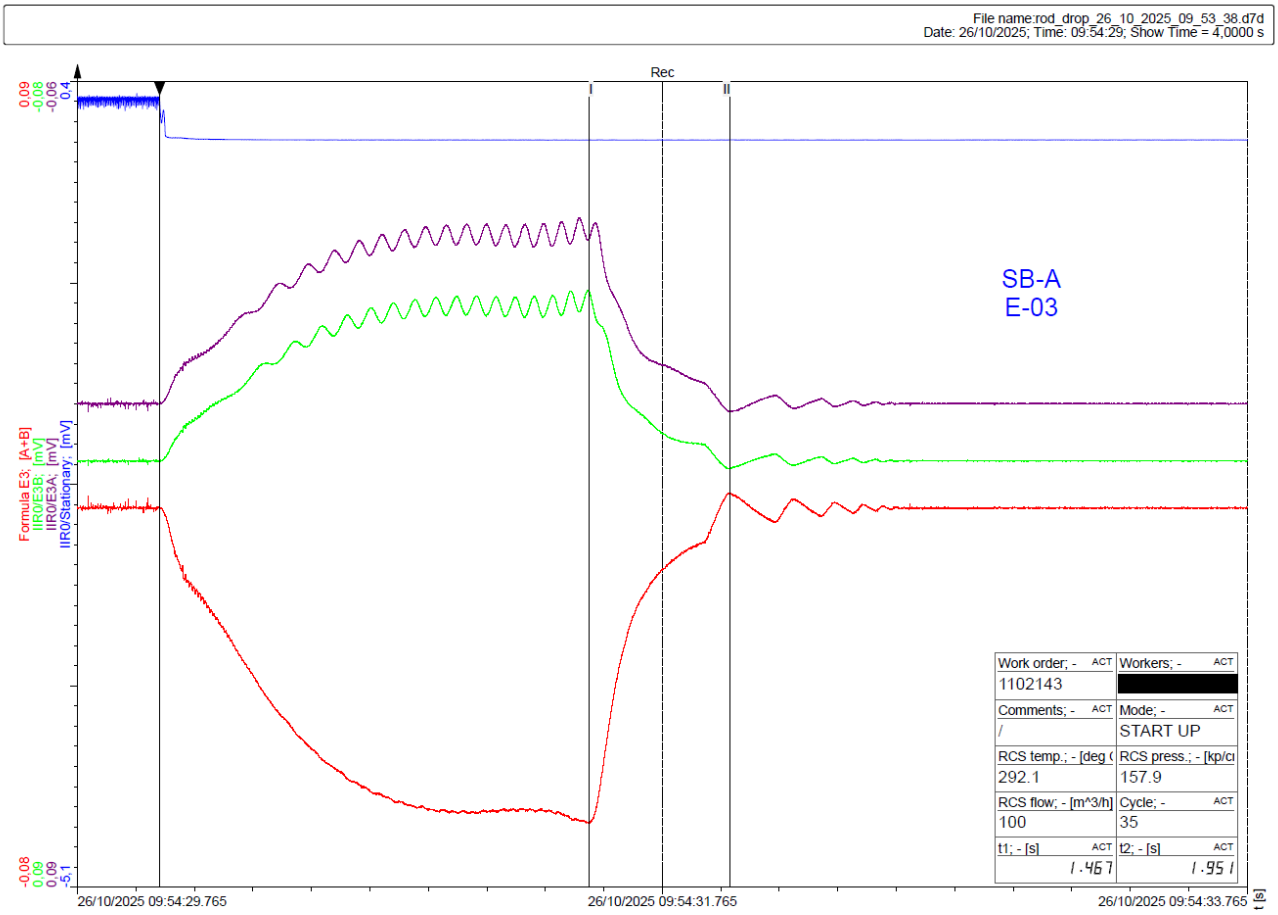

Figure 6: Rod Drop Timing diagram, using induced DC voltage method

If we analyse induced trace, we can observe the following markers:

1. First vertical marker, marked with black triangle, corresponds with the moment Reactor Trip Breakers are opened, interrupting CRDM Stationary coil current, depicted with blue signal. This represents T0, time when Shutdown rod E-03 starts to free fall into the core.
2. Observing Rod Drop trace, depicted with signal in red, we can see that Shutdown rod E-03 starts to accelerate using gravity, until it reaches maximum speed when red signal reaches maximum amplitude.
3. After second vertical marker, marked with symbol “I”, Shutdown rod E-03 starts to rapidly decelerate. This is the moment T1, when rod E-03 hits the “dashpot”. Dashpot is located at the end of rod travel and facilitates that falling Shutdown or Control rod gradually decelerates to prevent physical damage to the rod itself or to the fuel element in which the rod is located.
4. Third vertical marker, marked with symbol “II”, is placed at the moment T2. At this moment Shutdown rod E-03 stops and has zero velocity, meaning the rod has reached bottom position. Time interval between T0 and T2 represents actual Rod Drop Time for Shutdown rod E-03.
5. Signal depicted after marker T2, represents Shutdown rod E-03 “bouncing” on bottom position a couple of times, until it finally settles. This bouncing effect has no practical impact on the amount of negative reactivity that Shutdown rod E-03 has introduced in the core, so is not considered in measuring Rod Drop Time, but is analysed by

technicians to verify that the rod has maintained free travel and has not jammed at the bottom.

3.2 Gray Code Rod Drop Time Measurement using DRPI Advanced Display System

Legacy DRPI Display Unit was designed in 1970s and 70s level of technology did not support the possibility for Rod Drop Time measurement to be acquired just by using DRPI system. With the advent of new technology and embedded microcomputer systems, original designer of DRPI system has redesigned and upgraded the DRPI system to include a new Display Unit, called DRPI Advanced Display System (DADS).

Using Field-programmable Gate Array (FPGA) technology, new DADS display can address particular rods at a considerably faster rate, opening the possibility for Rod Drop Times to be measured within the display itself, with no need for additional measuring equipment.

During December 2025 outage, NEK has acquired and installed new DADS display to replace the aging Legacy DRPI Display in Main Control Room. As with legacy display, DADS's primary function is displaying actual rod position indication to Control Room operators during plant's power operation and emergency procedures. Rod Drop Measurement using Gray Code is an upgrade from original display unit. So, as part of Site Acceptance Test (SAT), NEK performed additional Rod Drop Measurements using DADS.

As mentioned, DADS being a replacement for just one part of DRPI system, the display unit, DRPI Data Cabinets and DRPI Detectors have not been affected by DADS installation. This still leaves the option for Rod Drop Time measurement to be acquired using legacy methods. In order to certify DADS for Rod Drop Time measurement, in December 2025 outage, two Rod Drops were performed in parallel, one using induced DC voltage method and one using DADS Gray Code Rod Drop.

To facilitate Rod Drop measurement, DADS display is connected to Reactor Trip Breaker auxiliary contacts to detect reactor shutdown, so in an event of an unplanned manual or automatic reactor shutdown, DADS can acquire and analyse Rod Drop Timing automatically.

In figure 7, we can observe Rod Drop Timing trace acquired using just the DADS display. It must be said that DADS trace represents actual position of the Shutdown rod E-03 while it is free-falling through the reactor core, while induced DC voltage method represents the speed of the rod as it is free-falling, an indirect measurement.

Like induced DC voltage method, Rod Drop trace, acquired by DADS, consists of following signals:

1. Blue – Train A Gray Code,
2. Lime – Train B Gray Code,
3. Red – Actual combined position of the Shutdown rod E-03

We can analyse the DADS trace and observe the following markers:

1. Time 0 on the time axis represents T0, the moment that Reactor Trip Breakers open and Shutdown rod E-03 starts to free fall into the core.
2. Observing the Rod Drop trace, we can see that the Shutdown rod E-03 starts to accelerate, until it reaches maximum speed. The speed of the rod is not directly apparent, like in induced DC voltage method, but can be identified in the time delta between individual positions of the falling rod. Just after T0, it takes significantly longer time period for actual position signal to change. As the rod accelerates through the core, time deltas between each individual position are reduced.
3. First vertical marker, marked as "Dashpot" (violet vertical line), represents the position of Shutdown rod E-03 as it hits the Dashpot, same as time marker T1 in induced DC voltage trace.

4. After time marker T1, Shutdown rod E-03 starts to decelerate, indicated as prolonged time deltas between individual rod positions.
5. Next vertical marker, marked as “Bottom” (green vertical line), indicates that Shutdown rod E-03 has reached bottom position. In this trace, marker “Bottom” is equivalent to time marker T2 in induced DC voltage trace and time between T0 and T2 represents Shutdown Rod E-03 Drop Time.
6. Trace after time marker T2 does not depict “bouncing” of the rod at bottom, as in induced DC voltage method. The bouncing magnitude is too small for DRPI system to detect a change in position, so part of the trace after the marker indicates that the rod has settled on the bottom position.
7. Last vertical marker marked as “Tech Spec” (yellow vertical line) indicates the Technical Specification limit for NEK.

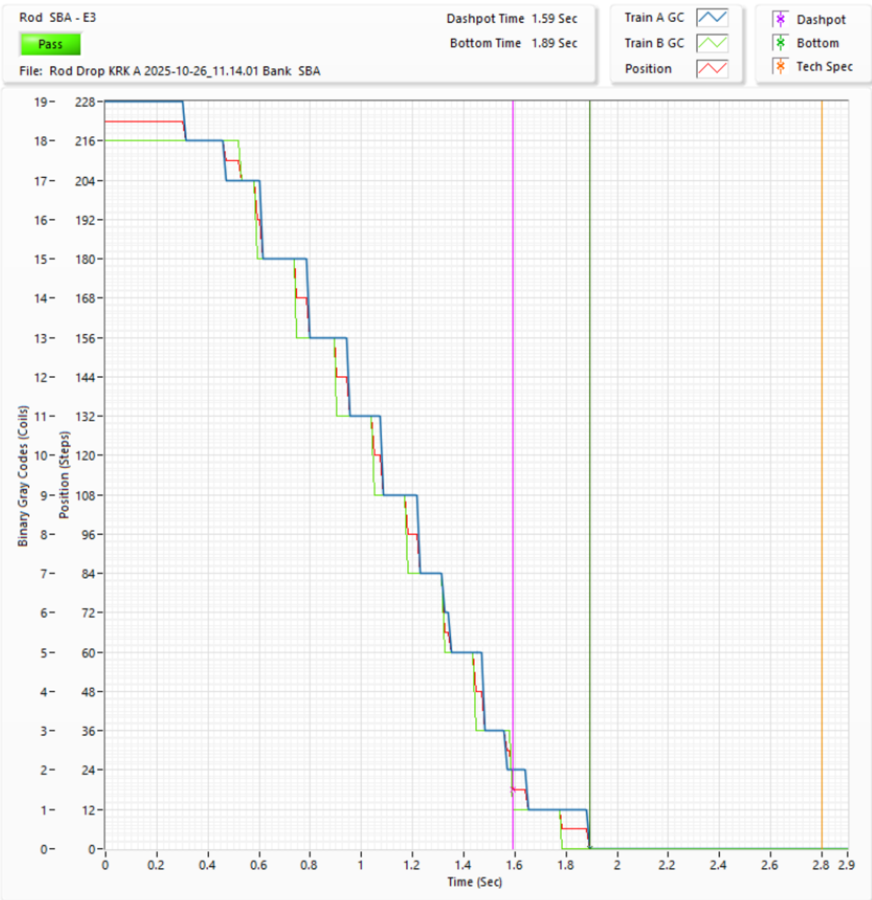

Figure 7: Rod Drop Timing diagram, using DADS

Though significantly different traces, each trace depict the same information, only acquired using different methods. Induced DC voltage method depicts rod speed as it is free falling through the core and DADS method depicts actual position of the free-falling rod.

While DADS trace misses some of the finer details that are part of the induced DC voltage trace, there are additional positive sides of DADS measurement that need to be taken into consideration.

4 CONCLUSION

This paper presents the operating principles of Digital Rod Position Indication system and its significance in power plant operation. Additional to providing Control Room operators with indication of actual position of each of the Shutdown and Control Rods, it serves as a service system to verify the operability of a system, vital for safe shutdown of the operating nuclear reactor, the Shutdown and Control Rods.

Commercial power plants like NEK, have been performing Rod Drop tests from initial operation right until present time and will continue to do so until the end of life of the plant. That being said, induced DC voltage method has been on the forefront of Rod Drop Time measurement and has been widely used throughout the nuclear industry. Presently, it is still the most used methodology for acquiring Rod Drop Timing so we must treat it like industry standard and all new or alternate methodologies must be measured against it.

In the process of evaluating Gray Code Rod Drop measurement, we will be analysing the methodology through certain key areas and comparing them to industry standard, the induced DC voltage measurement. Those key areas, starting with most significant one, are:

- **Rod Drop Time trace**: comparing Gray Code time trace to induced DC voltage trace, we can observe that it has all the information required to measure Rod Drop time from opening the Reactor Trip Breakers to full rod insertion. Furthermore, because we are dealing with actual rod positions, we can be positive that the rod in question has actually reached the bottom and has been fully inserted inside the reactor core. From the trace we can identify initial rod acceleration, maximum speed of free-falling rod, rapid deceleration as the rod hits the dashpot area as well as rod settling on the bottom position. What is not immediately apparent from Gray Code trace, compared to induced DC voltage trace are the “bouncing” of the rod after reaching bottom position and a clean speed profile of the free-falling rod. While these features are not critical to determining actual Rod Drop time, they can provide serious insight in proper rod and fuel element alignment, as well as providing indication that the rod is falling at free fall speed, thus ensuring that there are no physical obstructions and/or increased mechanical or hydro mechanical friction in the system.
- **Required equipment**: induced DC voltage measurement requires specific measuring equipment that has significant cost attached to it. For DADS Gray Code Rod Drop, all required equipment is part of the system itself, incurring no additional costs.
- **Personnel**: additional to the equipment itself, there is considerable man-hour cost associated with induced DC voltage measurement. That being system maintenance, calibration, connecting and verifying proper connection and operation of the measuring equipment before actual measurement is ready to be taken. With DADS Rod Drop, all measuring equipment is already in place, fully operational and ready to record Rod Drop times. All maintenance tasks associated with DRPI system, including components required for Rod Drop time measurement, are already part of established DRPI system maintenance activities performed in every outage.
- **Human Performance**: as stated above, induced DC voltage measurement system requires connecting multiple cables to DRPI Data Cabinets, located inside Containment. More often than not, process of connecting Rod Drop equipment is performed in very unpleasant environment, significantly adding to the probability of human error. Rod Drop measurement is often performed on or very near the outage critical path. Any additional time added to the critical path, due to human error can incur significant unplanned costs.
- **Knowledgebase**: one area where Gray Code Rod Drop methodology significantly underperforms, is extensive base of knowledge and thousands of induced DC voltage traces measured over the years. Senior maintenance workers, regularly performing Rod Drop measurements for years, can often detect and identify potential problems by just glancing at induced DC voltage traces. Gray Code Rod Drop method, being relatively new, will have to build that knowledgebase from the ground up.

Conclusion is, while still not common and widely used as induced DC voltage method, Gray Code Rod Drop method has some advantages that cannot be ignored. As legacy equipment faces maintenance challenges, new and upgraded systems will slowly start replacing old ones. As the digital age and system integration progresses, new and improved features like Gray Code Rod Drop are starting to become feasible. It is up to every plant operator and its regulatory body to evaluate and judge the acceptability of Gray Code Rod Drop measurement, as well as the level of digitalisation they are comfortable with.

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