Nondestructive Evaluation of Concrete Structures

A case study of 36 years old reinforced concrete in research reactor, Dhruva

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Abstract

Concrete structures are considered to be long lasting provided appropriate design, construction and regular maintenance are performed. Signs of ageing on the concrete structures appear in the form of cracks or distresses which prompts repair actions. Repair plans supported by Non Destructive Testing (NDT) results are considered to be a prudent approach for life extension. Dhruva research reactor located in Bhabha Atomic Research Centre, Mumbai was commissioned in the year 1985 and recently started showing signs of ageing. As a part of ageing management programme of the reactor, comprehensive inspection of concrete structures, including containment building was carried out using different NDT methods. Inspection results provided basis for finalizing the repair and renovation programme for civil structures. This paper covers different nondestructive tests carried out on the civil structures, results of the tests and ageing management of structures based on NDT inputs.

Keywords: Ultra-Sonic Pulse Velocity (USPV) Test, Rebound Hammer Test, Carbonation Test, Concrete core Test, Chemical Analysis, Crushing Strength, Water Absorption, Half-cell Potentiometer Test

1.0 Introduction

Research reactors constructed at Bhabha Atomic Research Center (BARC), Mumbai site are intended for production of isotopes, neutron beam research, verification of basic physics design parameters, manpower training etc. Dhruva research reactor, initially known as R-5 project, a 100 MWth tank type reactor, was fifth in the series. The reactor constructed indigenously achieved first criticality on 8 August, 1985. This paper will provide brief description of Dhruva, its civil structures and non-destructive examinations conducted as a part of life extension.

2.0 Dhruva Research Reactor

Dhruva Research Reactor, located at Bhabha Atomic Research Centre (BARC), Mumbai, India, is a vertical Tank type reactor. Fuel used in the reactor is metallic uranium cladded with aluminium. Moderator, reflector & coolant are heavy water (D2O) and the design provides intermixing of them. Reactor has been designed to provide neutron flux of $1.8 \times 10^{14} \text{n/cm}^2/\text{sec}$ at full reactor power. The reactor vessel is immersed in a pool of light water for simplification of shielding design. Reactor pool is made of high density concrete for reduction of radiation level to acceptable level in working area. An overhead storage tank of 18 lakh liters capacity, located above spent fuel storage building, has been provided for storage of de-mineralized (DM) water which is used for shutdown cooling of the reactor as well as emergency cooling water. Underground dump tank of capacity 22.5 lakh liters has been provided to collect the DM
water coming after cooling the reactor. A 100-meter high stack is provided for exhausting air from the reactor and spent fuel storage buildings after suitable filtering.

![DHRUVA Reactor](image)

Figure #1- Dhruva Reactor

### 3.0 Concrete as a structural material
Concrete is the most commonly used construction material due to advantageous factors like easy mouldability, simple manufacturing process, usage of locally available products, less production cost, good compressive strength etc. In addition, it offers good shielding property against radiation. Mainly normal concrete, heavy concrete and borated concrete are manufactured and used in nuclear plants which offers different density, permeability, wear resistance, shielding and, heat resistance properties. Concrete structures though, considered to be highly durable, do undergo deteriorating actions of operating conditions and surroundings like other engineering systems. Concrete undergo volume changes due to creep and shrinkage. Other effects like temperature, corrosion/erosion, radiation, vibration etc may also affect concrete and reduce its life. Periodic inspections and maintenance will help in controlling the deterioration of concrete structures and provide assurance for their continued service satisfying the requirements. Besides it gives an idea about the degradation mechanisms in operation.

### 4.0 In-service Inspection of concrete structures
Concrete is a mixture of stone and sand held together by a hardened paste of cement and water. In reinforced concrete, steel is used to increase tensile strength. Due to non-homogeneity of concrete, its inspection using conventional NDT techniques was difficult. With the experience gained in the usage of concrete and technological advancement, newer testing methods are being developed and used in the health assessment of concrete structures.

### 5.0 Inspection on Dhruva concrete structures
After three decades of service RCC structures of Dhruva started showing sign of ageing in the form of cracks and other distresses which prompted to take up the In-Service
Inspection (ISI) of concrete structures for assessing their condition and to generate an ageing management plan of civil structures. ISI data were also required for assessment of residual strength of structures for seismic analysis of the structures as per codal requirement.

All the main civil structures in DHRUVA namely, reactor containment or Reactor Building (RB), Service Building (SB), Spent Fuel Storage Building (SFSB), RCC Stack, and Light Water Dump Tank (LWDT) were included in the inspection programme. A brief description of the structures is as below;

5.1 **Reactor containment**
Reactor is housed in this concrete building. The building has a basement and sub-basement for housing various process equipments of primary heat transport systems, fueling machines, storage blocks and some other auxiliary systems. The reactor containment building admeasuring 44.2m x 33.5m x 44.4m high is designed for a positive pressure of 300 mm of WG and negative pressure of 100 mm WG.

5.2 **Service building**
Service building is located adjacent to reactor containment. It houses secondary cooling system, compressed air system, Demineralization Plant, sub-station, battery bank room etc. The building is made of a concrete framework of beams, columns and slabs. The building is a three storied one with 74.20m x 34.83 m in plan with a height of 17.70m from existing ground level.

5.3 **Spent fuel storage building (SFSB) and Over Head Storage Tank (OHST)**
It houses spent fuel storage bay for temporary storage of spent fuel removed from the reactor. It is concrete reinforced frame structure with an overhead concrete tank. SFSB building is of rectangular shape of around 34 meters height. This building consists of an overhead water storage tank of capacity 18 lakh liters. Total load of the structure is transferred to the soil through 18 columns of 600 mm x 2100 mm in size.

5.4 **Underground Dump Tank**
Dump tank is part of Dhruva Emergency Cooling Water (ECW) System. It is a rectangular underground RCC structure externally admeasuring around 56m x 13m and has 6.0m height above the raft level. The clear depth of the tank is around 5.6 m.

5.5 **Stack**
The ventilation stack is 102 m high (from ground level) reinforced concrete structure. It has a shell thickness of 0.15 m at exit end which is uniformly varying to 0.5 m at the top of ring raft. The cylindrical shell is rigidly connected at base with the ring foundation raft at 1.2 m below ground level. The diameter of raft foundation is 24.0 m. The thickness of the foundation ring raft is 1.5 m.

6.0 **In-Service inspection of Reinforced Cement Concrete (RCC) structures of Dhruva**
RCC structures of Dhruva were constructed in early eighties. Sign of ageing started appearing in the form of distress and cracks on some parts of structures. The plant
management considered various degradation mechanisms and chosen the following NDT techniques for the health assessment of the structures.

i. Visual inspection,
ii. Rebound hammer test,
iii. Ultrasonic pulse velocity test,
iv. Concrete core test
v. Water absorption test
vi. Carbonation depth test
viii. Half-cell potentiometer test.
ix. Permeability test
x. Visual inspection of under soil RCC structures.

6.1 Visual inspection:
Visual inspection is an essential precursor to any intended non-destructive tests. As the first step of NDT, exhaustive visual inspection of all concrete structures admeasuring approximately 50,000 Sq. meter area was taken up. Visual inspection could identify external condition of the structures, distresses, cracks, spalling, reinforce corrosion, sign of leakage etc. Photographs of distresses / cracks were taken for record. Locations and sample sizes of other NDTs to be performed were decided based on the inputs from visual inspection. Some of the degradations have been shown in following figures #2, 3 and 4.

![Fig #2- Reinforcement corrosion](image1)
![Fig #3- Spalling](image2)
![Fig. #4- Cracks in column](image3)

6.2 Rebound hammer test:
Rebound hammer / Schmidt test, used to evaluate the surface hardness of concrete. Rebound hammer test was performed as per guidelines given by IS: 13311 (Part 2): 1992 & BS 1881: Part 202:1986 to determine rebound number. Locations at which rebound hammer test was carried out was decided based on visual inspection, profometer scanning, surface condition, accessibility and size of structures. Rebound test was carried out at 115 locations in total. At each location average of 12 rebound numbers were taken as rebound number of the location. Rebound numbers obtained on all structures were more than 40 which indicated very good layer of concrete.
6.3 Ultrasonic Pulse Velocity (UPV) Test

Ultrasonic pulse velocity testing mainly used to measure the sound velocity of the concrete and indirectly the compressive strength of the concrete. The test was performed as per guidelines given by IS: 13311 (Part - I): 1992 & BS 1881: Part 203:1986. This test is basically wave propagation test & consists of transmitting ultrasonic pulses of 50-60 kHz frequency through a concrete medium for estimating velocity. Values of UPV obtained are used for qualitative assessment of the condition of concrete with regard to homogeneity, uniformity, integrity etc.

Three different ways of measuring UPV are followed:

i. Direct method
ii. Semi direct method
iii. Indirect or surface transmission.

Different transducer arrangements for above methods have been shown in Fig. 5.

![Transducers arrangement](image)

Fig. 5- Transducers arrangement

The direct transmission method is generally preferred,

Following velocity criterion for concrete quality grading is given by IS 13311 (Part-I):1992

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Ultrasonic Pulse Velocity by Cross Probing (Km/Sec)</th>
<th>Concrete quality grading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Above 4.5</td>
<td>Excellent</td>
</tr>
<tr>
<td>2</td>
<td>3.5 to 4.5</td>
<td>Good</td>
</tr>
<tr>
<td>3</td>
<td>3.0 to 3.5</td>
<td>Medium</td>
</tr>
<tr>
<td>4</td>
<td>Below 3.0</td>
<td>Doubtful</td>
</tr>
</tbody>
</table>

Based upon above criterion, grading of concrete quality is determined at respective test locations for direct probing. UPV obtained from different civil structures of Dhruva were in the range of 3.5 to 4.5 km/s which indicated good quality of concrete.

6.4 Concrete core test

Concrete cores samples were extracted from sound locations of the structures for assessment of water absorption, unit weight of concrete, carbonation & crushing strength. Locations and number of concrete core extraction were decided based on visual
inspections and size of the structures. Extracted cores were tested as per guidelines given in IS: 516-1959 (reaffirmed 1999) and were used for checking carbonation depth, unit weight of concrete, water absorption per unit volume and crushing strength. Concrete strength was found increasing and water absorption decreasing with respect to concrete density as intended. Crush tests results were indicating concrete quality between M-20 to M-30. Extracted concrete core and capped core for testing are shown in fig.6.

![Concrete Core Sample](image1)

![Capped Core Sample](image2)

Fig. 6- Extracted concrete core sample and capped for testing

6.5 **Carbonation depth test:**
Carbonation depth measurement test, used to determine whether moisture has reached the depth of the reinforcing bars and hence corrosion may be occurring. Concrete Carbonation is the process whereby carbon dioxide (in moist air) reacts with the lime and other alkaline materials in the concrete and creates calcium carbonate which reduces pH of concrete. This is the most common cause for loss of alkalinity in concrete. Rate of carbonation of concrete depends on Atmospheric humidity & Concrete permeability.

Carbonation depth can be measured in following two ways:

i. By spraying 1% phenolphthalein solution on freshly drilled out concrete core samples.

ii. By drilling a hole into the concrete in small increments of around 15mm and testing the powder removed for carbonate.

Here both the tests were performed. Carbonation depth found by spraying phenolphthalein solution on freshly cut core was varying between 10 to 20 mm of depth for different structures but carbonation analysis of powder collected from drilling was showing nil for all samples.

6.6 **Permeability Test**
Permeability test, used to measure the flow of water through the concrete. The test was carried out as per the German standard DIN 1048 / EN 12390-8 related to water permeability of hardened concrete specimens. For the test 73 mm dia cores were extracted from different structures. Core specimen were prepared with L/D ratio of 2 with both the ends perfectly parallel. The specimens were subjected to constant water pressure of 500±50 kPa for a period of 72 hours. After 72 hours, samples were split and water penetration depth into concrete was measured. Water penetration was found 52 to 88 mm in different samples.

6.7 **Chemical analysis (pH, chloride & sulphate content)**
Chemical analysis of the concrete was carried out to estimate the risk of reinforcement corrosion / degradation of concrete. For chemical analysis concrete powder samples were
collected from incremental depth of 15mm, 30mm and 45mm from the surface of different structures. Chemical analysis was carried out as per following guide lines.

i. **Determination of chloride content**

Chloride content of the concrete samples were determined as per guidelines given by IS: 14959 (Part 2): 2001. Chlorides present in concrete are fixed (water insoluble) as well as free (water soluble). Though it is the water soluble chlorides ions, which are of importance from corrosion risk point of view, yet total acid soluble (fixed as well as free) chloride contents are determined and compared with the limiting values specified for the concrete to assess risk of corrosion in concrete. As per IS: 456:200, Clause 88.2.5.2, Table 7, maximum total acid soluble chloride content as kg/m$^3$ of concrete is 0.6 for reinforced concrete. Chloride content was more than permissible in all structures.

ii. **Determination of Sulphate Content**

Sulphate content was determined as per guidelines given by BS 812 -118:1988. Sulphates react with hydrated aluminate phases in concretes to form the expansive compound ettringite, the primary destructive compound in sulphate attack. Sulphate can also react with calcium hydroxide in the paste to form gypsum. The crystallization of sodium sulphate salt due to wetting and drying also attacks concrete and appears as surface scaling. The total water-soluble sulphate content of the concrete mix, expressed as SO$_3$, should not exceed 4 percent by mass of cement in the mix. Sulphate content of all samples was within permissible limit.

iii. **Determination of pH of concrete**

pH of hardened concrete sample was determined as per guidelines given by IS: 3025 (part 2): 1983. pH value of the fresh or newly hardened concrete shall be in the range of 12 to 14, as the concrete is highly alkaline in nature. It is necessary that this value is maintained, to protect the steel from reinforcement corrosion. In case of old structures, pH value should be at least greater than 10. pH value of all samples were found more than 10 except one sample of service building which was showing pH - 9.

### 6.8 Half-cell potentiometer test:

Half-cell potentiometer test is used to assess the corrosion risk in a reinforced concrete structure. ASTM C 876 gives guidelines for half-cell potential measurement. Following two techniques can be used for half-cell potential measurement,

(i) The numeric technique & (ii) the potential difference technique.

In this case, numeric technique is adopted for interpretation of test results. In the numeric technique, the value of potential is used as an indicator of the likelihood of corrosion activity.

The potential measured at the surface of concrete can be interpreted as per ASTM 876 as:

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Phase of corrosion activity</th>
<th>Potential as measured by copper half cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial phase – Corrosion activity not taking place</td>
<td>More positive than - 200 mV</td>
</tr>
<tr>
<td>2</td>
<td>Transient phase – Corrosion activity uncertain</td>
<td>- 200 mV to - 350 mV</td>
</tr>
<tr>
<td>3</td>
<td>Final phase – Corrosion occurring positively</td>
<td>More negative than - 350 mV</td>
</tr>
</tbody>
</table>
Majority of half-cell potential measured were indicated mild risk of active corrosion of reinforcement steel. Basement area of service building was showing high risk because of seawater spillage in the area.

6.9 **Rebound Number V/s Comp. strength co-relation curve.**
As mentioned in IS: 13311 (Part 1), the rebound hammer test is not intended as a substitute for standard compression test, but as a method for determining the uniformity of concrete in the structure and comparing one concrete with another. The most satisfactory way of establishing a co-relation between compressive strength of concrete and its rebound number is to measure both the properties simultaneously on concrete cubes / cores. Hence, rebound hammer test was performed on concrete surfaces at core test locations before extracting concrete core samples and graph was plotted to generate site specific co-relation curve as shown in fig. 7 below.

![Site specific co-relation curve](image)

**Fig. 7- Site specific co-relation curve**

6.10 **Determination of unit weight of concrete & percentage water absorption.**
Concrete core samples were tested for assessment of unit weight of concrete (density) and percentage water absorption. Unit weight of concrete core sample was calculated with reference to the dry weight of concrete core sample. The corrected percentage water absorption was calculated by multiplying correction factor for length of the core sample as given in BS: 1881: Part 122:1983. Density of the concrete was found varying between 2.126 to 2.405 g/cm$^3$ whereas % of water absorption was found varying between 10.64 to 4.18 in increasing order of density.

6.11 **Visual inspection of pile cap of stack:**
Dhruva research reactor is located at Arabian Sea shore. Underground concrete of structures remains in contact of saline water. To see the effect of saline water on concrete, visual inspection of underground portion of containment, SFSB, service building and pile of stack was carried out after exposing them by excavation. No swelling, cracks or any other abnormalities were observed. Rebound hammer tests were also carried out on
exposed portion and found to be coherence to the values obtained on structures above the ground. Exposed portion of pile cap of stack is shown in Fig. 8 below.

Fig. 8- Concrete pile cap of stack

Based on the inputs from civil structures NDT, rehabilitations of structures were started.

7.0 Repair Methodology:
Based on the results of NDTs performed following repair plans / ageing management plans were adopted.
- Repair of cracked columns of structures using polymer modified mortar.
- Epoxy grouting and water proofing on the portion of structures showing seepage / leakage.
- Epoxy grouting to bridge cracks developed in concrete.
- Polymer modified mortar related structural repairs to reinforcement corrosion affected distressed areas of structures.
- Injection grouting in honeycombed concrete and / or sealing cracks developed in concrete.
- Micro-concrete jacketing and fibre wrapping of cracked concrete columns.
- Protective coating to form-finished external façade of all building walls.

8.0 Conclusion:
Compressive strength of all structures was estimated to be between M-20 to M-30 grade concrete which was matching with original design value of concrete. Rebound values of all concrete structures were above the 40 indicated good quality of concrete which was supported by USPV values. Water absorption in concrete was decreasing as the concrete density was increasing. Saline water has not affected underground RCC. Chloride content was slightly above the permissible limit but it has not affected reinforcement corrosion. Sever reinforcement corrosion was observed at the location where seawater spillage was taking place. Overall conditions of concrete structures were good and acceptable.

9.0 Summary:
Dhruva research reactor completed 33 years of operation. Various civil structures didn’t show any major degradation. Carbonation depth was observed to be between 10 to 20 mm deep. To prevent further carbonation, painting of the structures had been initiated and
completed. Jacketing of the cracked columns has been done. Repairing plan / restoration of structure supported by NDTs results provided targeted repair plan.

10.0 References:

The codes, standard and other relevant references are as follows:

[1]. In-Service Inspection Manual of Dhruva Research Reactor, India, 2011, Revision -0


[7]. ASTM C 876 – 91(1999)- Standard test method for half-cell potential measurement


[9]. IAEA-RCA Training Course on In-Service Inspection of Research Reactors Lecture notes: Jan 21 to Feb 1, 2002 Mumbai, India

[10]. Reports on Non-Destructive Testing of Dhruva Civil Structures, BARC, Trombay, Mumbai: July 2016