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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

REVIEW OF CURRENT PRACTICES AND REQUIREMENTS FOR THE INSPECTION OF PRESTRESSED CONCRETE PRESSURE VESSELS

by

K. J. Reimann

Materials Science Division

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K.J. Reimann

ABSTRACT

Code requirements for pre- and in-service inspection of prestressed concrete pressure vessels as utilized in gas-gooled reactors are reviewed and compared with practices and experiences during construction, commissioning, and operation of such reactors. The pre-service inspection relies heavily on embedded instrumentation for measurements of stresses, temperatures, and displacements. The same instrumentation is later used for in-service surveillance, which additionally includes visual examination of exposed surfaces, monitoring of tendon conditions, and measurement of tendon loads. Improvement of present monitoring instrumentation and/or techniques, rather than development of new in-service inspection methods, is recommended.

I. INTRODUCTION

The unique feature that differentiates gas-cooled reactors from other nuclear reactor types is the primary pressure vessel, which is fabricated of prestressed concrete. According to the rules of the ASME Boiler and Pressure Vessel Code, such a vessel is classified as a class 1 component. While rules for metallic class 1 components existed when construction of gas-cooled reactors was initiated, similar rules for prestressed-concrete class 1 components had to be developed and implemented. These rules evolved in part from practices and requirements of various organizations dealing with prestressed concrete, and in part from experience gained in the U.S. and abroad from the construction and operation of prototype gas-cooled reactors.

A literature review of current practices and requirements was conducted in order to assess the needs for development of additional in-service inspection techniques. The present report summarizes the findings and discusses areas where additional efforts would be beneficial.

II. ASME CODE REQUIREMENTS

The requirements for the construction of prestressed concrete nuclear pressure vessels, including inspection requirements, are contained in Section III, Division 2(1) of the ASME Boiler and Pressure Vessel Code. This code became mandatory on July 1, 1975. Section III, Division 2 does not cover post-construction requirements. These requirements, related specifically to in-service inspection, are covered in ASME Code Section XI, Division 2.(2) The latter code section, however, is not yet mandatory.

Other countries involved in gas-cooled reactor technology, such as Great Britain, France, and West Germany, have developed their own prestressed concrete pressure vessel requirements in the form of specifications, decrees, or study reports.

While there are many similarities among these documents, there are also some differences.(3) The ASME Code is unique in that it requires owners, constructors, and fabricators to be certified (Section III, Division 2, Subsection CA). Certification means in this case that quality assurance programs of the various participants satisfactorily meet all code requirements. Subsection CB of Section III, Division 2 addresses the rules and requirements for concrete reactor vessels. It covers areas such as materials specification and testing, design criteria, fabrication and construction requirements, construction testing and examination, and structural integrity tests of reactor vessels. The articles on materials, fabrication, and construction specify in detail not only the requirements for concrete but also for reinforcing and prestressing systems and liner materials. From a nondestructive testing viewpoint, only the articles on construction testing and examination and structural integrity testing of concrete reactor vessels are of interest. Table I (from Ref. 1) summarizes the required tests for concrete material during construction. These tests do not, in general, fall within the scope of routine NDE methods.

The structural integrity test performed on concrete reactor vessels after completion of the construction phase is the final acceptance test. The code requires a pressure test at 1.15 times the design pressure. The following are required prior to, during, and after the test:

(a) A visual examination of accessible exterior surfaces for surface cracking.

(b) Deflection measurements of the structure.

(c) Strain measurements inside and on the surface of the structure.

(d) Tendon force measurements.

(e) Temperature measurements.

(f) Pressure measurements.

If the measurements remain within specified percentages of predicted maximum values, the pressure vessel is accepted. The only routine NDE procedure required for the inspection of prestressed concrete pressure vessels by Section III, Division 2 of the ASME Code are visual examination and instrumentation measurements.

The rules and regulations for in-service inspection of concrete reactor vessels are covered in ASME Code Section XI, Division 2, Subsection IGK. This subsection makes a distinction between in-service examination and in-service monitoring and surveillance. The examination methods recommended for concrete reactor vessels are shown in Table II.(2)

TABLE I

TESTING FREQUENCIES FOR CONCRETE MATERIAL AND CONCRETE [a]

Material	Requirements	Test Method	Frequency
Cement	Standard physical and chemical properties	ASTM C 150	Each 1200 tons
Fly Ash and Pozzolans	Chemical and physical properties in accordance with ASTM C 618	ASTM C 311	Each 200 tons
Aggregate	Gradation	ASTM C 136	Once daily during production[1]
	Moisture content	ASTM C 566	Twice daily during production
	Material finer than #200 sieve	ASTM C 117	Daily during production
	Organic impurities	ASTM C 40	Daily during production
	Flat and elongated particles	CRD-C 119	Monthly during production
	Friable particles	ASTM C 142	Monthly during production
	Lightweight particles	ASTM C 123	Monthly during production
	Soft fragments	ASTM 235	Monthly during production
	Specific gravity and absorption	ASTM C 127 or ASTM C 128	Monthly during production
	Los Angeles abrasion	ASTM C 131 or ASTM C 535	Every 6 months
	Potential reactivity	ASTM C 289	Every 6 months
	Soundness	ASTM C 88	Every 6 months
Water and Ice	Compliance with CB-2223		
	Effect on compressive strength	ASTM C 109	Monthly
	Setting time	ASTM C 191	Monthly
	Soundness	ASTM C 151	Monthly
	Total solids	ASTM D 1888	Monthly
	Chlorides	ASTM D 512	Monthly
Admixtures	Chemical composition	Infrared spectrophotometry pH and solids content in accordance with ASTM C 494	Composite of each shipment
Concrete	Mixer uniformity	ASTM C 94	Initially and every 6 months
	Sampling method	ASTM C 172	
	Compression cylinders	ASTM C 31	
	Compression strength	ASTM C 39	One set of 2 cylinders from each 100 cu yd or a minimum of 1 set per day for each class of concrete given in CB-5234.2
	Slump	ASTM C 143	First batch placed each day and every 50 cu yd placed
	Air content	ASTM C 173 or ASTM C 231	First batch placed each day and every 50 cu yd placed
	Temperature		First batch placed each day and every 50 cu yd placed
	Unit weight/yield	ASTM C 138	Daily during production

NOTE:
(1) Twice daily during production if more than 200 cu yd are placed.

[a] Table CB-5200-1 of Ref. 1.

TABLE II

EXAMINATION METHODS FOR CRV COMPONENTS AND PARTS[a]

Examination Areas from Table IGK-2500	Components and Parts To Be Examined	Method
A	Top head concrete surfaces	Visual
B	Bottom head concrete surfaces	Visual
C	Side wall concrete surfaces	Visual
D	Support structure	(Later)
E	Unbonded prestressing anchor assemblies	
	(a) Tendon wire/strand ends	Visual
	(b) Tendon anchor assemblies	Visual
	(c) Cover caps/plates over tendon anchor assemblies and tendons	Visual
	(d) Corrosion protection	Visual

[a] Table IGK-2600 of Ref. 2.

The in-service monitoring and surveillance requirements specify

(a) Monitoring of tendon prestress forces.

(b) Surveillance of vessel deflections.

(c) Surveillance of prestressing systems for corrosion attack.

(d) Surveillance of liner material for radiation effects.

The requirements of Section XI, Division 2 for in-service inspection of concrete pressure vessels thus specify visual examination (crack mapping) and instrumentation measurements. It becomes apparent from the code requirements that nondestructive inspection of prestressed concrete pressure vessels by other than visual methods is difficult, and monitoring and surveillance of critical parameters will yield results which assure safe operation of the structure.

III. PRACTICES IN CONSTRUCTION AND OPERATION OF GAS-COOLED REACTOR VESSELS

Prestressed concrete reactor vessels have been in operation since the mid-1960s, and much experience has been gained. However, only one such pressure vessel is in operation in the U.S., at the gas-cooled reactor in Fort St. Vrain, Colorado. This reactor uses helium as the coolant, while most others utilize CO_2. The existing prestressed concrete pressure vessels differ in size and shape, but have one common feature: All are equipped with a water-cooled liner and insulation to reduce the temperature gradient through the concrete wall.

The design, construction, proof testing, and commissioning of prestressed concrete pressure vessels(4-31) in the U.S. and elsewhere proceeded along similar lines, often before any code requirements existed. The conceptual design was analyzed with computer modeling, and the results tested on instrumented scale models. The findings were used to formulate the final design, which took into account selection and placement of instrumentation to be embedded during construction. The construction often required unique equipment and detailed quality assurance to fulfill specification requirements. The number and type of instruments embedded in prestressed concrete pressure vessels vary from country to country and site to site. For example, 550 sensors were incorporated during the construction of the Fort St. Vrain pressure vessel. The initial numbers and survival rates of the various instruments are shown in Table III.(11)

TABLE III

PCRV STRUCTURAL INSTRUMENTATION[a]

Sensor/Measurement	Total No. of Sensors	
	Installed	Functional*
Load Cell on Tendons	27	27
Vibrating Wire Strain (VWG Gage in Concrete)	110	80
Carlson Strain Gage in Concrete	25	20
Weldable Strain Gage on Rebar	25	13
Weldable Strain Gage on Liner	103	57
Thermocouple (with VWG) in Concrete	69	60
Thermocouple on Liner	166	155
Moisture Monitor in Concrete	25	21
TOTAL	550	433

*At time of PCRV pressure test.

[a] From Ref. 11.

After five years of operation, 70% of the instruments are still operational and used for in-service surveillance. Additional visual inspections and crack mapping were done after construction and both before and after pressure testing. In some foreign concrete pressure vessels, crack growth was monitored with crack gauges and vessel deflections under pressure were measured with optical telescopes, Invar tapes, manometric equipment, and dial gauges. The results indicate a good correlation between measured and calculated values.

The instrumentation required for pressure testing of prestressed concrete pressure vessels is an integral part of the vessel and thus very suitable for in-service monitoring. Strain and temperature data are collected at regular time periods (every month at Wylfa, England), while moisture is measured at longer time intervals (four times a year at Wylfa). A large number of gauges were used in some of the earlier vessels in order to obtain detailed experimental data. This number was subsequently reduced for faster evaluation of results. Periodic mapping and measuring of surface cracks is another part of the in-service monitoring and surveillance practice. Tendon loads are checked periodically on a statistical basis (1% of total number), with accompanying visual examination of the concrete under the anchor plates. Samples of tendons or tendon wires are visually (and sometimes chemically) examined for corrosion attack, usually during tendon load surveys.

In-service monitoring and surveillance of prestressed concrete pressure vessels bore out that while the prestressing load is reduced somewhat by tendon relaxation and concrete creep, the load will remain above the minimum design level for the projected 30-year life span. Some slippage in the cable anchor system, breakage of tensioning cable strands, and movement of anchor plates into the concrete are also observed. In a single case (Dungeness, England), an abnormally high level of corrosion pitting of tendons was detected during plant construction. This corrosive attack was caused by water ingress into the ducts and subsequent emulsification of the corrosion-preventing grease. Stress measurements after prolonged operation (> 15 years) indicate that the stress remains within predicted limits. Temperature data show that while the temperature distribution remains constant, some "hot" spots develop after a prolonged period of full-power operation. Crack mapping and crack-growth monitoring show some crack growth and appearance of new cracks, but these remain rather small; none has reached dimensions requiring repair. Prestressed concrete pressure vessels equipped with moisture gauges exhibited no change in moisture content.

All in all, in-service monitoring and surveillance of prestressed concrete pressure vessels, as currently practiced, seems adequate to assure safe operation, as borne out by the fact that the first such vessel (Marcoule, France) has operated since 1960 without incident.

IV. DISCUSSION AND RECOMMENDATIONS

Development of a code for prestressed concrete pressure vessels and actual design and construction of such a vessel in the U.S. proceeded almost simultaneously. All such vessels in the U.S. and abroad are instrumented for pressure proof testing, and the instrumentation is subsequently used for in-service monitoring and surveillance. The surveillance includes visual examination for surface cracks and tendon conditions. Implementation of in-service monitoring and surveillance has yielded satisfactory results to date, and use of additional inspection techniques would only increase costs and downtime.

Some concern exists regarding excessive leakage through concrete as a consequence of faulty construction (numerous voids), especially in containment vessels. Preliminary results abroad(20) show the potential application of "sonic coring" tests to inspection of concrete pressure vessels. The sonic coring method utilizes low-frequency (50-100 kHz) ultrasound to inspect the concrete between two adjacent tendon tubes by measuring the time of flight of the ultrasonic pressure wave. The large number of tendons in a pressure vessel, and the necessity to fill the tendon tubes with water as a couplant, would make the inspection rather expensive and time-consuming. Ultrasonic through-transmission as a means of inspecting concrete structures was evaluated in the past(32,33) with encouraging results. However, application of this method to prestressed concrete pressure vessels is destined to fail because of scattering by the multiple layers of tendons, and the limitations imposed by one-sided access. The same is true for radiographic examinations, where background radiation and the wall thickness will cause additional problems.

The adequacy of present in-service monitoring and surveillance indicates that attention should be redirected from development of new inspection methods to improvement of monitoring instrumentation and techniques. Areas which should be addressed include:

(a) Developing more robust strain gauges to ensure a higher rate of survival.

(b) Developing a technique and/or model to detect and compensate for erroneous gauge readings.

(c) Determining whether strain results are really required or whether stress gauges (such as Carlson and Glötzel gauges) or deflection- and movement-detection devices would yield more relevant results.

(d) Determining whether the application of laser methods to measurements of dimensional changes would yield more accurate and consistent results than currently used manometric or optical systems.

Additional efforts should be directed toward establishing (a) the optimum number and location of gauges for a given vessel design, (b) the best way to present data, and (c) data normalization methods that would facilitate performance comparisons among different prestressed concrete pressure vessels.

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