

MAGNOX DECOMMISSIONING DIALOGUE TIMESCALES WORKING TWG

CONTACT WITH DR GASSAM NOUNU

AND

POSSIBLE MODES OF DEGRADATION OF THE MAGNOX CONCRETE STRUCTURES
OVER THE EXTENDED SAFESTORE PERIOD

CLIENT: THE ENVIRONMENT COUNCIL

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ABSTRACT

Contact with Gassan Nounu indicated that although his interest is in the durability of concrete structures he has no specific expertise and experience in application to Magnox reactors and their decommissioning. It was considered unlikely that Gassan Nounu would be able to contribute within the time available to the Dialogue and, because of this, a short review of available publications was undertaken and is presented here.

Applied to the concrete biological shields and (later) reactor pressure vessels of the Magnox reactors, any substantial loss of strength and damage to the concrete structures as a direct result of irradiation is likely to be confined to the inner face of the structure, perhaps extending into the wall to a depth of 300 to 400mm, or slightly more depending on the detailed geometry of particular localities. Because the biological shields are massive, thick-walled structures the remaining structure would be largely unaffected by radiation damage, although some thermal (tension) cracking of the outer wall may have developed over the years of operation. However, regard should be given to any departures from good concreting practice at the time of build. For example, untried aggregates may have been utilised to optimise the radiation attenuation and neutron capture characteristics, and novel additives, such as plasticers and (cure) accelerators/retarders, may have been introduced to facilitate the build of the reactor biological shields and later RPVs – incautious use of such additives has been shown to cause longer term degradation of concrete structures.

Although it may not be possible to forecast all of the uncertainties about the concrete matrix and concrete structures over the projected life of *Safestore*, it should be realistic to incorporate common-sense features into the *Safestore* design that will enable the concrete to be routinely monitored to ensure that the conditions and limits (strength, etc) of its *Safestore* function are not exceeded.

MODES OF DEGRADATION OF CONCRETE STRUCTURES OVER THE SAFESTORE PERIOD

At the request of Paul Dorfmann, I contacted Dr Gassan Nounu to explore his concerns relating to the potential for degradation of the Magnox concrete structures during the extended *Safestore* period. Gassan Nounu is a lecturer in the Faculty of Built Environment at the West of England University (Bristol) and he has an interest in the durability of structural concrete.

We discussed Magnox decommissioning and, particularly, the range of time scales over which the concrete structures might be left in situ, applying these to the two basic types of reactor structure (steel and concrete reactor pressure vessel). Gassan Nounu opined that although he personally had not undertaken any research into the irradiation (and other related) effects on concrete and concrete structures (including steel reinforcement and tendons, where applicable), nor had he reviewed the subject at any level, he believed that it might be an interesting area of work.

I asked Gassan Nounu to provide me with an estimate of the cost for him to complete a first-stab review of the available publications in this field, suggesting a title '*A Review of Publications relating to the Durability of the Concrete Matrix and Concrete Structures subject to Irradiation during Reactor Operation and throughout the proposed Safestore Periods of Decommissioning*' – Gassan Nuonu is to advise me of this and I, in turn, will report back to the Timescales Group should it wish to proceed with the work.

That said, Gassan Nounu did not seem to have much of an understanding of the reactor biological shielding and RPV (where applicable) containment designs, the operating regime and the conditions expected during the essentially passive Safestore period leading to final dismantlement. Before Gassan Nounu could undertake any meaningful review he would need to be thoroughly briefed on this with this briefing, in itself, probably requiring a greater effort and time than the proposed literature review.

BRIEF REVIEW OF CONCRETE UNDER AND FOLLOWING IRRADIATION

In the likelihood that the Timescales Group will not proceed with a separate literature review, it might be appropriate for me to briefly review the effects of irradiation on concrete and its durability.

Constituents of Concrete

First, concrete comprises natural aggregate (sand and stones) mixed with and bound into a matrix of cement.

The cement is made from a calcareous material, such as limestone or chalk, and from alumina and silica found as clay or shale. The base material is crushed and fed into a high temperature kiln in which it undergoes a series of chemical reactions, eventually emerging as clinker which is ground with gypsum. In the presence of water cement forms products of hydration, producing a firm and hard paste-like mass which has both adhesive and cohesive properties.

The aggregate of concrete forms at least three-quarters of the volume of concrete. The aggregate might be considered to be an economic substitute for the more expensive cement or, on the other hand, as a basic strength element which is held and locked together by the hardened cement past. Aggregates are classified in terms of size, strength and chemistry, with all of these features contributing to the overall strength and durability of the concrete.

Concrete Structures

Concrete structures are reinforced with steel, usually in the form of bars between 12 to 30-40mm in diameter. The steel reinforcement is more commonly in the form of bars that are embedded within and bonded to the concrete matrix by the cement paste (the earlier Magnox reactor biological shields), or with steel tendons that are either pre- or post-stressed and which are generally free to move within channels passing through the concrete (Oldbury and Wylfa Magnox reactors where the reactor pressure vessel is a concrete structure).

Concrete Radiation Shields

Concrete is commonly used as a shielding material against high energy X-rays, gamma rays and neutrons because it combines radiation absorption properties with good mechanical characteristics, durability, and economic structural use.

Concrete shields against gamma radiation are primarily effective through their Compton scattering effect (one of the mechanisms through which photons interact with matter), in which photons undergo an elastic

collision with an atomic electron in such a way that energy and momentum are conserved. Gamma ray absorption requires a high density of the shield so the design would be for a concrete mix with relatively small-sized aggregate, high compaction and low (air) voidage.

In addition to absorbing gamma rays, reactor shields have to attenuate neutrons, which are the heavy particles of the atomic nuclei. These particles, because they have no electric charge, are slowed down only on collision with atomic nuclei. For efficient neutron shielding, the material must contain some heavy elements (to slow down the fast neutrons), and a quantity of hydrogen (to slow down the intermediate neutrons and to absorb the slow neutrons). Because, on absorption of slow neutrons, hydrogen emits gamma rays, the presence of boron (which is more effective) would be a desirable component of compact reactor shielding systems. However, care is required as water-soluble boron compounds reduce the development of strength of concrete during the curing (setting) phase; on the other hand, the addition of water-insoluble boron compounds provides the same radiation protection without an adverse effect on the mechanical properties of concrete (Foster, Dubrovskii).

Thus for the attenuation of neutrons and absorption of gamma rays concrete satisfies both the requirements of high density for gamma shielding and with its high hydrogen content it moderates and absorbs neutrons.

Free Water Content

For neutron absorption the required hydrogen content required is about 0.45% by weight for normal density concrete, and this is reached by a water content representing approximately 4 per cent of the weight of the concrete. Some of this water is chemically combined in the hydrated cement paste, some may be free water, and some may be in the form of the water of crystallization in aggregate. Fully dried-out concrete has a hydrogen content of about 0.25 per cent by weight (Gill, Hyde), so that nearly one-half of the hydrogen required has to be found outside the chemically combined water. For this reason, the choice of suitable aggregate may be important with, for example, aggregates containing silica contain a large amount of oxygen which also assists in moderating neutrons. Silica based cements may have been used in the Magnox biological shield concrete structures because of the higher oxygen content which improves neutron absorption.

Radiolysis affects the interstitial liquid in concrete in that oxygen is reduced mainly by peroxide trapping (Bouniol) which is at the expense of calcium in solution with the cement paste and which may result in a loss of adhesion of the paste.

Temperature Stresses

Attenuation of radiation results in a rise in temperature of the shielding concrete as the absorbed energy of radiation is converted to heat – this temperature rise is in addition to any heat being absorbed from the coolant gas and thermal radiation from the RPV or reactor core. The expected radiation induced temperature rise within the concrete relates to the incident flux from the operation core could be as high as 60° to 80°C, being greatest in that part of the shield closest to the radiation source. Thus the temperature rise is non-uniform throughout the shield so that thermal stresses arise, with the stress distribution being further complicated by the forced cooling of the shield surfaces adopted in the Magnox steel RPV designs.

To inhibit stress related damage and failure, in account of temperature rise the maximum incident energy flux is related to the allowable compressive or tensile stress in concrete. For the steel RPV Magnox reactors this resulted in relatively massive (thick walled) biological shields, although at a cost of increasing tangential tension at the outer surface which had to be restrained by heavy steel reinforcement.

The temperature distribution within the shield is affected not only by the distribution of the absorbed energy but also by the thermal properties of concrete. The desirable thermal properties of shielding concrete are high thermal conductivity (to minimize high local rise in temperature), low coefficient of thermal expansion (to minimize strains due to temperature gradients) and low drying shrinkage (to minimize differential strains). While high creep is not necessarily disadvantageous, it is important to be able to predict its magnitude.

Deterioration of Concrete Physical Properties

Thermal stresses are not the only reason for limiting the temperature rise in a shield: at elevated temperatures, the strength of concrete may be adversely affected, creep may be increased, and the attenuation of neutrons may also be reduced as water is driven out of the concrete; a reduction in attenuation as high as 30 per cent has been observed. For

these reasons, a limit on the maximum temperature should be imposed in design.

The effects of high temperature (~50°C) and high levels of irradiation (~10¹⁰n/mm²) for six months yielded a two-thirds reduction in strength (Batten), although irradiation alone did not result in a strength deterioration (Tipton), other than for concrete samples with crystalline quartz aggregate in which failure of the cement paste bond occurred (Dubrovskii). When aluminous cement was used, the strength was reduced to about one-third of the original value; this high loss may be related to the chemical conversion of this type of cement.

It seems reasonable to expect that creep of concrete is unaffected by radiation except in so far as temperature is increased, and this enhances creep and accelerates drying. It is possible, however, that displacement of water molecules or hydrogen atoms by irradiation causes some damage. The practical significance of any influence of irradiation on creep is not very large as the damaging action is reduced by about 90 per cent in a 300 to 400 mm thickness of concrete of the biological shield (slightly more for a concrete RPV), so that any effects on the structure would be limited to its inner face.

SUMMARY

Applied to the concrete biological shields and (later) reactor pressure vessels of the Magnox reactors, any substantial loss of strength and damage to the concrete structures as a direct result of irradiation is likely to be confined to the inner face of the structure, perhaps extending into the wall to a depth of 300 to 400mm, or slightly more depending on the detailed geometry of particular localities. Because the biological shields are massive, thick-walled structures the remaining structure would be largely unaffected by radiation damage, although some thermal (tension) cracking of the outer wall may have developed over the years of operation.

Although irradiation damage may not in itself compromise the overall durability of the concrete structures during the extended *Safestore* period, regard should be given to any departures from the established and proven practise of concreting at the time of build. For example, untried aggregates may have been utilised to optimise the radiation attenuation and neutron capture characteristics, and novel additives, such as plasticers and (cure) accelerators/retarders may have been

introduced to facilitate the build of the reactor biological shields and later RPVs.

Although it may not be possible to forecast all of the uncertainties about the concrete matrix and concrete structures over the projected life of *Safestore*, it should be realistic to incorporate common sense features into the *Safestore* design that will enable the concrete to be routinely monitored to ensure that the conditions and limits (strength, etc) of its *Safestore* function are not exceeded.

REFERENCES

- 1) BATTEN A. W. C., *Effect of irradiation on the strength of concrete* (U.K. Atomic Energy Authority, Harwell, pp. 10, 1960).
- 2) BINGHAM W. E., *Low activation shielding materials for nuclear reactor environmental test chambers, Nuclear Structural Engineering*, 2, pp. 243-7 (Amsterdam, 1965).
- 3) Belian, Anthony P. Latkowski, Jeffery F.;Morse, Edward C.; *Experimental studies of concrete activation at the National Ignition Facility using the Rotating Target Neutron Source* , Fusion Technology, v 34, n 3 pt 2, Nov, 1998, Proceedings of the 1998 13th Topical Meeting on the Technology of Fusion Energy, Jun 7-11 1997, Nashville, TN, USA, p 1028-1032 Publisher: ANS, La Grange Park, IL, USA ISSN: 0748-1896 CODEN: FUSTE8
- 4) Bouniol, P. Aspart, A.; *Disappearance of oxygen in concrete under irradiation: The role of peroxides in radiolysis*, Cement and Concrete Research, v 28, n 11, Nov, 1998, p 1669-1681 Publisher: Elsevier Sci Ltd, Exeter, Engl ISSN: 0008-8846 CODEN: CENRAI
- 5) DUBROVSKII, V B. SH. IBRAGIMOV, M. YA. KULAKOVSKII, A. YA. LADYGIN and B. K V. B.. PERGAMENSHCHIK, *Radiation damage in ordinary concrete, English Translation in Soviet Atomic Energy*, 23, No.4, pp. 1053-8 (Oct. 1967).
- 6) DUBROVSKII V. B., SH. SH. IBRAGIMOV, A. A. LADYGIN and B. K. PERGAMENSHCHIK, *Effect of neutron irradiation on some properties of heat-resistant concretes, English Translation in Soviet Atomic Energy*, 21, No.2, pp. 740-4 (Aug. 1966).
- 7) FOSTER B. E., *Attenuation of X-rays and gamma rays in concrete, A.S.T.M. Mat. Res. and Stand.*, 8, No.3, pp. 19-24 (March 1968).
- 8) Ganguly, Chaitanyamoy; Anantharaman, Sundaresan; Sivaramakrishnan, Karai S.; *Effect of neutron irradiation on the mechanical properties of microalloyed steel for reinforced cement concrete, ASTM Special Technical Publication*, n 1125, 1992, 15th International Symposium on *Effects of Radiation on Materials*, Jun 19-21 1990, Nashville, TN, USA, p 1304-1310 Sponsored by: ASTM Publisher: Publ by ASTM, Philadelphia, PA, USA, 1992 ISSN: 0066-0558 CODEN: ASTTA8 ISBN: 0-8031-1477-X

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- 9) GILL S., *Structures for nuclear power* (London, C. R. Books Ltd., 1964). HYDE R. B., Fulfilling requirements for materials for nuclear power projects, *J. Brit. Nuclear Energy Soc.*, 3, No.1, pp. 61-4 (Jan. 1964).
 - 10) IANSS J., Etude de betons speciaux de protection contre les radiations nucleaires, *Revue Universelle des Mines*, No.8, pp. 7 (Liege, Aug. 1962).
 - 11) Krasznai, J.P.; *Radiochemical characterization of regular- and high-density concrete from a decommissioned reactor*, Waste Management, v 13, n 2, 1993, p 131-140 ISSN: 0956-053X CODEN: WAMAE2
 - 12) Nakajima, Nobuya; Onizawa, Kunio; Suzuki, Masahide; *Technical issues for life evaluation of light water reactor components*, Nippon Genshiryoku Gakkaishi/Journal of the Atomic Energy Society of Japan, v 33, n 1, Jan, 1991, p 53-61 ISSN: 0004-7120 CODEN:
 - 13) Pugliesi, R. Andrade, M.L.G.; *Study of cracking in concrete by neutron radiography - Applied Radiation and Isotopes*, v 48, n 3, Mar, 1997, p 339-344 Publisher: Elsevier Science Ltd, Oxford, Engl ISSN: 0969-8043 CODEN: ARISEF
 - 14) SEBOK F., *Role of water content in concrete structures shielding against atomic radiations*, *Hungarian Technical Abstracts*, 16, No.3, p. 94 (1964) (*Melyepito estudomilnyi Szemle*, 13, No.12, pp. 566-70, 1968).
 - 15) Soo, P.. Milian L. W *Sulfate-attack resistance and gamma-irradiation resistance of some Portland cement based mortars*, Washington, DC : Division of Engineering, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, 1989
 - 16) THOMAS D. R., *Temperature and thermal stress distributions in concrete primary shields for nuclear reactors*, *Nuclear Structural Engineering*, 1, pp. 368-84 (Amsterdam, 1965).
 - 17) Yarar, Yasemin; *Activation characteristics of concrete shields containing colemanite* Journal of Nuclear Materials, v 233-237, n Pt B, Oct 1, 1996, Proceedings of the 1995 7th International Conference on Fusion Reactor Materials, ICFRM-7, Sep 25-29 1995, Obninsk, Russia, p 1511-1515 ISSN: 0022-3115 CODEN: JNUMAN