EVALUATION OF RADIATION INDUCED THERMAL STRESSES IN A REINFORCED CONCRETE SHIELD WITH COMPUTER CODE-"NUCLAS"

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ABSTRACT

Ghana currently operates a Research Reactor ,a Gamma Irradiation Facility, a Radiotherapy Centre and a Radiographic Non-Destructive Testing Laboratory. Each of these facilities has a concrete radiation shield as a major safety device.

Inevitably, a concrete radiation shield in performing its functions is subjected to nuclear heating. Beyond certain limits this phenomenon can have deleterious effects upon the performance of the shield. This paper discusses the evaluation of the stresses resulting from the nuclear heating of a concrete radiation shield using a computer code named "NUCLAS". Results of these stresses as obtained from NUCLAS on the analysis of the Ghana Research Reactor 1(GHARR-1) are presented.

KEYWORDS: *Nuclear heating, shielding ,computer code, thermal stresses.*

INTRODUCTION

The function of a nuclear shield to mitigate ionising radiation to acceptable limits makes it one of the most important components of a nuclear assembly. A shield may also perform other important functions such as contain and/or support some other components of the nuclear assembly. To perform these functions satisfactorily, the shield must remain intact for its intended lifetime. The structural integrity of a nuclear shield, under various kinds of possible loading therefore, forms an important consideration in its design and construction.

Concrete is used very commonly as a shielding material, but its performance as a structural material under elevated temperatures and thermal cycling however, needs careful consideration and perhaps some improvement to enhance its application as a nuclear shielding material.

Several factors combine to influence the strength of concrete when subjected to heating[1].These include chemical and physical changes within the concrete. While some of these may enhance its strength, a greater number of others have detrimental effects on it. In particular changes that result in the setting up of thermal stresses within the concrete have only detrimental effects on the strength of concrete during first-time heating.

A procedure, which has been translated by the authors into a computer code, for evaluating the radiation induced thermal stresses on a reinforced concrete radiation shield is presented. The project was carried out having in perspective the concrete shields of the Ghana Research Reactor-1 and the Gamma Irradiation Facility, both of which are situated at the Ghana Atomic Energy Commission. The vertical cross-sectional views of these facilities are shown on Figure 1[2] and Figure 2[3] respectively.

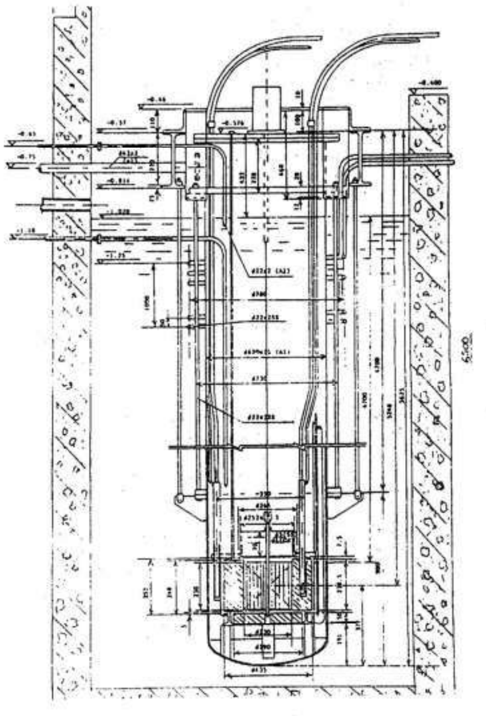

Fig. 1: Elevation view of GHARR-1 Assembly Showing its Shield System


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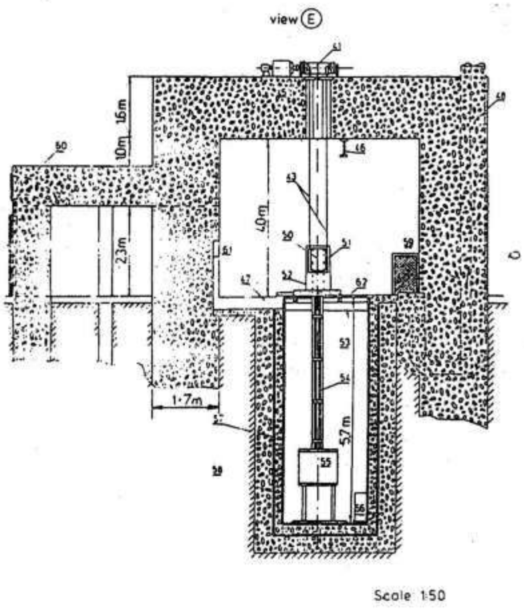


Fig. 2: Elevation View of GIF-1 Assembly Showing its Concrete Shield

CONCRETE RADIATION SHIELDING

The Importance of Concrete as a Shielding Material

Concrete is widely used as a shielding material for nuclear power plants, research reactors, particle accelerators and medical facilities. This is due to a number of qualities concrete has that favours it for shielding application. These include:

- good gamma attenuation properties (contains heavy elements suitable for gamma attenuation)
- good neutron attenuation properties (contains heavy and light elements such as hydrogen)
- good structural properties (has sufficient compressive strength, amenable to reinforcement to take bending/tension, low coefficient of material expansion etc.)
- ease of construction (this includes ease of handling and ease of casting into complex shapes)
- low cost (relatively inexpensive material and low maintenance cost).
- ease of varying composition to meet specific requirements (special additives and aggregates may be employed to achieve specific requirements)

Effects of Nuclear Heating on a Concrete Radiation Shield

The heating of a nuclear radiation shield is unavoidable because, the attenuation process itself involves the conversion of nuclear energy into heat energy in the shield. The radiation particles or photons ultimately transfer their energy to the kinetic energy of the electrons(or positrons) of the shielding medium, which then dissipate their energy as heat as they are brought to rest.

The nuclear heating rate at any point in the medium depends upon the nuclear energy being deposited there per unit mass or volume of the medium. The calculation of this therefore requires knowledge of the energy and spatial dependence of the particle flux in the medium. As the spatial dependence of the particle flux may very likely not be uniform throughout the medium, the heating rate will vary spatially and lead to the generation of thermal stresses in media of low thermal conductivity. Concrete has very low thermal conductivity and may suffer significant thermal stresses when subjected to intense nuclear radiation.

Response of concrete to heating

The response of concrete to elevated temperatures and thermal cycling is a subject being currently investigated intensely especially in the Nuclear arena. The problems presented in arriving at unifying conclusions include the heterogeneous nature of concrete and the unlimited varieties of concrete specimens that may be realised. Variations in experimental conditions may also lead to varying results even for similar concrete.

The general effect in increase in temperature on the strength of concrete is small and somewhat irregular at temperatures lower than about 250°C as illustrated in Figure 3[4].

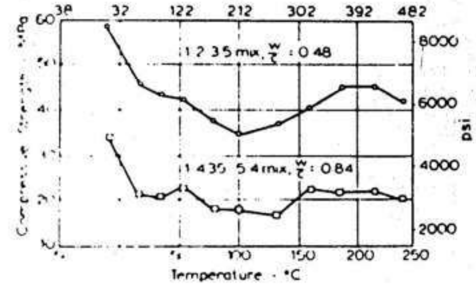


Fig. 3[4]: Compressive strength of concrete after heating to different temperatures.(calcareous aggr.; specimen tested at the exposure temperature)

Under certain conditions, such as thermal cycling and high rates of heating and cooling, however, the integrity of concrete could be compromised even at temperatures much lower than 250°C. It may be stated in general terms that at temperatures above about 300°C the strength of concrete declines sharply. This is illustrated in Figure 4[5]. There are exceptions to this, however, and it is being argued by Khoury [6] that it is possible to design a concrete mix that could retain most of its strength at temperatures up to about 600°C

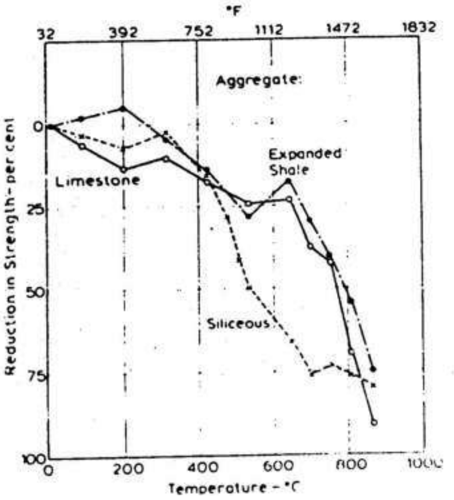
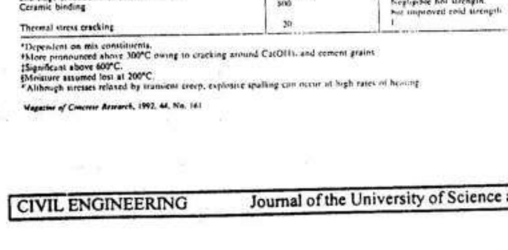


Fig.4[5]: Reduction in compressive strength of concrete heated without application of load and then tested hot; average initial strength of 28MPa.

The underlying mechanisms that influence the strength of unsealed concrete during first-time heating are summarised in Table 1[7]. The interest here, however, is narrowed to a "thermal stress cracking" which arise as a result of differential heating of the concrete mass. Because concrete has a low thermal conductivity differential heating could give rise to high temperature gradients and hence differential expansion between the hot and cold regions. This will result in the generation of internal stresses which are tensile in effect. If these tensile stresses exceed or are comparable to that of concrete, cracking may result at joints, in poorly compacted parts of the concrete or in the planes of reinforcing bars [8]. Once the reinforcement bars are exposed they conduct heat and thus accelerate the action of heat. Also these stresses could lead to spallation, void formation and load shifting [9].

Table 1:



Mechanisms influencing strength of unsealed concrete during first-time heating (relative importance is not indicated) [9]

Mechanism	Approximate temperature range: °C	Gain or loss in strength
Aggregate thermal instability	Aggregate-dependent	L
Thermal incompatibility and parasitic stresses (relaxed by transient creep)	20-600 +	L
Changes in strength of bond shell	20	G or L*
Aggregate-paste chemical reaction	20-200 +	G or L*
Increase in temperature of water-gel system	20-200§	L
Accelerated hydration	20-90§	G
Accelerated hydration	90-200§	G or L (C/S ratio dependent)
Loss of free water	20-200§	G
Loss of physically bound water increase in surface tension	80-200§	G
Hydrothermal reactions	100-200§	G or L (C/S ratio dependent)
Pore pressure stresses¶	100-200§	L
Shrinkage stresses (relaxed by transient creep)	20-200§	L
Changes in chemical binding on dehydration of C-S-H	100-300 +	G (?)
Decrease in porosity	20-80 (?)	G (?)
Increase in porosity	[illegible]80-600 +	L†
Dissociation of Ca(OH)$_2$	390-450	L (perhaps insignificant)
Thermal effect	20-600 + (melting at 1350°C)	L‡
2nd stage breakdown of chemical bonds	600-750	L
Ceramic binding	800	Negligible hot strength, but improved cold strength
Thermal stress cracking	20	L

*Dependent on mix constituents.
†More pronounced above 300°C owing to cracking around Ca(OH)$_2$ and cement grains.
‡Significant above 600°C.
§Moisture assumed lost at 200°C.
¶Although stresses relaxed by transient creep, explosive spalling can occur at high rates of heating.

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Thermal Stress Cracking has a major influence on the integrity of the shield and the computer Code - "NUCLAS" evaluates these stresses .

Thermal Stresses in a Reinforced Concrete Shield

Figure 5[10] shows the maximum temperature rise in a slab of concrete as a function of incident energy flux.

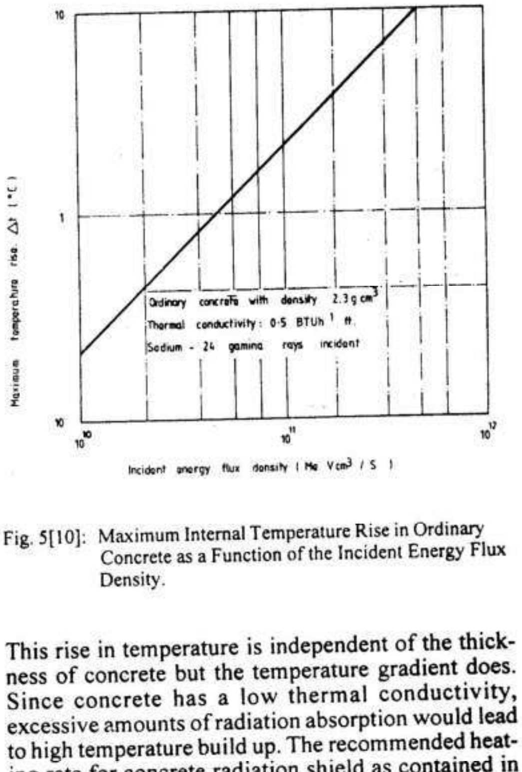

Fig. 5[10]: Maximum Internal Temperature Rise in Ordinary Concrete as a Function of the Incident Energy Flux Density.

This rise in temperature is independent of the thickness of concrete but the temperature gradient does. Since concrete has a low thermal conductivity, excessive amounts of radiation absorption would lead to high temperature build up. The recommended heating rate for concrete radiation shield as contained in the Engineering Compendium on Radiation Shielding[9] is 0.001W/cm^3/s which corresponds to an incident radiation of 4×10^{10}MeV/cm^3/s. This will induce a temperature rise of 6°C in the concrete.

Figure 6[10] shows the temperature rise distributions in a concrete shield for a saturated, a partly dried and a completely dried shield conditions. Such a temperature profile in concrete is not favourable to its integrity especially if the maximum temperature rise is high and the temperature gradients are steep. It has been reported by Thorne[13] that the effect of the maximum and average temperature rises is more extreme, their values increasing by 80 percent when the first 10 per cent of the shield has dried. This could be attributed to a cumulative effect of shrinkage stress and thermal stresses.

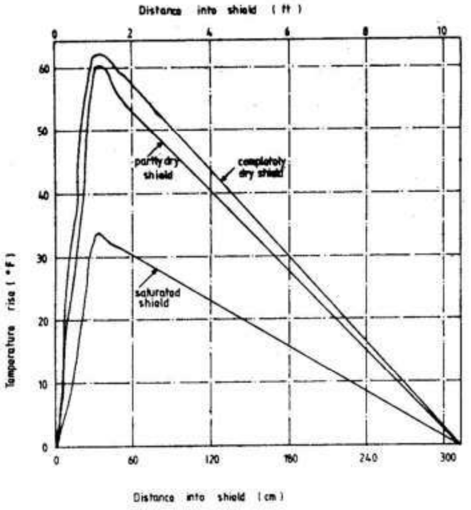

Fig. 6[10] : Temperature Distributions in a Concrete Shield.
(1°F=0.55556°C, 1ft=0.3048m)

If temperature gradients in the shield are high as could be easily generated in a dried shield or in the dried inner regions of a shield the magnitude of thermal stress cracking would be significant and may lead to spallation, cracking and possibly load shifting. This effect is more so with concrete shields, such as the GIF Irradiation Chamber ,that are directly exposed to the radiation. The Engineering Compendium on Radiation Shielding[9] limits the temperature gradient in the shield to 1°C/cm.

EVALUATION OF RADIATION INDUCED THERMAL STRESSES

The causes and effects of thermal stress cracking were discussed in the last section. They arise due to temperature gradients set up in the shield and are proportional to these gradients. The temperature gradients in turn depend upon the volumetric heating rates at varying depths across the thickness of the shield. If the flux densities of the various species of radiation at any depth into the shield are known , then the volumetric heating rate at that point may be estimated. Thus the radiation induced thermal stresses in a reinforced concrete shield may be evaluated.

The following steps are employed by NUCLAS for the evaluation of the thermal stresses in the concrete radiation shield.

(i) For each energy group of neutrons the volumetric heating rate, $H_0(W/cm^3)$ at the depth x in the concrete, is evaluated using the formulae (1) and (2) [9].

$$H_0(x) \sim 1.6 \times 10^{-13}\Sigma_c(E)\phi(x).E_B \qquad (1)$$

or

$$H_0(x) \sim 1.28 \times 10^{-12}\Sigma_c(E)\phi(x) \qquad (2)$$

Where

$\Sigma_c(E)$ = macroscopic capture cross-section [cm^{-1}] for neutrons of energy E.

$\phi(x)$ = neutron flux (energy E) at point x [n/cm^2s].

E_B = binding energy in MeV for the capture reaction(= 8MeV for most reactions)

$H_0(x)$ has the units - W/cm^3

(ii) For each energy group of gamma radiation the volumetric heating rate $H_0(x)[W/cm^3]$ at point x is evaluated using the formula (3.3) [9].

$$H_o(x) \sim 1.6\times10^{-13}\mu_{en}(E)\phi(E).E_\gamma \qquad (3)$$

Where

μ_{en} = energy absorption coefficient [cm^{-1}] for gamma rays of energy E.

$\phi(E)$ = flux [$photon/cm^2s$] of gamma photons of energy E_γ.

(iii) For a mixed spectrum of neutrons and gammas the volumetric heating rate is calculated for each component separately and the results summed to obtain the total heating rate at the particular point.

(iv) The temperature rise at a point x within the shield due to nuclear heating is estimated by means of equation (4)[9].

$$\Delta T(x) = H_o\lambda^2[1 - e^{-x/\lambda}]/k \quad [°C] \qquad (4)$$

where

x = distance into the shield[cm]

H_o = heating rate at a point x in shield [W/cm^3].

λ = local relaxation length taken equal to $1/\Sigma_R$ for neutrons or $1/\mu$ for gammas

Σ_R = fast neutron removal cross section $[cm^{-1}]$

μ = gamma ray linear absorption coefficient for the concrete

k = concrete thermal conductivity expressed in W/cm °C

(v) The temperature gradient at any point x in the shield is given by equation (5)[9].

$$\frac{dT(x)}{dx} = \frac{Ho\lambda exp(-x/\lambda)}{k} \qquad (5)$$

(vi) The average stress σ_o in kg/cm2 developed in a slab of material of thickness L[cm] for an initial heating rate H $[W/cm^3]$ at the surface of the material is given by equation (6)[9].

$$\sigma_o = P_o - \ddot{E}H_o\lambda^2\alpha\{1-2\lambda/L-(1-2\lambda/L)e^{-l/\lambda}\}k(1-\gamma) \qquad (6$$

where

P_o = average slab loading in kg/cm^2

$\ddot{E}$ = elastic modulus of slab material in kg/cm^2

Λ = relaxation length of material in cm

α = linear temperature coefficient of expansion in $[°C]^{-1}$

k = thermal conductivity of the material in W/cm °C

γ = Poisson's ratio = 0.14 for concrete

(vii) The thermal stress $\sigma(x)$ $[kg/cm^2]$ at any point x in the concrete shield is given by equation (7)[9].

$$\sigma(x) = \sigma_o + \alpha\ddot{E}\Delta T(x)/(1-\gamma) \qquad (7)$$

Where

$\Delta T(x)$ = temperature rise [°C] at point x given by equation (6)

Upon evaluating the fluxes due to the various species of radiation at each mesh point in the concrete shield, NUCLAS then evaluates the corresponding heating rates, temperature rises and thermal stresses there. The cumulative values of each of these parameters at any mesh point is subsequently evaluated.

RESULTS AND DISCUSSIONS

NUCLAS was used for the evaluation of the nuclear heating rates, temperature rises and the radiation induced thermal stresses in the concrete tank of GHARR-1 for a constant operating thermal power of 30kW and for 150kW corresponding to the accident event of releasing all the cold excess reactivity of the reactor with all the rabbit tubes filled witn water.

Distribution of heating rate, temperature rise and thermal stresses in simplified GHARR-1 shield are shown on figures 7, 8, and 9 [11] respectively for a constant operating thermal power of 30kW. The removal of the reflector to simplify the shield could significantly affect the validity of these results, but the general distribution of these parameters in the concrete layer, nevertheless, follows the general trend in similar data. The shape of the spatial distribution of the temperature rise as in Figures 8 and 11 compares well with that presented by Thorne[10] in Figure 6.

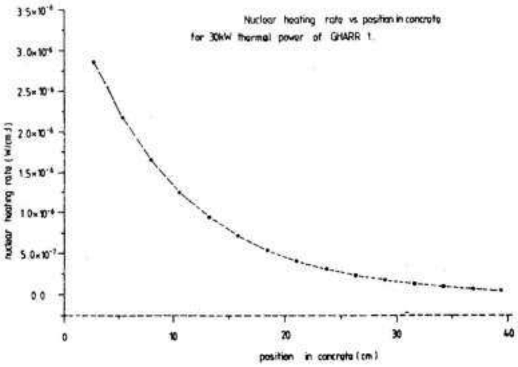

Fig. 7: Nuclear heating Rate vs Position in Concrete for 30kVA Thermal Power of GHARR

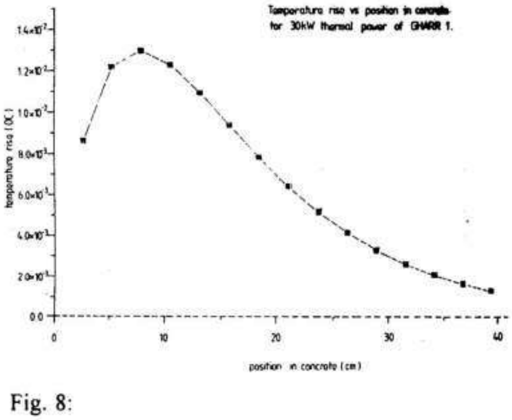

Fig. 8:

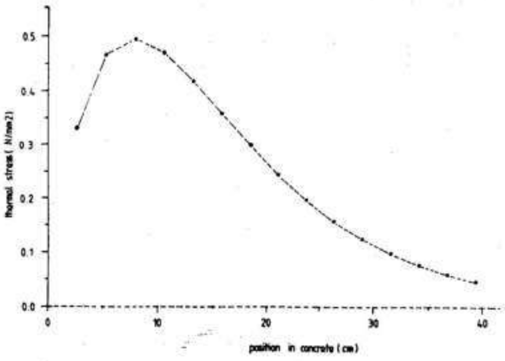

Fig. 9: Radiation Induced Thermal Stress vs Position in Concrete for 30kW Thermal Power GHARR 1

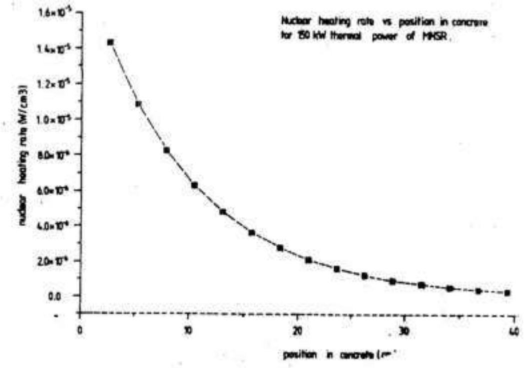

Fig. 10: Nuclear

Figure 9 gives the maximum value of thermal stresses in the concrete to be about 0.5N/mm² (tensile) for the condition of zero initial average loading of shield. Compared with the tensile strength of concrete (~ 3.5N/mm²) this alone does not constitute a threat to the integrity of the GHARR-1 concrete shield. More so the concrete tank is under pressure and the resulting stresses are compressive in the radial direction so that the assumption of zero initial average loading of shield will only lead to an overestimation of the tensile thermal stresses. In the absence of water in the pool, however, and should the power of the reactor escalate, and if there are initial cracks in the tank the magnitude and effect of these thermal stresses would be of significance.

In the event of releasing all the cold excess reactivity of the reactor when all the rabbit tubes are filled with water, power may escalate to a peak value of about 150kW. This peak value is assumed constant for the analysis of the shield as depicted by figures 10, 11, and 12[11]. Figure 12 gives the maximum value of the radiation induced tensile stress to be 2.475N/mm². This is of significance compared with the tensile strength of concrete(~3.5N/mm²).

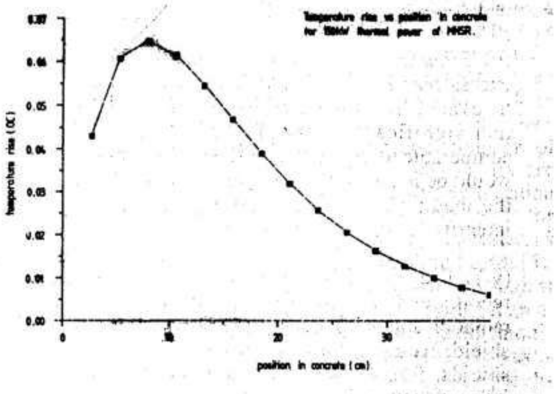

Fig. 11:

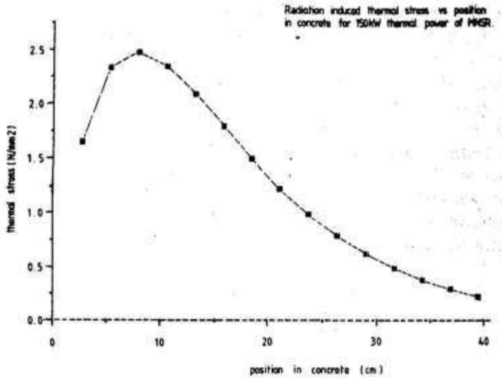

Fig. 12:

SUMMARY

(i) The generation of radiation induced thermal stresses in a concrete radiation shield is inevitable.

(ii) Radiation induced thermal stresses can lead to spallation, crack propagation and progressive weakening of a reinforced concrete shield; the extent of damage depending upon the intensity and the mode of application of the radiation.

(iii) The evaluation of radiation induced thermal stresses in a reinforced concrete shield is, by reason of (i) and (ii), necessary for its complete safety analysis. This is achievable by the use of the "user-friendly" reactor shielding code named "NUCLAS", which is specialised for water/concrete shields.

(iv) Upon investigating the concrete tank of the Ghana Research Reactor-1(GHARR1), using NUCLAS, it was found that under normal operating conditions, the tank was not subject to any significant thermal stresses.

(v) Under the accident event of releasing all the cold excess reactivity of GHARR-1 when all the rabbit tubes are filled with water, it was found by NUCLAS that significant thermal stresses of magnitude comparable to that of the tensile strength of concrete would be induced in its concrete tank. Depending on the loading and initial conditions of the tank, its integrity could be compromised.

(vi) The use of NUCLAS and by observing the recommended limits for incident energy flux of radiation and thermal stresses in a concrete radiation shield, would afford designs of reactor concrete shields, free of the deleterious effects radiation induced thermal stresses.

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