APPENDIX IV

Seismic Behaviour of Current and Proposed CANDU 6 Reactors

IV-1. CANDU 6 WEIGHTS AND AREAS

IV-1.1 CANDU 6 Areas: See Figures 4-12 & 4-13

Pressure-bearing Area of ES (less area of cal tubes)

$A_{ES} = (\pi/4)(300)^2 - 380((\pi/4)5.5^2) = 70\,685 - 9\,028 = \underline{61\,650\text{ in}^2}$

Cross-section area of Calandria tubes

$A_{CT} = 380(\pi)5.0(0.05) = \underline{298\text{ in}^2}$

Cross-Section of Calandria Shell:

$A_{CS} = 300(\pi)1.12 = \underline{1\,150\text{ in}^2}$

IV-1.2 CANDU 6 Weights:

W one end shield steel = both tube sheets + shell + 380[lattice tubes - LT holes]

$= 0.283\{(\pi/4)(266)^2(5) + \pi(266(1.5)36 + 380[\pi 5.5(0.4)36 - \pi/4((5.5^2)5)]\}$

$= 0.283\{278\,700 + 45\,200 + 49\,410\} = 0.283\{373\,300\} =$ 105 650 lbs

W cal shell = perimeter x length x t (ignore notch dia)

$= 0.283\{\pi(300)(240)(1.12)\} = 0.283\{254\,500\} =$ 72 020 lbs

W one support shell & plate

$= 0.283\{\pi(270)(1)36 + \pi(285)18(2.75)\} = 0.283\{74\ 860\} =$ 21 180 lbs

W 380 cal tubes = perimeter x length x t

$= 0.236\{\pi 5.0(0.05)(240)380\} = 0.236\{71\ 628) =$ 16 900 lbs

W one ES balls & water = (fraction balls + water){ gross vol ES - vol ES steel - lattice tube holes}

$= \{0.65(0.283) + 0.35(0.036)\}\{(\pi/4)(266)^2(41) - 373\ 300 - (\pi/4)5.5^2(36)380\}$

$= \{0.197\}\{2\ 285\ 300 - 373\ 300 - 325\ 010\} = 0.197(1\ 586\ 990) =$ 312 640 lbs

W h.water in cal = gross vol cal - vol cal tubes

$= 0.039\{(\pi/4)(300)^2(240) - 380(\pi/4)5.1^2(240)\} = 0.039\{16\ 964\ 600 - 1\ 863\ 050\}$

$= 0.039\{15\ 101\ 550\} =$ 558 960 lbs

W 380 full FCs = PT + (%vol x water) + fuel + EFs + Shield Plugs (Actuals via D. Brown)

$= 380\{0.236(\pi 4.2(0.2)(240) + 0.6(0.039)(\pi/4)(5)^2 (552) + 12(50) + [500 + 160]\}$

$= 380\{ 150 + 253 + 600 + [500 + 160] \} = 380 \times 1\ 663 =$ 631 940 lbs

W RCUs = 32 SO/CA + 21 ADJ + 6 ZC + 6 LIS + 34 FD + 99 loc'r + 99 [thim/4 + GTX/4]

$= 0.236[(\pi)(300)][(32)0.6(5)(0.06) + 21(0.6)3.5(0.05 + 6(4.5)0.1 + 34(0.8)0.1]$

$+ 99(20) + 0.283)(99)[\pi(6)0.4(60) = 2\ 980 + 1\ 980 + 2\ 110 =$ 7 070 lbs

W one Fuelling machine = 25 000 lbs

IV-1.3 CANDU 6 Total Weights

W_1 = TOTAL DRY SHIPPED ASS'Y (excl FCs & RCU) = <u>342 580</u> lbs

W_T = GROSS TOTAL FULL REACTOR ASS'Y (excl. only FMs) = 2 165 830 lbs

IV-2. THERMAL EXPANSIONS

IV-2.1 Present Design: Unrestrained Thermal Expansions

Expansions for half-length ie. *from mid-plane for symmetrical reactor*: $\delta = L \times \alpha \times \Delta T$;

(i) Calandria tube (install at 65°F [18°C]; operate at 150°F [65°C])

L_{axial} = 120"; $\alpha = 3.2(10^{-6})$ /°F; ΔT = (150 - 65) = 85°F

δ_{CT} = 120 x 3.2(10^{-6}) x 85 = 0.0326 ins

(ii) Calandria shell (ignoring the annular plate) (install at 65°F ; operate at150°F)

L_{axial} = 120" $\alpha = 9.0(10^{-6})$ /°F ΔT = (150 - 65) = 85°F

δ_{CS} = 120 x 9.0(10^{-6}) x 85 = 0.0918 ins

(iii) Concrete vault - axially (install calandria at 65°F; operate vault at 90°F [32 °C] in mid-thickness)

L_{axial} = 120" α = 3 to 5 x (10^{-6}) /°F ΔT = (90 - 65) = 25°F

δ_W = 120 x 4.0(10^{-6}) x 25 = 0.0120 ins

IV-2.2 Traditional Design plus Bolted Support Plates Both Ends: See Figure 4-18. Loads Under Restrained Thermal Expansion and Normal Pressure Load

(i) Thermal Restraint Loads for Calandria with Sub-shells and Bolted Support Plates Both Ends

If they were free to expand, the calandria tubes and vault would expand by amounts shown in **section IV-2.1**, above.

However, in this structure, the calandria expands more than the vault, therefore the calandria tubes are compressed, and the support plate at the vault end walls is compressed, to attain the same net deflection z.

Therefore, the calandria tube is compressed an amount:

$\epsilon_{CT} = \delta_{CT}{}^{*} - z$; but $\epsilon_{CT} = P/k_{CT}$ under load P (a) & (b)

and the support plates are dished outwards under the same force P, by the amount:

$\epsilon_{SP} = z - \delta_{W}$; but $\epsilon_{SP} = P/k_{SP}$ (c) & (d)

Stiffness $k_{CT} = EA/L$ for CT ; and $E = 13(10^6)$,
$A = 298\ in^2$, $L = 120$ in,

then $k_{CT} = 13(10^6) \times 298/120 =$ $32.28(10^6)$ lb/in

Stiffness $k_{SP} =$ $25(10^6)$
(Provided from FEM analysis for standard CANDU 6)

Equationa (a), (b), (c) & (d) are solved for P:

$$0.0326 - P/\,32.28(10^6) = P/\,25(10^6) - 0.0120$$

from which P = <u>628 355</u> lb
and $z = 0.0326 - 628\,355/\,32.28(10^6) =$ <u>0.0131</u> ins

and <u>Basic Compressive Stress in CT =</u> $\sigma_{CT\,1}$ = <u>628 355/ 298 =</u> <u>2 110 psi</u>

(ii) <u>Added Thermal Restraint Superimposed due to End Shield Dishing</u>

With the same temperatures and distributions on tube sheets as in standard CANDU 6, the same self-balancing system of sresses is superimposed on the CTs, due to the central region of the end shields bowing apart from each other, balanced by the edge regions being pushed towards each other. The central CTs exhibit tensile stresses in the order of 3 000 psi, while the CTs near the edge exhibit stresses in the order of 4 500 psi, See **Figure 2-27**, ie,

<u>Superimposed compressive stress</u> on CTs near the edge =
$\sigma_{CT\,2}$ = <u>4 500 psi</u>

(iii) <u>Internal Pressure Loads</u>

Use normal pressure at calndria mid-height is 4 psi cover gas pressure plus 12.5 feet static head:

Total force due to pressure acting on end shield net area = (4 + 12.5(62.4/144))61 650 = 580 540 lb

Tensile stress on CT = 580 540/ 298 = $\sigma_{CT\,3}$ = 1 950 psi

Then, total compressive stress on CT = σ_{CT} = 2 110 + 4 500 - 1 950 = 4 660 psi

IV-2.3 Straight Main Shell Design with Rigid Support Both Ends:
Loads Under Restrained Thermal Expansion and Normal Pressure Load

(i) Thermal Restraint Loads for Straight Main Shell Calandria with Rigid Supports Both Ends

If they were free to expand, the calandria shell, calandria tubes and vault would expand by amounts shown in section IV-2.1, above.

However, in this structure, the calandria shell expands more than either the calandria tubes or the vault, therefore the calandria tubes are stretched, the calandria shell is compressed and the supports at the vault end walls are deformed outwards, to attain the same net deflection *z*.
Therefore, the calandria tube is stretched an amount:

$\epsilon_{CT} = z - \delta_{CT}$; but $\epsilon_{CT} = P_{CT}/k_{CT}$ under tension P_{CT} (a) & (b)

and the supports are displaced outwards under the force P_W by the amount:

$\epsilon_S = z - \delta_W$; but $\epsilon_S = P_W/k_S$ (c) & (d)

and the calandria shell is compressedby the force P_S by amounts:

$\epsilon_{CS} = \delta_{CS} - z$; but $\epsilon_{CS} = P_{CS}/k_{CS}$ (e) & (f)

also, $P_S + P_{CT} = P_{CS}$ (g)

Stiffness of calandria shell: $E = 29.5(10^6)$, $A_{CS} = 300\pi 1.12 = 1055\ in^2$,
$L = 120$ in,

then $k_{CS} = EA/L$ for CS = $29.5(10^6)1155/120$ = $260(10^6)$ lb/in

Equation (a), (b), (c), (d), (e), (f) & (g) are solved for P_{CT} :

P_{CT} = 1 514 000 lb

and Basic Tensile Stress in CT = σ_{CT1} =1 514 000/ 298 = 5 080 psi

(ii) Added Thermal Restraint Superimposed due to End Shield Dishing

As for above calculation, the central CTs exhibit tensile stresses in the order of 3 000 psi, while the CTs near the edge exhibit stresses in the order of 4 500 psi, ie,.

Superimposedc compressive stresses on CTs near the edge = σ_{CT2} = 4 500 psi

(iii) Internal Pressure Loads

The total force due to pressure is the same as for the previous calculation, but this force is carried mostly on the CS, and only partly on CTs. If thev total force is shared in proportion to their stiffnesses, then theCTs carry 32.28/ 260 of the total;

P_{CT2} = 1 514 000 x 32.28/ 260 = 188 000 lb

and Tensile stress on CT = σ_{CT3} = 188 000/298 = 630 psi

Therfore, total tensile stress on CT =

σ_{CT} = 5080 - 4 500 + 630 = 1 210 psi

(iv) Compressive Load in Calandria Shell

From equations in (i): P_{CS} = 3 200 000 lb

and compressive stress in Calandria Shell =

σ_{CS} = P_{CS}/ A_{CS} = 3 200 000/ 1155 = 3 030 psi

(v) Effect of Stiffer Support

It is noted that the preferred design will have the annular Support Shell welded directly to the embedment, rather than using the present Bolted Support Plate. In this case, the stiffness of the support would more closely approach that of the vault wall itself, which is estimated to be 100 (10^6) to 150(10^6) lb/in. If the Support stiffness is taken as k_S = 100(10^6) lb/in in the above solution, we find little change in the Calandria Tube load:

P_{CT} = 1 274 000 lb

and Basic Tensile stress = $\sigma_{CT\,1}$ = 1 274 000/ 298 = 4 280 psi

Adding the Stresses due to the End Shield and due to Internal Pressure:

Total tensile stress on CT = σ_{CT} = 4 280 - 4 500 + 630 = 410 psi

and Calandria Shell Load becomes: P_{CS} = 7 280 530 lb

and compressive stress on CS is σ_{PCS} = 7 280 530/ 1155 = **6 300 psi**

Both of these stresses are still very acceptable.

IV-3.0 SEISMIC BEHAVIOUR

IV-3.1 Present Reactor Design

(i) Basic Modes: **See Figures 4-14, -15 & -16.**

The RSA system may be seen as the two End Shield masses, each with half of all the included masses* attached; the two halves are connected and supported through several paths, but principly the calandria tubes and the bolted support plate. The entire system is supported in the embedment rings in the vault walls. There are two principal modes of seismic response motion: the first mode is due to the mass of the *unbolted* half being driven by the spring of the calandria tubes; the second is due to the total mass of *both* halves being driven as a whole by the spring of the *support plate.*

Masses M/2 = W_T/ 2(386) = 2 805 slugs

M_f = (W_{FM} + W_{FC}/2)/386 = 67 slugs

Their seismic response motions occur at their resonant frequencies, found as:

$f_1 = \quad (1/2\pi)\sqrt{K_{cf}/(M/2 + M_f)} = \qquad (1/2\pi)\sqrt{16.14(10^6)/(2\,872)} =$ <u>11.7 Hz</u>

and $\quad f_2 = (1/2\pi)\sqrt{K_{bf}/(M + M_f)} = \qquad (1/2\pi)\sqrt{25(10^6)/5\,677} =$ <u>10.6 Hz</u>

(ii) End Shield Mode:

The inner region of *each* mass moves relative to the outer region. This mode has frequency:

$f_3 = (1/2\pi)\sqrt{2K_{es} / (2M/4 + Mf)} = (1/2\pi)\sqrt{2(2.5)(10^6)/(2\,872)} =$ <u>6.6 Hz</u>

(iii) FM at non-PA End:

Here, the mass of the fuelling machine at the *non*-positioner end is driven by the spring of the pressure tube itself. Its frequency is:

$f_4 = (1/2\pi)\sqrt{K_{pt} / M_f} = \qquad (1/2\pi)\sqrt{143\,000/ 67} =$ <u>7.4</u> Hz

Where Stiffness $K_{pt} = EA/L$ for PT: and $E = 13(10^6)$, $A = 4.2\pi 0.2 = 2.64\ in^2$, $L = 240$ in

then K_{pt} =

<u>143 000</u> lb/in

IV-3.3 Straight Mainshell design with Rigid Supports

<u>(1) Basic Mode</u>: See **Figure 4-20.**

The support plate stiffness is selected to raise the frequency of the fifth mode sufficiently to reduce PA and RJ loads, but without applying compression to calandria tubes. The calandria shell stiffness is higher than that of the vault walls, and its expansion will dominate this condition. The support is directly welded to the embedment, rather than bolting the support plate. As noted in thermal calculations above, the support stiffness will approach that of the vault end wall itself, and a value midway between the two is used, $60(10^6)$ lb/in.

The frequency found for f_5 is raised to be:

$f'_5 = (1/2\pi)\sqrt{2K'_{bs} / (2M/2 + M_f)} = \quad (1/2\pi)\sqrt{(2)60(10^6)/ 5\,677} =$ <u>23.1</u>Hz