MASTER

OAK RIDGE NATIONAL LABORATORY

Operated by

UNION CARBIDE NUCLEAR COMPANY

Division of Union Carbide Corporation

Post Office Box X

Oak Ridge, Tennessee

ORNL
CENTRAL FILES NUMBER

58-11-1

External Transmittal Authorized

COPY NO. 104

DATE: December 31, 1958

SUBJECT: Preliminary Report on Heat Generation and Stresses
in the Wall of a Spherical HRE-4 Pressure Vessel

TO: Distribution

FROM: R. D. Cheverton

ABSTRACT

This report considers the heat generation and thermal stresses in spherical HRE-4 vessels 3 to $4\frac{1}{2}$ ft in diameter with clad and solid stainless steel walls. Parameters included thorium slurry concentrations and moderator material (D_2O and H_2O).

The primary purpose of this preliminary study was to determine the influence of thermal stresses on the selection of the core size for the HRE-4 reactor. Curves are presented which facilitate relatively rapid determination of stresses for the range of vessels considered.

It is concluded that steady-state thermal stresses in the clad or solid stainless steel vessels considered will not have to be a determining factor in the selection of a core size, provided the power density does not exceed approximately 15 kw/l in the clad vessels and 8 kw/l in the solid stainless steel vessels.

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report. The information is not to be abstracted, reprinted or otherwise given public dissemination without the approval of the ORNL patent branch, Legal and Information Control Department.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

PRELIMINARY REPORT ON HEAT GENERATION AND STRESSES
IN THE WALL OF A SPHERICAL HRE-4 PRESSURE VESSEL

Introduction

The original concept of the HRE-4 design included a single region core vessel similar in configuration to that shown in Fig. 1. The diameter of

Fig. 1. Schematic Representation of Original HRE-4 Pressure Vessel.

the spherical portion was to depend upon several criteria such as criticality with either H_2O or D_2O as the moderator with various slurry concentrations; limiting power densities and total desired power; thermal stresses; etc. From the standpoint of thermal stresses, the composite vessel presents a particular problem in that the cone wall thickness must be about twice that of the sphere on the basis of pressure stress alone. The greater amount of heat generation in the cone wall results in a difference in free radial expansion of the cone and sphere at the cone-sphere intersection. The resultant localized discontinuity bending stresses will increase the total stresses significantly above the ordinary pressure and thermal stresses in the sphere.

The purpose of this preliminary analysis was to determine the effect of core diameter on heat generation and stresses in the wall. To avoid complications at this time, the core vessel was considered to be a complete sphere, all discontinuities being neglected. In order to keep the total power down while keeping the power density up, the range of sphere diameters was selected as three feet to four and one-half feet.

The design and fabrication of a clad vessel is complicated by comparison to a non-clad vessel. The advantages of using the clad design are the greater strength of the carbon steel base materials as compared to austenitic materials

such as type 347 stainless steel, the possibly lower cost of the clad shell, and perhaps most important in nuclear reactor systems, the lower value of $\alpha E/k$ for the carbon steels, where α , E , and k are the coefficient of thermal expansion, Young's modulus, and thermal conductivity, respectively. However, if the thermal stresses in an all stainless vessel are sufficiently low for the predicted operating conditions, then certainly, from the standpoint of stresses, vessels of the size being considered for the HRE-4 could be made of austenitic material. Therefore, both carbon steel vessels clad with type 347 stainless steel and all stainless steel (type 347) vessels have been considered in this study.

The various cores calculated are listed in Table 1. The only all stainless steel vessel calculated was $3\frac{1}{2}$ ft in diameter with zero thorium concentration.

Table 1

Core Inside Diameter ft	Moderator	Thorium Concentration g/liter
3	H ₂ O	0, 200, 400
$3\frac{1}{2}$	H ₂ O	0, 200, 400
4	D ₂ O	0, 200, 400
$4\frac{1}{2}$	D ₂ O	0, 200, 400

Calculation of Heat Generation and Temperature Distribution

Calculations for heat generation in the wall included the gamma energy from the core gammas and from the capture gammas in the wall. The method of calculation was based primarily on the use of infinite media buildup factors, the methods being identical to those used in reference (1). The use of these methods in finite vessel walls tends to overestimate the heat generation, a supposition fairly well validated in references (1) and (2) by a comparison between calculated and experimentally determined heat generation rates in the HRT pressure vessel. However, since two sources of gammas are considered and cannot be distinguished one from the other in the experimental analysis of heat generation, it is not known how the error in the calculated total heat generation varies with varying ratios of the two gamma sources. In the case of the HRT the two sources, or at least their resultant heat generations in the vessel wall, are about equal. Since the error in the HRT calculations appears to be about plus 100%, it is tentatively concluded that for any of the ratios of gamma sources encountered in this study the answer will be conservative.

The net neutron currents into the vessel wall as calculated by Prince (3) and used herein are listed in Table 2. They were calculated using twenty fast groups and one thermal group. The fast currents tabulated are the sums of the twenty fast groups. In the heat generation calculations the average energy of the fast group was selected as 700 ev.

Table 2

Core ID ft	Thorium Conc. g/liter	Moderator	J_1/P	J_2/P
			$\frac{\text{Fast Neuts} \times 10^{11}}{\text{cm}^2 \text{ sec Mw}}$	$\frac{\text{Thermal Neuts} \times 10^{11}}{\text{cm}^2 \text{ sec Mw}}$
3	0	H ₂ O	2.70	2.63
	200	H ₂ O	2.79	2.25
	400	H ₂ O	2.87	1.99
3½	0	H ₂ O	1.69	1.76
	200	H ₂ O	1.75	1.51
	400	H ₂ O	1.80	1.34
4	0	D ₂ O	4.21	4.63
	200	D ₂ O	4.21	1.39
	400	D ₂ O	3.78	0.29
4½	0	D ₂ O	2.79	4.04
	200	D ₂ O	2.79	1.25
	400	D ₂ O	2.56	0.30

The neutron currents into the wall are to some extent a function of the vessel wall thickness; however, for wall thicknesses greater than about three inches the neutron currents are essentially independent of the wall thickness. The wall thicknesses used in the calculation of currents listed in Table 2 were in excess of three inches. For thinner walls the net neutron currents will increase with decreasing wall thickness. From the standpoint of heat generation it is estimated that this latter effect is more than offset by the increasing gamma attenuation error (use of infinite media buildup factors) discussed previously, and therefore no correction was applied.

The results of the heat generation calculations are summarized in Table 3. The volume heat generation rates listed are the values in the wall at the inside surface; the power levels were such as to produce equal power densities in the four different diameter vessels with a total power of 5 Mw in the $4\frac{1}{2}$ -ft diameter vessel.

Table 3

Core ID ft	Mod.	Thor. Conc. g/liter	Core γ Heating watts/cm ³	Cap. γ Heating watts/cm ³	Total watts/cm ³
3	H ₂ O	0	1.04	0.113	1.15
	H ₂ O	200	0.706	0.102	0.808
	H ₂ O	400	0.565	0.092	0.657
3-1/2	H ₂ O	0	1.16	0.117	1.29
	H ₂ O	200	0.753	0.105	0.858
	H ₂ O	400	0.592	0.096	0.688
4	D ₂ O	0	0.670	0.456	1.126
	D ₂ O	200	0.506	0.197	0.703
	D ₂ O	400	0.430	0.112	0.542
4-1/2	D ₂ O	0	0.681	0.525	1.206
	D ₂ O	200	0.510	0.220	0.730
	D ₂ O	400	0.429	0.117	0.546

To obtain a meaningful comparison between core and capture gamma heating in the wall, the latter values, as listed in Table 3, were taken from an essentially linear extrapolation of a semilog plot of the capture gamma heating vs. distance in the wall. The actual curve for wall capture gamma heating has a depression near the inside surface so that the actual inside surface value is not a good indication of the total heat generation rate in the wall.

The figures in Table 3 appear to indicate that decreasing the size of the vessel decreases both the core and capture gamma heating, although the trend is not very pronounced.

The temperature distributions in the wall resulting from the removal of the internally generated heat and from various temperature differences between the inner and outer surfaces of the wall were determined using the calculated heat generation values in a finite difference solution of the general heat conduction equation. The resultant temperature distributions were then used directly in the stress equations.

Stresses

The stresses considered in this preliminary study were the tangential stresses on the inside surface of the cladding, at the interface between the cladding and base material, and at the outer surface of the base material..

The thermal stresses in the reactor vessels being considered are a function of the diameter, total wall thickness, cladding thickness, material properties, temperature distribution through the wall, reactor power, type moderator, and slurry concentration. For the initial studies the cladding thickness was selected as 0.200 inches for all clad vessels.

A simple and general method of presenting the results of the parametric study is to write the thermal stress equations in terms of two coefficients and the temperature difference across the wall as illustrated in equation (1). The values

$$\frac{\sigma}{P} = \left(\frac{C_1}{P} \right) + C_2 \left(\frac{\Delta T}{P} \right) \quad (1)$$

where σ = tangential stress
 P = reactor power
 C_1 = coefficient dependent on heat generation
 C_2 = coefficient dependent on geometry
 ΔT = outside surface temperature
- inside surface temperature

of C_1/P and C_2 have been plotted against total wall thickness for four inside radii and three slurry concentrations in Figs. 2, 3, 4, 5, and 6. The slurry concentrations are in grams of thorium per liter. The meaning of the subscripts used with the stress symbol is as follows:

- t - indicates tangential stress
- a, b, c - indicate stress at inside, interface, outside radius, respectively
- T - indicates thermal stress
- ab, bc - indicate stress in cladding, base material, respectively (necessary only at interface)

Of particular interest will be the case of no heat flow from the outside surface. The temperature differences across the wall for this case are given in Fig. 7.

The pressure stresses per unit pressure are given in Fig. 8.

Figures 2 through 8 can be used to examine the stresses over the ranges indicated.

Results

One purpose of this study was to determine the effect of core size and slurry concentration on thermal stresses. As indicated in Figs. 2 through 6 and Table 3, increasing the thorium concentration decreases the thermal stresses. Figure 9 shows how the maximum thermal stress in a clad vessel varies with thorium concentration for two different heat transfer boundary conditions.

Figures 2 through 6 show, of course, that the thermal stresses are a function of the wall thickness. In order to select a satisfactory wall thickness, the pressure and thermal stresses must be added and their sums plotted against wall thickness. This has been done for the four vessel sizes listed in Table 1, using the case of zero thorium concentration and equal power densities with 5 Mw in the $4\frac{1}{2}$ -ft diameter vessel. The resultant curves shown in Fig. 10 show that as the diameter is increased the minimum (with respect to wall thickness) total stress increases.

It should be emphasized at this point that it certainly is not necessary to use the optimum wall thickness indicated in Fig. 10 unless the maximum possible power density is desired. For instance, assume that the power density used in obtaining the curves in Fig. 10 are maximum allowable values based on some criterion other than stresses in the vessel wall. Now consider the $3\frac{1}{2}$ -ft diameter clad vessel, and assume that the allowable pressure stress in the cladding is 14,900 psi and in the base material 17,500 psi. Using Fig. 8 and assuming 2000 psi system pressure, the minimum wall thickness, considering pressure stresses only, is 1.03 inches based on the stress in the base material. The pressure stress in the cladding for that wall thickness is 14,200 psi. The allowable total (pressure + thermal) stress in the cladding, where the stresses are a maximum for this particular case, is $1.5 \times 14,900 = 22,300$ psi. Referring again to Fig. 10, it is observed that the total stress for a 1.03-inch wall is only 18,800 psi. The "optimum" wall thickness is about 1.5 inches and therefore about 50% greater than required.

A similar check on the other clad vessels in Fig. 10 shows that the four clad vessels have satisfactory stresses.

To really optimize the design, the power density should be increased until the minimum stress indicated in Fig. 10 is equal to 1.5 times the allowable pressure stress, or until the pressure stress is equal to its allowable value, whichever limit is reached first. Increasing the power density will decrease the optimum wall thickness and therefore increase the pressure stress.

The total stresses in an all stainless steel vessel are compared with those in the clad vessels in Fig. 10. For the same boundary condition of no heat removal from the outer surface, the total stresses corresponding to the respective optimum wall thicknesses in the stainless steel vessel are about 1.5 times those in the same diameter clad vessel, and the optimum thickness is less than for the clad vessel. In order to reduce the pressure and thermal stresses in the stainless steel vessel to the allowable values without adding thorium to the system, the temperature drop across the vessel wall must be reduced. As indicated by the lower dashed curve in Fig. 10, the objective is easily attained.

Since the addition of thorium to the system reduces the thermal stresses, it can be concluded that the steady-state thermal stresses in the clad or solid stainless steel vessels considered will not have to be a determining factor in the selection of a core size, provided the power density does not exceed approximately 15 kw/l for the clad vessels and 8 kw/l for the all stainless steel vessels.

The possibility of using a moderator consisting of a mixture of light and heavy water for the smaller reactors has been under consideration. The curves in Fig. 10 indicate that the use of a D_2O moderator will result in lower stresses for the same diameter vessel. Thus, light-heavy water mixtures in the 3- and $3\frac{1}{2}$ -ft diameter vessels will result in lower stresses.

Fig. 2. Thermal stress equation coefficients for $a = 18$ in.

Fig. 3. Thermal stress equation coefficients for $a = 21$ in.

Fig. 4. Thermal stress equation coefficients for a = 24 in.

Fig. 5. Thermal stress equation coefficients for $a = 27$ in.

Fig. 6. Thermal stress equation coefficients for a type 347 s.s. vessel wall with $a = 21$ in.

Fig. 7. Temperature difference across wall vs. wall thickness, for various thorium concentrations and assuming no heat removal from outer surface.

Fig. 8. Pressure stress vs. wall thickness.

Fig. 9. Thermal stress vs. thorium concentration for a clad vessel with $a = 21$ in., power = 2.35 Mw. and $(c - a) = 1.5$ in.

Fig. 10. Total (pressure + thermal) stress vs. wall thickness for several cores with zero thorium concentration.

REFERENCES

1. R. D. Cheverton and E. R. Volk, Steady-State Pressure and Thermal Stresses in the HRT Pressure Vessel, ORNL CF-58-7-43.
2. R. E. Aven, HRT Pressure Vessel Temperature During Operation - An Evaluation Using Data from Run 16, ORNL CF-58-7-35.
3. B. E. Prince, Neutron Currents into HRE-4 Pressure Shell, HRP-58-314.

DISTRIBUTION

1. HRP Director's Office
Rm. 259, Bldg. 9204-1
2. G. M. Adamson
3. S. E. Beall
4. A. M. Billings
5. E. G. Bohlmann
6. S. E. Bolt
7. E. S. Bomar
8. J. R. Brown
9. W. D. Burch
10. R. H. Chapman
11. R. D. Cheverton
12. H. C. Claiborne
13. E. L. Compere
14. R. S. Crouse
15. J. S. Culver
16. D. G. Davis
17. R. J. Davis
18. J. L. English
19. D. E. Ferguson
20. C. H. Gabbard
21. W. R. Gall
22. R. S. Greeley
23. J. C. Griess
24. W. R. Grimes
25. P. A. Haas
26. P. H. Harley
27. P. N. Haubenreich
28. J. W. Hill
29. E. C. Hise
30. C. J. Hochanadel
31. G. H. Jenks
32. D. T. Jones
33. P. R. Kasten
34. F. Kertesz
35. L. J. King
36. R. B. Korsmeyer
37. N. A. Krohn
38. C. G. Lawson
39. R. E. Leuze
40. W. H. Lewis
41. R. A. Lorenz
42. M. I. Lundin
43. R. N. Lyon
44. W. L. Marshall
45. J. P. McBride
46. H. F. McDuffie
47. H. A. McLain

48. R. A. McNees
49. J. R. McWherter
50. R. L. Moore
51. L. F. Parsly, Jr.
52. R. L. Pearson
53. F. N. Peebles
54. M. L. Picklesimer
55. S. A. Reed
56. D. M. Richardson
57. R. C. Robertson
58. M. W. Rosenthal
59. H. C. Savage
60. C. H. Secoy
61. C. L. Segaser
62. E. M. Shank
63. M. D. Silverman
64. M. J. Skinner
65. I. Spiewak
66. R. W. Stoughton
67. J. A. Swartout
68. E. H. Taylor
69. D. G. Thomas
70. M. Tobias
71. D. S. Toomb
72. W. E. Unger
73. R. Van Winkle
74. A. M. Weinberg
75. K. W. West
76. J. C. Wilson
77. C. E. Winters
78. F. C. Zapp
79. T. H. Mauney
- 80-81. REED Library
- 82-83. Central Research Library
- 84-85. Document Reference Library
- 86-100. Laboratory Records
101. ORNL-RC

EXTERNAL

102. D. H. Groelsema,
AEC, Washington
103. Dr. W. E. Johnson,
Westinghouse
- 104-119. TISE, AEC