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TRANSIENT PRESSURE IN THE WATER
BOILER KINETIC EXPERIMENT

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TRANSIENT PRESSURE IN THE WATER BOILER KINETIC EXPERIMENT

By D. L. Hetrick and M. E. Remley

I. SUMMARY

This report summarizes the results of theoretical studies to date on the effect of inertial pressures in water boiler transients. The presentation may be summarized as follows: (1) derivation of the equation for transient pressures in a partially enclosed container of water, (2) development of the equation of state for a mixture of water and radiolytic decomposition gas, (3) calculation of peak power as a function of reactor period, and (4) discussion of the effect of limited void space above the solution.

It is intended that these results should serve as an indication of the magnitude of the inertial effects as a guide for planning the experimental program for KEWB (Kinetic Experiments Water Boiler). More refined studies will continue during the design and construction of the KEWB facility, and data obtained in the early, low reactivity transients will be used to modify and further refine the calculations for the fast transients.

The reactor test cores will be designed and tested to withstand pressures at least two and one-half times the maximum peak pressures calculated under the most pessimistic assumptions. It is concluded that the attainable pressures represent no hazard to equipment, personnel or environs.

II. INERTIAL EFFECT IN WATER

The calculation of transient pressures follows a procedure employed by Hansen¹ in his study of burst characteristics for fissionable assemblies. The equations to be solved subject to the proper boundary conditions are the equation of state

$$dP = \left(\frac{\partial P}{\partial T}\right)_V dT + \left(\frac{\partial P}{\partial V}\right)_T dV \quad (1)$$

and the equation of motion

$$\rho \frac{\partial^2 \vec{s}}{\partial t^2} = -\nabla P, \quad (2)$$

where pressure, temperature, volume change and displacement $\vec{s}$ are functions of position and time. Using the definition of bulk modulus

$$K = -V \left(\frac{\partial P}{\partial V}\right)_T$$

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and assuming a linear equation of state, Eq. (1) becomes

$$P = T \left(\frac{\partial P}{\partial T} \right)_V - K \nabla \cdot \vec{s} \quad (3)$$

where P and T are respectively pressure and temperature rise and where

$$\nabla \cdot \vec{s} = \Delta V/V = -\Delta\rho/\rho. \quad (4)$$

An important simplification, justified by Hansen,¹ is obtained by assuming that the energy in gas production, elastic deformation, etc., is small compared to the thermal energy. Hence

$$\frac{\partial T}{\partial t} = \frac{n}{c}$$

where n is the neutron density expressed as total instantaneous power in kilowatts and c is the core heat capacity in kilowatt-seconds per Centigrade degree.

The simplest geometrical model which retains the essential characteristic of a partially free surface is that of a rigid cylinder with ends open to atmospheric pressure. It is shown by Hansen¹ that if a portion of the solution surface is open to the atmosphere, the elasticity of the metal shell which contains the solution does not contribute significantly to pressure relief.

Assuming exponential time dependence with reciprocal period ω , Eq. (2) becomes

$$\omega^2 \rho \vec{s} = -\nabla P.$$

Forming ∇P from Eq. (3) and substituting yields

$$\omega^2 \rho \vec{s} = - \left(\frac{\partial P}{\partial T} \right)_V \nabla T + K \nabla \nabla \cdot \vec{s}. \quad (5)$$

In the cylindrical model, let the displacement vector be

$$\vec{s} = e_r \xi + e_z \eta$$

where e_r and e_z are radial and axial unit vectors, respectively. If rotation is absent, $\nabla \times \vec{s} = 0$ and

$$\frac{\partial \xi}{\partial z} = \frac{\partial \eta}{\partial r}.$$

Under these conditions the expression $\nabla \nabla \cdot \vec{s}$ becomes explicitly

$$\begin{aligned} \nabla \nabla \cdot \vec{s} &= e_r \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} - \frac{1}{r^2} + \frac{\partial^2}{\partial z^2} \right) \xi + e_z \left(\frac{\partial}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2} \right) \eta \\ &= e_r D_r \xi + e_z D_z \eta. \end{aligned}$$

The scalar equations represented by Eq. (5) are therefore the inhomogeneous Helmholtz equations

$$\left. \begin{aligned} D_r \xi - \frac{\omega^2 \rho}{K} \xi &= \frac{1}{K} \left(\frac{\partial P}{\partial T} \right)_V \frac{\partial T}{\partial r} \\ D_z \eta - \frac{\omega^2 \rho}{K} \eta &= \frac{1}{K} \left(\frac{\partial P}{\partial T} \right)_V \frac{\partial T}{\partial z} \end{aligned} \right\} \quad (6)$$

where ξ , η and T are now to be interpreted as coefficients multiplying the factor $\exp(\omega t)$.

Consider the temperature distribution

$$T = T_0 J_0(k_1 r) \cos k_2 z. \quad (7)$$

The differential equations obtained by substitution of Eq. (7) into Eq. (6) are satisfied by

$$\left. \begin{aligned} \xi &= A \left[J_1(k_1 r) - \frac{J_1(k_1 a)}{I_1(\mu a)} I_1(\mu r) \right] \cos k_2 z \\ \eta &= A \left[\frac{k_2}{k_1} J_0(k_1 r) + \frac{k_2 J_1(k_1 a)}{\mu I_1(\mu a)} I_0(\mu r) \right] \sin k_2 z \end{aligned} \right\} \quad (8)$$

where the radial displacement is chosen to vanish at the cylindrical surface $r = a$, and where

$$A = k_1 \frac{T_0}{K} \left(\frac{\partial P}{\partial T} \right)_V / (k_1^2 + k_2^2 + \omega^2 \rho / K), \quad (9)$$

$$\mu^2 = k_2^2 + \omega^2 \rho / K. \quad (10)$$

The free surfaces at the ends of the cylinder are represented by the boundary condition

$$P(r, \pm b) = 0$$

where b is the half-height of the cylinder. By Eq. (3),

$$\nabla \cdot \vec{s} \Big|_{z=\pm b} = \frac{1}{K} \left(\frac{\partial P}{\partial T} \right)_V T(r, \pm b).$$

The solution given by Eq. (8) cannot satisfy this condition unless

$$T(r, \pm b) = 0; \quad k_2 = \pi / 2b. \quad (11)$$

For other values of k_2 it is necessary to write the displacements as infinite series whose coefficients are determined by expanding $T(r, \pm b)$ in a series of radial functions. The use of Eq. (8) for the displacements together with the restriction Eq. (11) is a simplification which yields somewhat pessimistic results because a non-vanishing driving temperature at the free surface would tend to relieve internal pressure more rapidly.

The pressure is then calculated by substituting Eq. (8) and (9) into Eq. (3). The result is

$$P = \frac{T_0 (\partial P / \partial T)_V \omega^2 \rho / K}{k_1^2 + k_2^2 + \omega^2 \rho / K} \left[J_0(k_1 r) + \frac{k_1 J_1(k_1 a)}{\mu I_1(\mu a)} I_0(\mu r) \right] \cos k_2 z, \quad (12)$$

together with the auxiliary relations Eq. (10) and (11). In Eq. (12) the factor $\exp(\omega t)$ is now to be considered as contained in T_0 .

In order to obtain an estimate of the inertial effect in water, it is possible to consider Eq. (3) as consisting of the difference between a driving term and a pressure relief term. The driving term is

$$T \left(\frac{\partial P}{\partial T} \right)_V = T_0 \left(\frac{\partial P}{\partial T} \right)_V J_0(k_1 r) \cos k_2 z = A e^{\omega t}$$

while the relief term is

$$\mathbf{K} \nabla \cdot \vec{\mathbf{s}} = T_0 \left(\frac{\partial \mathbf{P}}{\partial T} \right)_V \frac{k_1^2 + k_2^2}{k_1^2 + k_2^2 + \omega^2 \rho} \frac{1}{K} \left[J_0(k_1 r) - \frac{\omega^2 \rho / K}{k_1^2 + k_2^2} \frac{k_1 J_1(k_1 a)}{\mu I_1(\mu a)} I_0(\mu r) \right] \cos k_2 z = B \omega t.$$

The time lag with which the pressure relief (volume expansion) follows the driving pressure may be written

$$\Delta t = \frac{1}{\omega} \ln (\bar{A}/\bar{B})$$

where the bars indicate volume averages. Using

$$\overline{J_0(k_1 r)} = \frac{2}{k_1 a} J_1(k_1 a)$$

$$\overline{I_0(\mu r)} = \frac{2}{\mu a} I_1(\mu a)$$

one finds

$$\bar{B}/\bar{A} = 1 - \frac{\omega^2 \rho / K}{k_1^2 + k_2^2} - \frac{\omega^2 \rho / K}{k_1^2 + k_2^2 + \omega^2 \rho / K} \cdot \frac{k_1^2}{\mu^2}.$$

The numerical values subsequently employed justify the use of the approximation

$$\ln \frac{1}{1-x} \approx \ln (1+x) \approx x.$$

The time lag is then

$$\Delta t = (\omega\rho/\mathbf{K}) \left/ \left(\frac{1}{k_1^2 + k_2^2} + \frac{k_1^2/\mu^2}{k_1^2 + k_2^2 + \omega^2\rho/\mathbf{K}} \right) \right. . \quad (13)$$

For numerical calculations, the physical constants used for water are bulk modulus $k = 20,000$ atm. and density $\rho = 1$. For the cylindrical model, the radius of the free surface is 9.6 cm (corresponding to a two-liter void in a 30 cm diameter sphere). The solution volume is taken to be 14.1 liters; this is to be represented by half of the cylinder, hence $b = 48.6$ cm.

The radial power distribution is assumed to extrapolate to zero at twice the cylinder radius, hence

$$k_1 = \frac{2.405}{2a} = \frac{2.405}{19.6} = 0.125 \text{ cm}^{-1}$$

and

$$k_2 = \frac{\pi}{2b} = \frac{\pi}{97.2} = 0.0323 \text{ cm}^{-1}$$

The value of μ is then obtained from Eq. (10), and the resulting time lag is plotted in Fig. 1 as a function of the reactor period.

The extreme smallness of this time lag confirms the assertion made by Hansen.²

... for dilute solutions the obtainable values of α_1 (multiplication rate) are too small to permit the importance of inertia effects regardless of the assembly rates.

The assertion is evidently valid insofar as it concerns the ability of thermal expansion to follow a rapid power rise in a solution having the same bulk modulus as water. However, when there

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is appreciable gas production, the bulk modulus suffers a sharp decrease, the time lag increases, and there may be appreciable inertial pressures.

III. EQUATION OF STATE WITH GAS PRODUCTION

Since most of the fission energy goes into thermal energy, it is possible to derive an equation of state for the mixture of solution and gas bubbles in which a given temperature rise corresponds to the production of a certain amount of gas. For the liquid,

$$dP = \left(\frac{\partial P}{\partial T}\right)_{V_l} dT + \left(\frac{\partial P}{\partial V_l}\right)_T dV_l \quad (14)$$

where V_l is the liquid volume. If V_g is the gas volume, the total volume V_t is

$$V_t = V_l + V_g$$

and

$$dV_l = dV_t - dV_g.$$

Hence

$$dP = \left(\frac{\partial P}{\partial T}\right)_{V_l} dT + \left(\frac{\partial P}{\partial V_l}\right)_T dV_t - \left(\frac{\partial P}{\partial V_l}\right)_T dV_g. \quad (15)$$

Using the gas law,

$$V_g = NRT/P$$

where the number of moles is

$$N = c\Delta T/\phi_g$$

and where ϕ_g is the total fission energy corresponding to the production of one mole of radiolytic decomposition gas. Hence

$$V_g = \frac{Rc}{\phi_g} \frac{T\Delta T}{P} \quad (16)$$

and

$$dV_g = \frac{Rc}{\phi_g P} \left[(T + \Delta T)dT - \frac{T\Delta T}{P} \right] dP.$$

Substituting in Eq. (15) and solving for dP yields

$$dP = \frac{\left[\left(\frac{\partial P}{\partial T}\right)_{V_l} + \frac{KRc}{V_l\phi_g} \frac{T + \Delta T}{P} \right] dT - \frac{K}{V_l} dV_l}{1 + \frac{KRc}{V_l\phi_g} \frac{T\Delta T}{P^2}} \quad (17)$$

Comparison with Eq. (14) shows that for the mixture of solution and gas the effective values of the thermodynamic derivatives are

$$\left(\frac{\partial P}{\partial T}\right)_{V_1} = \left[\left(\frac{\partial P}{\partial T}\right)_{V_1} + \frac{KRc}{V_1 \phi_g} \frac{T + \Delta T}{P} \right] \left(1 + \frac{KRc}{V_1 \phi_g} \frac{T \Delta T}{P^2} \right) \quad (18)$$

$$\left(\frac{\partial P}{\partial V_t}\right)_T = -K \left/ \left[V_1 \left(1 + \frac{KRc}{V_1 \phi_g} \frac{T \Delta T}{P^2} \right) \right] \right. \quad (19)$$

where $(\partial P/\partial T)_{V_1}$ and K are respectively the pressure coefficient and bulk modulus of the liquid alone. Defining effective bulk modulus of the mixture as

$$K_{\text{eff}} = -V_t \left(\frac{\partial P}{\partial V_t}\right)_T,$$

Eq. (19) becomes

$$K_{\text{eff}} = KV_t \left/ \left[V_1 \left(1 + \frac{KRc}{V_1 \phi_g} \frac{T \Delta T}{P^2} \right) \right] \right.$$

Using Eq. (16),

$$K_{\text{eff}} = K \left(1 + \frac{Rc}{V_1 \phi_g} \frac{T \Delta T}{P} \right) \left/ \left(1 + \frac{KRc}{V_1 \phi_g} \frac{T \Delta T}{P^2} \right) \right. \quad (20)$$

The heat capacity of the core is taken to be 57.6 kw-sec/°C and the value of ϕ_g is 5380 kw-sec/mole (based on 15 cm³ of decomposition gas at standard conditions per watt-hour³). Letting $V_1 = 14.1$ liters and $K = 20,000$ atm, Eqs. (18) and (20) become

$$\left(\frac{\partial P}{\partial T}\right)_{V_1} = \left[\left(\frac{\partial P}{\partial T}\right)_{V_1} + 340 \frac{P_s}{T_s} \frac{T + \Delta T}{P} \right] \left(1 + 340 \frac{P_s}{T_s} \frac{T \Delta T}{P^2} \right) \quad (21)$$

$$K_{\text{eff}} = \left(K + 340 \frac{P_s}{T_s} \frac{T \Delta T}{P} \right) \left/ \left(1 + 340 \frac{P_s}{T_s} \frac{T \Delta T}{P^2} \right) \right. \quad (22)$$

where P_s and T_s refer to standard conditions. Note that the volume expansion coefficient β , which is

$$\beta = \frac{1}{V_t} \left(\frac{\partial V_t}{\partial T}\right)_P = \frac{1}{K_{\text{eff}}} \left(\frac{\partial P}{\partial T}\right)_{V_t},$$

becomes

$$\beta = \left[\left(\frac{\partial P}{\partial T}\right)_{V_1} + 340 \frac{P_s}{T_s} \frac{T + \Delta T}{P} \right] \left/ \left(K + 340 \frac{P_s}{T_s} \frac{T \Delta T}{P} \right) \right. \quad (23)$$

Since the pressure coefficient for the liquid alone is

$$\left(\frac{\partial P}{\partial T}\right)_{V_1} = 20 \text{ atm/°C}$$

the presence of gas production increases the pressure coefficient and volume expansion (at standard temperature and pressure) to 18 times their values for water alone. (The factor used by Hansen is 70 instead of 18). Hence gas production is extremely important as a shutdown mechanism, provided the inertial pressures are small.

In order to evaluate the inertial effects it is necessary to obtain solutions of Eq. (5) with the coefficients given by Eqs. (21) and (22). In principle this requires solution of a partial differential equation whose coefficients are functions of the dependent variable. The procedure

followed is a stepwise calculation in time, using Eq. (12) to find the central pressure, with the pressure coefficient and bulk modulus in each interval determined by the time-average pressure and temperature within the interval.

IV. REACTIVITY COEFFICIENTS AND PEAK POWER

From Eq. (12) the central pressure rise is

$$P = \frac{T_0(\partial P/\partial T)_V \omega^2 \rho/K}{k_1^2 + k_2^2 + \omega^2 \rho/K} \left[1 + \frac{k_1 J_1(k_1 a)}{\mu I_1(\mu a)} \right] \quad (24)$$

where the temperature rise is

$$T_0 = \frac{1}{c} \int \eta dt = \eta/\omega c.$$

The numerical computation consists essentially in finding the pressure rise in each small time interval using the pressure and temperature appropriate to that interval. In a particular interval,

$$\Delta T_0 = \frac{1}{\omega c} \Delta \eta = \frac{1}{\omega c} \Delta(\eta_0 e^{\omega t}) = \frac{\eta}{c} \Delta t.$$

Defining

$$f(k_1 \omega) = \frac{\omega \rho/c}{k_1^2 + k_2^2 + \omega^2 \rho/K} \left[1 + \frac{k_1 J_1(k_1 a)}{\mu I_1(\mu a)} \right],$$

the pressure rise in an interval becomes

$$\Delta P = \frac{f}{K} \left(\frac{\partial P}{\partial T} \right)_V \eta \Delta(\omega t).$$

The form appropriate for computation is

$$P_{i+1} = P_{i-1} + \frac{f_i}{K_i} \left(\frac{\partial P}{\partial T} \right)_i \eta_i \omega (t_{i+1} - t_{i-1}).$$

Note that n is in kilowatts and c in kw-sec per degree.

The results of the computations for five values of the period $1/\omega$ are presented in Fig. 2. It must be borne in mind that each is valid only for an exponential power rise having the specified period. Since the power will drop below an exponential curve before peak power is attained, the pressures shown are high; in reality, these pressures may correspond more closely to peak pressures in the transient, allowing for some overshoot.

Since the pressure at peak power is most important in determining the effect of gas bubbles on reactivity, the use of Fig. 2 will overestimate the pressure effect, perhaps as much as a factor of two. This is because the continuation of an exponential curve to the time of turn-around in a transient leads to an overestimate of peak power by roughly a factor of two.

The results of this calculation are now to be applied to modify previous calculations of peak power.⁴ In those calculations, the coefficients were chosen such that the total energy coefficient of reactivity was eight times that calculated for temperature alone. This appears rather conservative in view of the factors of 18 and 70 mentioned previously; it was chosen to be consistent with some indications of the effect of bubbles on reactivity in steady-state operation of SUPO.⁵

Since the purpose of the present calculations is to indicate the effect of transient pressures on the reactivity held by gas bubbles, the temperature coefficient (reactivity change due to thermal expansion of the fluid) is taken as a constant. From the earlier calculations, the peak power for a particular period is used to find the pressure rise from Fig. 2. Assuming that the gas reactivity coefficient is proportional to the gas volume, and that the peak power is inversely proportional to the reactivity coefficient at peak power, the pressure rise from Fig. 2 is used to calculate a new peak power. This procedure is iterated through the number of steps necessary to obtain convergence.

The peak inertial pressure obtained in this manner is plotted in Fig. 3 as a function of the period. Note that the pressure rise varies slightly more rapidly than the square of the reciprocal period.

Curves of peak power computed with and without consideration of inertial pressures are shown in Fig. 4. The relative increase in peak power $(n - n_0)/n_0$, where n and n_0 are peak powers with and without inertial pressures, is shown in Fig. 5. Note that in the important part of the range (periods from 5 to 10 milliseconds) the relative difference varies approximately as the reciprocal period squared, as suggested previously by Dr. Manson Benedict.⁶ For shorter periods this dependence on period is less severe because the higher pressures tend to offset the sharp reduction in pressure coefficient and bulk modulus caused by gas production.

Fig. 6 shows the effect of inertial pressures on the energy production in the transients. The uppermost curve is the total energy that would be released if the effect of gas production on reactivity were zero. The effect of gas (in those transients where the time scale is small compared to the average bubble residence time) is to limit the fast transient to only one-eighth the energy production calculated without gas bubbles. The bubbles subsequently diffuse, returning reactivity slowly enough that the remaining energy production is similar to a small ramp-rate transient, with the end result that the temperature eventually rises only about half as much as it would in a fast transient limited by temperature alone. The inertial effect modifies this behavior sharply for the shorter periods, but even at 4 milliseconds the calculated total energy release is not severe.

In addition to the inertial pressures, there will probably be a supplemental pressure source arising from the physical constraint of the gas-liquid mixture which occurs when the solution has expanded sufficiently to fill the void space in the core vessel. For this reason, a spherical vessel with a vertical relief tube presents an additional problem not present in the open-ended cylinder employed in the calculation of Section III. However, for the same initial void volume, the sphere does represent an improvement over a closed cylinder with a relief tube.

An upper limit for the transient pressure may be obtained for the spherical core by considering the upper curve of Fig. 6, which neglects entirely the gas reactivity coefficient. With this pessimistic model for shutdown, the total energy is 27 megawatt-seconds for a reactor period of four milliseconds. This period corresponds to the maximum reactivity release required for this experimental program. For this case the total gas production is 112 liters at standard conditions. With an initial void volume of two liters, the pressure would be 56 atmospheres if there were no pressure relief at all and if the water were incompressible.

The experimental cores to be employed in the transient tests will be designed to contain a minimum pressure of 90 atmospheres without exceeding the yield point. They will be subjected to static pressure tests of 60 atmospheres before installation in the reactor testing facility. This assures that all vessels will contain a pressure of 140 atmospheres without rupture. It should be noted that, in reality, there would be a much less severe transient pressure surge, accompanied by two effects which contribute to reactivity reduction: (1) pressure relief and (2) expulsion of fissionable solution into the overflow chamber.

The above discussion points out the prime importance of the necessity for the investigation of the void volume as a parameter affecting the faster transients. However, the highly pessimistic calculation outlined above indicates that the investigation can be conducted in the facility as presently designed with no problems of containment.

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Fig. 1. Inertial Time Lag for Expansion of Water vs Reactor Period

Fig. 2. Pressure Rise vs Power During Exponential Power Rise
Having Period τ Seconds

Fig. 3. Pressure Rise at Peak Power vs Reactor Period

Fig. 4. Peak Power vs Reciprocal Period Calculated Both With and Without Consideration of the Effect of Inertial Pressure on the Reactivity Coefficient

Fig. 5. Relative Increase in Peak Power Caused by Inertial Pressure vs Reactor Period

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Fig. 6. Energy vs Reactivity and Reactor Period

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