CHARACTERIZATION OF DYNAMIC LOADS ON THE LMFBR ROTATING SHIELD

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Abstract

The rotating shields structure is a potential weak point of some current designs of primary containment against postulated whole core explosions. The calculation of the effect of transient loads on this structure, resulting from such an explosion, is therefore important in developing a safety case. The transient loads are usually calculated by computer codes such as ASTARTE, SEURBNUK, REXCO or ICECO and the effect of these loads on the structure by a suitable finite element code. Such procedure can be lengthy and costly. The present paper proposed a procedure which allows the consequences of changes in the transient loads, resulting from design changes for example, to be quickly and simply gauged.

The load-impulse method of characterizing dynamic response of a structural system is well established. Provided loads with a similar temporal variation are compared, it can be shown that the dynamic response depends on only two features of the load, an average load and a time integrated load or impulse. The scope of this approach has been extended by Youngdahl who has shown, for structures which deform in a rigid-plastic manner, that complex loading histories can be equated to a rectangular form of loading, in a precise manner for simple structures and in an approximate manner for more complicated structures.

This paper proposes that the failure characteristics of the rotating shields for which extensive plastic deformation is involved, be calculated for rectangular type loadings. The complex transient loadings calculated for various explosions and various changes in the primary vessel design can then be reduced to an equivalent rectangular form and the consequencial response of the shields structure deduced.

To illustrate the proposed procedure the response of a simple bolted structure to a load consisting of an initial high load followed by a lower load is calculated, with the time integrated load being kept constant whilst the relative times of application of the two loads and also their relative values are varied. The results are expressible in graphical form from which can be deduced the proportion of the total integrated load-time history allowed at the higher load level without failing the bolted structure.

The procedure described in this paper is a significant simplication of the method of calculating rotating shields structures response, particularly where parametric surveys are contemplated.

1. Introduction

The response of a structure to a transient load depends on the complete time history of the loading, $F(t)$, but to a good approximation the response depends on only two features of the load, an average value and a suitably defined time integrated load. The idea that for a given response, a given amount of deformation for example, a locus of coupled values of average load and time integrated load can be constructed has become known as the load-impulse characterization of dynamic response. Abrahamson and Lindberg [1] apply this approach to simple rigid-plastic systems showing that the response is a unique function of these two features of the load history for loadings which have the same temporal shape.

The usefulness of the load-impulse characterization of the dynamic response of plastically deforming structures has been greatly increased by the work of Youngdahl [2]. He shows that the functional dependence of the response on the two features of the load history developed for a rectangular loading history can, to a good degree of approximation, be applied to a load with a general time history provided that average load and time integrated load are defined in a suitable manner.

The dynamic loading of plastically deforming structures is of specialized interest, the interest being generally limited to systems designed to protect against rare extreme loading conditions. The eccentrically rotating shields forming part of the top closure of a LMFBR vessel could, in certain very rare and imperfectly understood circumstances, be subjected to a large dynamic load and designs make provision for preventing the ejection of the shields under such circumstances. Frequently rings of tie bolts are provided which if called upon to operate would act in a predominantly plastic mode. The analysis of their operation can therefore make use of Youngdahl's definition of effective load and impulse described in section 2.

In section 3 the response of a simplified model of the rotating shields to a sudden load F_o applied for a time t_o is calculated. It is shown that a specified deformation is given by combinations of load and time integrated load $I = F_o t_o$ described by

$$I^2 \ (1 - B/F_o) \ = \ \text{constant} \qquad (1)$$

where B is the plastic flow resistance, such as might be offered by stretch bolts.

Section 4 extends this analysis of the response of stretch bolts to general forms of loading by making use of effective impulses and average loads defined in section 2.

Section 5 applies this general approach to a type of loading in which a large, plastic flow inducing, load is followed by a much smaller load whilst section 6 further applies this to the shield impact and response problem.

2. Definitions of Effective Load and Effective Impulse

For realistic complex rotating shield loadings Youngdahl's [2] definition of effective load and impulse must be used. If the loading is $F(t)$ then a quantity I_e, the effective impulse is defined as

$$I_e \ = \int_{t_1}^{t_2} F(t)dt \qquad (2)$$

where t_1 is the time at which plastic deformation first starts and t_2 is the time at which plastic deformation finally stops. (This time is not the time at which the load drops below that needed to statically yield the structure but some later time when the plastic resistance has brought all motion to an end.)

The definition of an average force is more complex: first a mean time t_m is defined

$$t_m = 2 \int_{t_1}^{t_2} (t - t_1)\, F(t)dt/I_e \qquad (3)$$

and an effective load F_e is then defined by

$$F_e = I_e/t_m \qquad (4)$$

Youngdahl studies four structures, the circular plate and the reinforced cylindrical shell under uniform pressure, the free-free beam with a central concentrated force and the circular cylindrical shell with a ring load and shows that relations of the type

$$I_e^2 \; f(F_e) = \text{constant} \qquad (5)$$

are approximately true. For the first two problems the relation is exact for small values of F_e/B and asymptotically true for large values. The one dimensional rigid plastic stretch bolt model of the rotating shield structure discussed here is mathematically equivalent to the first of these problems and it is shown later that equation (5) then takes the simple form given by equation (1) (with F_e replacing F_o and I_e replacing I).

The time t_2 when plastic deformation ends is not known a priori but it can be shown that

$$I_e \sim B(t_2 - t_1) \qquad (6)$$

where this relation is exact for the first three of Youngdahl's structures and approximately so for the last. Given a general load history, such as that shown in figure 1, t_2 can be located graphically using equations (6) and (2). Impulse delivered whilst the load is above the yield line must be made up by the area below the yield line before plastic flow ceases.

The existence of the relationship expressed by equation (6), allowing the time at which plastic deformation ends to be simply determined is the vital link which allows the Youngdahl method to be applied in practice.

3. Response of the Simple Model to Rectangular Loading

Consider a rigid structure, of total mass M, held down to a rigid base by bolts which behave in a rigid perfectly plastic manner. A symmetric loading force F(t) is applied to the structure in such a way as to deform all the bolts by the same amount. The motion of the structure and the deformation of the bolts is then given by the equation

$$M\, d^2y/dt^2 = F(t) - B \qquad (7)$$

from such a time t_1 that F(t) first exceeds the plastic flow stress B to the time t_2 when both F(t) is below B and remains so and all plastic flow has ceased.

For the load $F(t) = F_o$ for $t<t_o$, $F(t) = 0$ for $t>t_o$ equation (7) becomes

$$M\, d^2y/dt^2 = F_o - B \qquad (8)$$

which integrates to give the velocity after a time t_o

$$M(dy/dt)_o = (F_o - B)\; t_o \qquad (9)$$

and the distance after a time t_o

$$y_o = (F_o - B)t_o^2/2M \qquad (10)$$

Plastic flow continues until the kinetic energy at time t_o is converted to plastic work. If the final deformation is y_m then

$$B.y_m = (F_o t_o)^2 (1 - B/F_o)/2M \qquad (11)$$

equivalent to equation (1).

4. Response of the Simple Model to Complex Loadings

For a general loading function equation (7) integrates to

$$M\,(dy/dt) = \int_{t_1}^{t} (F(r) - B)\,dr \qquad (12)$$

which can be integrated again to give the deformation

$$M.y = \int_{t_1}^{t} (t - r)\,F(r)\,dr - B\,(t - t_1)^2/2 \qquad (13)$$

Plastic deformation stops when the velocity dy/dt reduces to zero which happens at a time t_2 given by

$$B\,(t_2 - t_1) = \int_{t_1}^{t_2} F(r)\,dr \qquad (14)$$

This equation is identical to equation (6). The final amount of plastic deformation y_2 is then given by equation (13) using equations (14) and (2)

$$B.M.y_2 = I_e^2/2 - B\int_{t_1}^{t_2} (r - t_1)\,F(r)\,dr \qquad (15)$$

Using the mean time t_m defined by equation (3) and the effective load defined by equation (4) this becomes

$$B.M.y_2 = I_e^{\,2}\,(1 - B/F_e)/2 \qquad (16)$$

The usefulness of this relation depends on the ease with which I_e and F_e can be found for a given loading history. This involves firstly the location of t_2 and the calculation of I_e, both of which are to be found by integrating (F(r) – B) until zero is obtained, and secondly the evaluation of the weighted integration given in equation (3).

Equation (16) can be written as

$$\frac{I_e^{\,2}}{2M}\left(1 - \frac{B}{F_e}\right) = E = \frac{I_o^2}{2M} \qquad (17)$$

where the constant of the basic locus equation has been written first as the energy E required to cause the chosen degree of deformation and secondly in terms of a limiting impulse I_o. The significance of the limiting impulse is that its value determines the system deformation for very large and correspondingly brief loads. In fact for loads applied to plastically deforming structures the value of impulse dominates when the mean time t_m is less than I_o/B. By contrast for elastically deforming structures the value of impulse dominates for loads applied for less than the period of resonance. The time I_o/B will generally be much longer than the period of elastic resonance.

5. Example for Piecewise Rectangular Loading

Possible types of loading history on the roof of the primary vessel following a postulated whole-core excursion in a liquid metal cooled fast breeder reactor are shown in figures 2. High loadings due to the hammer pressure ρcU are possible from the time coolant of density ρ, moving with speed U, hits the roof for the time it takes a rarefaction wave to travel with sound speed c from the nearest free, or nearly free surface. Thereafter the pressure is likely to fall and be controlled by the pressure within the vapourized and expanding core or by the stagnation pressure $\frac{1}{2}\rho U^2$ of the moving coolant. The initial high loading is likely to exceed that needed to sustain plastic flow in the bolts.

For illustrative purposes assume a high loading F_1, greater than B, from time zero until time t_a and a lower loading F_2, less than B, from t_a until time t_b as shown in figures 2. The time, t_2, at which plastic deformation ends is given by equation (14);

$$Bt_2 = F_1 t_a + F_2 (t^* - t_a) \qquad (18)$$

where t^* is the smaller of t_2 and t_b. Figures 2a and 2b illustrate the two possibilities. If the load at the lower level lasts for only a short time, as shown in figure 2a, then in equation (18) $t^* = t_b$ which gives $Bt_2 = F_1 t_a + F_2 (t_b - t_a) \equiv I$ where I is total impulse, so that

$$t_2 = I / B \qquad (19a)$$

This equation holds provided $t_b < I/B$. If the time at which the load at the lower level ends, t_b, is greater than I/B then the situation is as shown in figure 2b and equation (18) becomes $Bt_2 = F_1 t_a + F_2(t_2 - t_a)$ so that

$$t_2 = t_a(F_1 - F_2)/(B - F_2) \qquad (19b)$$

The effective impulse is, by equations (2) and (14) just Bt_2 so that

$$I_e = I \quad \text{if} \quad t_b < I/B \qquad (20a)$$

$$I_e = (I - F_2 t_b)/(1 - F_2/B) \quad \text{if} \quad t_b > I/B \qquad (20b)$$

The mean time t_m as defined by equation (3) is given by

$$I_e t_m = t_a^2 F_1 + ((t^*)^2 - t_a^2)F_2 \qquad (21)$$

The effective loading force F_e is defined by equation (4). If the load at the lower level lasts only for a short time, $t_b < I/B$, $t^* = t_b$ and

$$F_e = I^2/(t_a^2 F_1 + (t_b^2 - t_a^2)F_2) \qquad (22a)$$

If $t_b > I/B$ then the effective force is given by the more complex expression

$$\frac{B}{F_e} = \left(\frac{B - F_2}{F_1 - F_2}\right)^2 \frac{F_1}{B} + \left[1 - \left(\frac{B - F_2}{F_1 - F_2}\right)^2\right] \frac{F_2}{B} \qquad (22b)$$

To summarize: for loadings of the type shown in figure 2a, the effective impulse is the total impulse whilst the effective force decreases with increasing t_b provided the total impulse remains constant. For loadings of the type shown in figure 2b, the effective impulse is less than the total impulse decreasing with increasing t_b, other things being equal; the effective force now depends only on the level of the upper and lower loads and would remain constant with increasing t_b if these load levels remained the same.

6. Application to Shield Impact and Response

Consider now more specifically the possible upsurge of coolant towards the roof of the primary containment following a postulated whole-core excursion. A certain amount of work is done by the expanding core on the coolant up to the time it hits the roof and the coolant will have acquired a certain amount of impulse. The roof has to take up this impulse but the nature of the forces seen by the roof can be modified by load limiting crush layers, deflector systems etc. A coolant mass of 500 tonne, say, moving at a speed of 40 m/s just prior to roof impact has an impulse of 20 MN.s and a kinetic energy of 0.4 GJ and might result from an whole-core excursion with a nominal "excursion yield" of several gigajoule. Hammer impact pressures would be about 80 MPa, whilst jet stagnation pressures would be less than a megapascal; pressure after the relief of the shock pressure would be probably controlled by the pressure within the core debris.

The central rotating shield part of the roof in some current designs for pool type reactors has an area of about $100 m^2$. A suggested arrangement for holding the shields in place to the rest of the roof is a set of 1m long stretch bolts with a total area of $1 m^2$, say. The bolts could stretch say 5% before breaking, with a flow stress, B, of 500 MN, that is an energy absorption of 25 MJ.

Figure 3 shows the failure locus for stretch bolts with the properties just described and corresponding to breaking at 5% strain. The locus has the form given by equation (17), that is

$$I_e^2 (1 - B/F_e) = 2M.E = 50 \text{ (MN.s)}^2 \qquad (23)$$

where in evaluating the numerical value of 2ME the mass M of the responding structure, the rotating shields, has been taken as 1000 tonnes. A rapid loading by an impulse I_o of 7 MN.s causes failure. Combinations of effective load and impulse lying to the left and below the failure line do not produce failure of the bolts; combinations lying to the right and above the line do cause failure.

The load to the shield is never truly impulsive. At worst the impulse is in the form of a hammer pressure of 80 MPa, giving a loading of 8000 MN which lasts for 2.5 ms. This loading is represented by the point A in figure 3 and is well on the breaking side of the failure locus. This is not surprising since almost half the incident kinetic energy is transferred to the roof in this mode of loading.

Compare now loadings in which the same total impulse of 20 MN.s is applied to the roof but partly as an initial loading of 8000 MN and later as a subsequent loading at a lower level. If the higher loading lasts for a time t_a (less than 2.5 ms) then the lower loading ends at a time t_b given by

$$t_b = (I - (F_1 - F_2)\, t_a)/F_2 \qquad (24)$$

where I is the constant total impulse and F_1 and F_2 the higher and lower loading levels respectively.

If t_b is little larger than t_a then the loading history is as in figure 2a; the effective impulse is the total impulse but the effective load decreases with increasing t_b (equation 22a). For larger values of t_b the loading history is as in figure 2b; the effective impulse decreases with increasing t_b (equation 20b) but the effective load takes on a constant value determined by the values of the loading levels (equation 22b). The locus of effective loads and impulses is marked on figure 3; starting with the point (I = 20 MN.s, F_e = 8000 MN) the locus moves vertically downwards as t_b increases until the value of $t_b = I/B$ = 40 ms when the locus continues as a horizontal line moving to the left.

Horizontal lines corresponding to lower loading values of 0.8 B, 0.4B and 0.2 B are shown on figure 3, corresponding to continued lower pressure of 4 MPa, 2 MPa and 1 MPa respectively.

Note that as the lower loading value becomes smaller the value of the effective loading force rises. Equation (22b) has a useful approximation which illustrates this point. The factor multiplying F_1/B will often be small so that

$$F_e \sim B^2/F_2 \qquad (25)$$

However as F_2 becomes smaller it is to be expected that the loading becomes less damaging. This is true and can be illustrated by considering the proportion of high level loading in the loading history which just produces 5% strain in the bolts for different values of the lower loading level. Take for example the locus on figure 3 which levels off at an effective load of 1180 MN, corresponding to F_2 = 200 MN. At the right angle turn in the locus t_b is, as already shown, equal to I/B = 40 ms, whilst t_a = 1.54 ms. At the point where the locus cuts the failure line for the bolts t_a has reduced to 0.72 ms and the effective impulse to 9.5 MN.s. It will now be shown that the value of t_a when the horizontal line cuts the bolt failure line increases as the value of the lower loading level decreases; that is the bolts can stand more high level loading when the following low level loading is reduced.

The value of t_a is given by first solving the hyperbolic locus equation, equation (17), using the effective loading given by equation (22b), to determine the effective impulse at the intercept and then using equation (20b) and (24). These two latter equations give

$$t_a = I_e(1 - F_2/B)/(F_1 - F_2) \qquad (26)$$

Substituting for I_e from equation (17) then gives

$$t_a = I_o(1 - F_2/B)/\ (F_1 - F_2)\sqrt{(1 - B/F_e)} \qquad (27)$$

An approximate analytic solution can be got by using equation (25) rather than 22b). I_e is then determined by

$$I_e^{\ 2}\ (1 - F_2/B) = I_o^{\ 2} \qquad (28)$$

so that $$t_a = I_o\sqrt{(1 - F_2/B)}/(F_1 - F_2) \qquad (29)$$

The variation of t_a with the value of the lower level force is shown in figure 4. The line is from equation (27) whilst the circled points are the more precise values. For values of F_2 greater than about 440 MN it is the vertical portion of the load locus which cuts the hyperbolic failure curve. The relevant values on figure 4 are evaluated on this basis but no simple analytic expression exists.

The above shows quite clearly that loads which are lower than that needed to support plastic flow cannot be neglected if they are applied after flow has been started by some higher loading. The same low loads could be ignored if they occurred prior to the high loading but it must be remembered that dynamic amplification of the initial loads could increase their effective value.

7. Practical Application

The double rectangular pulse discussed in the previous section is a highly idealized representation of the loading of the primary containment roof area which might result in the extremely unlikely event of a prompt critical nuclear excursion. An example of a more precisely calculated estimate of such a loading is shown in figure 5, calculated using the US code REXCO for a conceptual commercial size (12 MW(e)) pool-type LMFBR design [3]. The initial high impact loading is followed by a lower longer lasting force whose level seems to be determined by the yield strength of the walls and the residual pressure in the core. The explosion considered is a nominal 2.7 GJ.

The response of real roof and shield structures would certainly be more complex than could be represented by the simple model used for illustration in this paper. A finite element code treatment is likely to be required. However this response could almost certainly be characterized to a useful degree of approximation by a load-impulse relation, which could be constructed, relatively simply, for a series of rectangular loadings. The effect of more complex loading histories, such as that shown in figure (5), could then be inferred by the methods presented in this paper.

Such an approach would be particularly useful when making parametric surveys. However some direct calculations of the effect of a detailed representation of expected loadings are necessary, both as a check on the simple method and for the purpose of presenting the formal safety case.

References

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[2] C.K. YOUNGDAHL, "Correlation Parameters for Eliminating the Effect of Pulse Shape on Dynamic Plastic Deformation". Journal of Applied Mechanics, Vol. 37, TRANS ASME, Vol. 92, Series E, pages 744 - 752 (1970).

[3] A.H. MARCHERTAS et al., "Analysis and Application of Prestressed Concrete Reactor Vessels for LMFBR Containment" Nuclear Engineering and Design, Vol. 49, page 155 (1978).

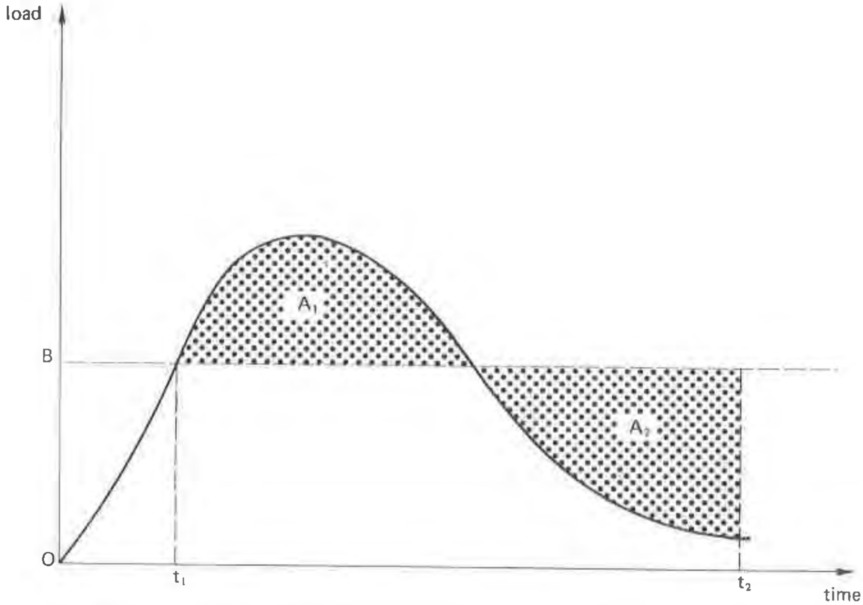
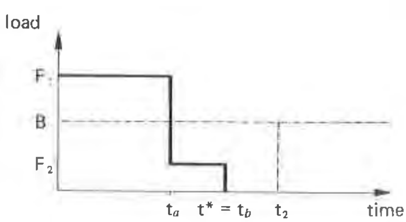


Figure 1 A general loading history showing the times t_1 and t_2 for the start and end of plastic deformation. Time t_2 is located by the requirement that Area A_1 is equal to Area A_2



(a) Lower level load for short time

(b) Lower level load for long time

Figure 2 Plastic deformation can end after ($t_2 > t_b$) or prior ($t_b > t_2$) to end of loading. t^* in Eqn (18) is earliest of two times

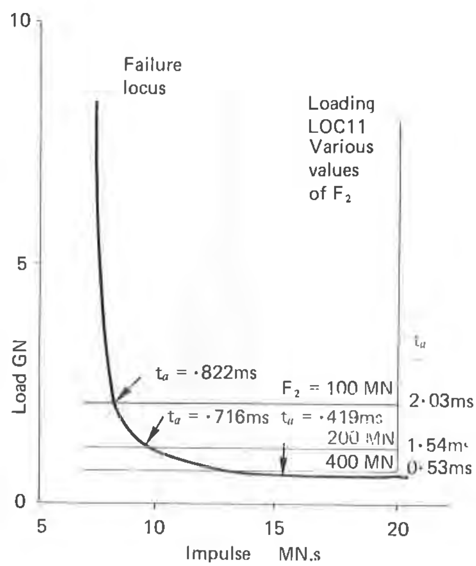


Figure 3 Load — impulse diagram showing failure locus for stretch — bolted roof and loading locus for double rectangular pulse.

Higher load of 8GN acts for time t_a. F_2 is size of later lower load

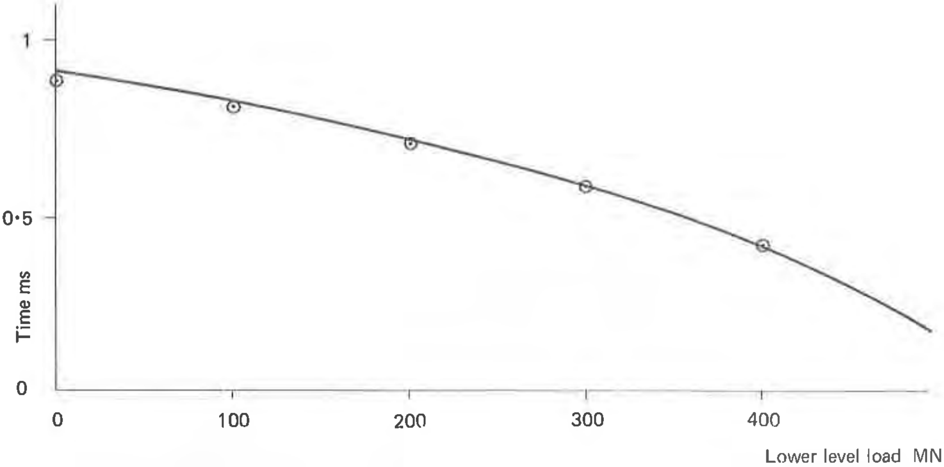


Figure 4 If lower level loading has a value given by the ABSCISSA then the stretch – bolts fail if the upper level prior loading lasts for a time interval greater than that indicated by the ordinate

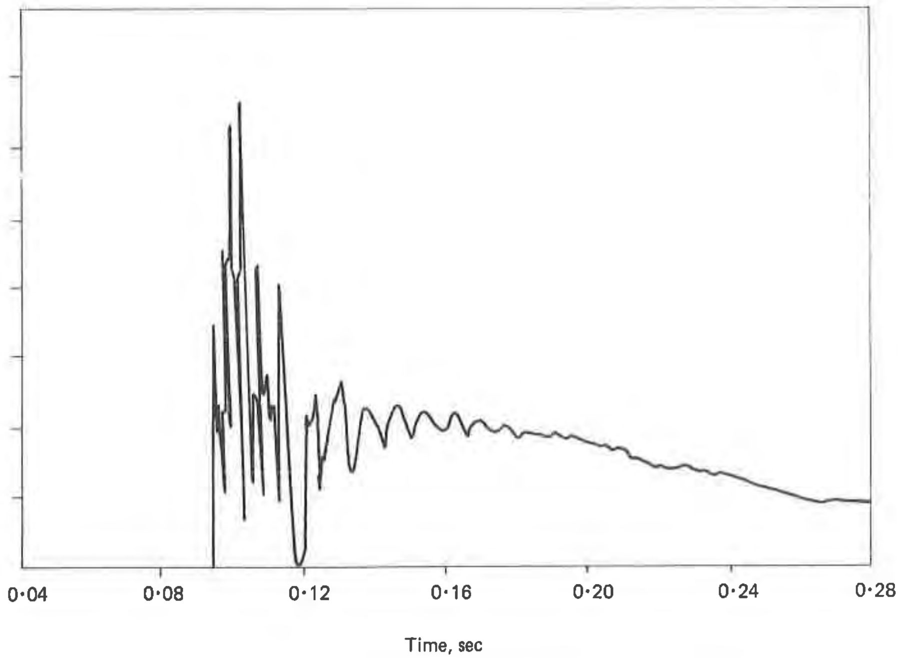


Figure 5 Typical roof--loading for pool type LMFBR