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			PAGE 1 OF 20	

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SUBJECT:

Inertial Pressure Calculations for KEWB

CONTENTS:

I	STATEMENT OF PROBLEM	PAGE 1
II	SUMMARY OF RESULTS AND RECOMMENDATIONS	PAGE 1
III	METHOD USED, DESCRIPTION OF EQUIPMENT, SAMPLE CALCULATIONS . . .	PAGE 2
IV	REFERENCES AND APPENDICES	PAGE 5

I STATEMENT OF PROBLEM

The problem is to calculate the inertial pressure in KEWB for given power trace.

II. INTRODUCTION: FISSION NUCLEATION MODEL

The basic assumption of this paper is that the inertial pressure rise is attributable to fission-nucleated bubbles. These "hard" bubbles cause the pressure of the solution to rise in two manners: first, the nucleation of a "hard" bubble compresses the surrounding solution (if the solution can not flow away rapidly enough) with consequent inertial pressure rise; secondly, the diffusion of radiolytic gas from the solution into the bubble causes the gas pressure to increase, again with consequent inertial pressure rise in the solution.

Fission nucleation of bubbles of radiolytic gas has never been directly confirmed. However, fission nucleation of vapor bubbles has been observed by Ghormley⁽¹⁾. The important ideas used in the present analysis concerning fission nucleation⁽²⁾ are that the process starts to occur at a certain critical radiolytic gas concentration, the bubbles formed have the critical radius corresponding to the critical gas concentration, and one or two bubbles are formed per fission event.

(1) Ghormley, Journal of Nucl. Energy 6, 300, (1958)

(2) C. Warner, Trans. of the American Nucl. Soc. 2, No. 2, 175 (1959)

TECHNICAL DATA RECORD

PROGRAM _____

PROJECT _____

TDR NO. 5543

DATE 3/17/60

PAGE 2 OF 20

A second model for inertial pressure calculations is based on the surface nucleation of bubbles; i.e., all bubbles are nucleated on impurities found throughout the KEWB core. The diffusion of gas into these "soft" bubbles then causes the inertial pressure rise. The existence of such "soft" bubbles appears certain, since void is observed experimentally in transients (eg., $\tau = 36$ ms) where the gas concentration never exceeds the critical gas concentration, this critical concentration⁽³⁾ corresponding to an energy release, $E_c \approx 0.4-0.5$ Mw-sec. If the periods with which the pressure initially builds up are much smaller than the reactor periods, (as appears to be the case in transients No. 168B ($\tau \approx 2$ ms) and No. 158B ($\tau \approx 5.8$ ms)), then the fission nucleation model with its threshold would appear more likely than the pure surface nucleation model with its continuous production of bubbles at all energy releases. This TDR will not treat the pure surface nucleation model.

It is, however, necessary to consider the "soft" surface nucleated bubbles within the fission nucleation model, since the "soft" bubbles have an appreciable effect on the compressibility of the solution and thus on the pressure rise.

III. CALCULATIONS WITHOUT DIFFUSION

In this section, diffusion into the "hard" bubbles is neglected. (Diffusion into the "soft" bubbles will be neglected throughout the TDR).

The compressibility of the mixture of solution and "soft" bubbles is calculated from the observed pressure traces. The velocity of sound is estimated from the compressibility, and independently from the time taken to reach peak pressure. The poor agreement between these calculations is interpreted as evidence for the necessity of including diffusion in the calculations.

a) Calculation of Mixture's Compressibility

The compressibility of the mixture is given by

$$K = - \frac{1}{V} \frac{dV}{dp} = K_0(1-f) + \frac{f}{P + \frac{4\sigma}{3R}} \quad (1)$$

(3) D. L. Hetrick, TDR 3148

TECHNICAL DATA RECORD

TDR NO. 5543

DATE 3/17/50

PAGE 3 OF 20

PROGRAM

PROJECT

$$K_0 = 50 \times 10^{-6} \text{ Atm}^{-1}$$

f = void fraction

R = bubble radius

P = pressure in water

V = mixture volume

If each fission yields N bubbles of radius R for $E > E_c$, then the inertial pressure at the core bottom is given by

$$K \frac{dP}{dE} = \frac{1}{V} \frac{dV}{dE} = N \left(\frac{4}{3} \pi R^3 \right) \frac{2.1 \times 10^{16} \text{ fissions/Mw-sec}}{V_{\text{core}}} \quad (2)$$

$$V_{\text{core}} = 11.3 \times 10^3 \text{ cm}^3$$

Since the mixture at the core bottom is approximately motionless until an expansion wave from the free surface propagates in⁽⁴⁾.

According to our assumptions mentioned earlier, the radius R is the critical radius corresponding to energy E_c ,

$$R = R_c = \frac{2\sigma}{P_G - P} \quad (3)$$

$$P_G = (\text{Henry's constant})^{(5)} \times (\text{radiolytic gas concentration}) \\ = 39.4 E_c (\text{Mw-sec}) \text{ Atmospheres} \quad (4)$$

Examination of Fig. 1 indicates that E_c (the pressure is assumed to start rising at $E = E_c$) depends weakly on the transient's period. Thus E_c varies from approximately 0.40 Mw-sec ($\tau = 2.08$ ms) to 0.60 Mw-sec ($\tau = 5.78$ ms). This variation may be explained by the fact that a given energy release E corresponds to a certain amount of radiolytic gas. The fraction of that gas in solution (rather than in "soft" bubbles) will decrease as the reactor period increases. The threshold for fission nucleation is really determined by the gas concentration in solution. The appropriate E_c for (4) is then 0.40 Mw-sec. Some idea of the variation of critical volume with choice of E_c is seen in the following table:

(4) C. Warner, TDR 5318

(5) See BMI-1067 for effect of dissolved U on Henry's constant.

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

TECHNICAL DATA RECORD

PROGRAM _____

PROJECT _____

TDR NO. 5543

DATE 8/17/60

PAGE 4 OF 20

E = 0.3 Mw-sec	0.4 Mw-sec	0.5 Mw-sec	0.6 Mw-sec
$P_G = 11.8 \text{ Atm.}$	15.8	19.7	23.6
$R_c = 1.15 \times 10^{-5} \text{ cm}$	$.85 \times 10^{-5}$	$.68 \times 10^{-5}$	$.56 \times 10^{-5}$
$V_c = 6.39 \times 10^{-15} \text{ cm}$	2.6×10^{-15}	1.3×10^{-15}	$.71 \times 10^{-15}$

where $\sigma = 65 \text{ dyne/cm}$, $P = \frac{1}{2} \text{ Atm}$ and $V_c = \frac{4}{3}\pi R_c^3$

The KEWB traces (see Fig. 1) yield the following values for the initial $\frac{\partial P}{\partial E}$

$\tau(\text{ms})$	2.08	2.51	4.23	5.78
$\frac{\partial P}{\partial E} \frac{\text{Atm}}{\text{Mw-sec}}$	14.3	13.0	10.5	8.9

There is fair uncertainty in the calculation of these derivatives.

Using $V = 2.6 \times 10^{-15} \text{ cm}^3$ in (2) and the above table, one finds

$\tau(\text{ms})$	2.08	2.51	4.23	5.78
$\frac{K}{N}(\text{atm}^{-1})$	4.99×10^{-4}	5.93×10^{-4}	6.80×10^{-4}	8.05×10^{-4}
$C(N=1)$	$4.4 \times 10^4 \text{ cm/sec}$	4.1×10^4	3.8×10^4	3.5×10^4

where the initial velocity of sound c in the water-"soft" bubble mixture (assuming $N=1$, i.e., 1 bubble per fission) is calculated from⁽³⁾

$$\frac{c}{c_0} = \sqrt{\frac{K_0 \rho_0}{K \rho}} \approx \sqrt{\frac{K_0}{K}}$$

$$c_0 = 1.4 \times 10^5 \text{ cm/sec}$$

$$K_0 = 50 \times 10^{-6} \text{ Atm}^{-1}$$

$$c(N=2) = .707 c(N=1)$$

The velocity of sound increases from $c(N=1)$ as "hard" bubbles are added to the mixture (See pages

The second estimate of the velocity of sound is obtained from the time, Δt , to reach peak pressure. It is here assumed that the pressure at the core bottom rises until an expansion wave (traveling with local sound velocity) reaches the bottom from the free surface⁽⁴⁾. The velocity of sound (a time average) is then $c = \text{core height} \div \Delta t$. The time Δt to reach peak pressure can be read off of Figures 2 and 3:

TECHNICAL DATA RECORD

PROGRAM _____

PROJECT _____

TDR NO. 5543

DATE 2/17/60

PAGE 5 OF 20

τ	Δt	$c = \frac{24\text{cm}}{\Delta t}$
2.08 ms	3 ms	8×10^3 cm/sec
5.78 ms	4 plus ms	6×10^3 cm/sec

The values of c in the last column should be compared with 5×10^3 cm/sec obtained from "slaps" on the pressure traces at top and bottom of the core (6).

The pressure trace in Fig. 3 should be compared with that in the Figure TDR 5313, (p. 10). The flat top in the experimental trace has been interpreted as due to the constricting effect of the KEWB sphere on the solution. This constriction prevents the pressure relief as shown in the figure in TDR 5313.

The sound velocities calculated from $\partial P / \partial E$ are approximately 5 times bigger than the velocities calculated from the time to reach peak pressure. This discrepancy has been taken as an indication that diffusion into the "hard" bubbles is important. In this connection, it should be noted that $\frac{dP}{dE}$ in (2) is the pressure rise due to nucleation (see RES on (2)) rather than dissipation on any other pressure increasing mechanism e.g., heating. Use of a more correct and smaller $\frac{\partial P}{\partial E}$ in (2) implies a larger K and thus a smaller c . This correction would bring the two calculations of c into closer agreement.

The calculations with diffusion in the next section show that diffusion is indeed important.

IV. CALCULATIONS WITH DIFFUSION

In this section, diffusion into the "hard" bubbles is included. It is assumed that the mixture of "hard" and "soft" bubbles are always in mechanical equilibrium. It is again assumed that there is no pressure relief (at the core bottom where the pressure is measured) due to the

(6) R. E. Wimmer, A Summary of Experimental Results of the Spherical Core Investigations in the KEWB Program. Paper 25-2, Summer Meeting, American Nuclear Society, Gatlinburg, June 17, 1959. (See p.3).

TECHNICAL DATA RECORD

PROGRAM

PROJECT

TDR NO. 5543

DATE 5/12/60

PAGE 6 OF 20

water expanding away (until an expansion wave can propagate in from the free surface).

The inertial pressure is calculated from the following equations:

$$N_S V_S(t) + N_H(t) V_H(t) = N_S V_S(t=0) \quad (5)$$

where

$V_{S,H}(t)$ = volume of a "soft", ("hard") bubble at time t .

N_S = number of "soft" bubbles = constant

$N_H(t)$ = number of "hard" bubbles at time t

Equation (5) expresses the idea that the "hard" bubbles compress the "soft" bubbles and the compression of the water is negligible.

The pressure P in the water can be expressed in two ways:

$$P = P_0 \frac{V_S(t=0)}{V_S(t)} \quad (6)$$

and

$$P = \frac{\eta_H(t)}{V_H(t)} kT - \frac{2\sigma}{R_H(t)} \quad (7)$$

or

$$= \frac{\eta_H(t)}{V_{Hmax}} kT \left(\frac{V_{Hmax}}{V_H} \right) - \frac{2\sigma}{R_{Hmax}} \cdot \left(\frac{R_{Hmax}}{R_H} \right) \quad (7')$$

where

$\eta_H(t)$ = number of gas molecules in a "hard" bubble
 $N_S V_S(t=0)$

$$V_{Hmax} = \frac{N_S V_S(t=0)}{N_H(t)}$$

P_0 = initial pressure

The soft bubbles are assumed sufficiently large that the surface tension force $\frac{2\sigma}{R_S}$ is negligible.

If $\eta_H(t)$ and $N_H(t)$ can be determined and the constants $P_0, N_S V_S(t=0)$, and T are given, then the inertial pressure P can be calculated from equations (5), (6), and (7'). We shall calculate graphically for the case

ATOMICS INTERNATIONAL

A Division of North American Aviation Inc

TDR
NO 5543
DATE 8/17/60
PAGE 7 OF 20

$$\begin{aligned} P_o &= \frac{1}{2} \text{ Atm} \\ \sigma &= 65 \text{ dynes/cm} \\ T &= 322^\circ \text{K} \\ \tau &= 2.08 \text{ ms (See Fig. 2)} \end{aligned} \quad (8)$$

and compare the resulting pressure traces with experiment.

Combining (5) and (6)

$$\frac{V_H}{V_{Hmax}} = 1 - \frac{P_o}{P} = r \quad (9)$$

Rewriting (7')

$$\eta_H = \left[P r^{1/3} + \frac{2\sigma}{R_{Hmax}} \right] \frac{V_{Hmax} r^{2/3}}{kT} \quad (10)$$

In Figure 4, equation (10) is plotted, r being eliminated by (9) and the constants used are given by (8). If now R_{Hmax} and η_H are known as functions of time, the pressure P can be read off of Figure 4 as a function of time.

Calculation of $R_{Hmax}(t)$:

The quantity $R_{Hmax}(t)$ is given by

$$\frac{4}{3} \pi R_{Hmax}^3(t) = \frac{N_s V_s(t=0)}{N_H(t)} \quad (11)$$

where

$$\begin{aligned} N_H(t) &= 3.1 \times 10^{16} \text{ N} \times (\text{Power}) \times t \\ &= (3.1 \times 10^{16})(1 \text{ bubble per fission})(300 \text{ Mw})t \\ &= 9.3 \times 10^{18} t \end{aligned}$$

An average power is used for simplicity.

The quantity $N_s V_s(t=0)$ can be estimated from the estimated initial velocity of sound (cf Table page 8):

C_{initial}	$3 \times 10^3 \text{ cm/sec}$	6×10^3
$K \sim 1/c^2$	1.1×10^{-7}	2.8×10^{-8}
$f_s \sim KP = \frac{1}{2} K \times 10^6$	.055	.014
$N_s V_s(t=0) = 11.3 \times 10^3 f_s$	620 cm^3	157 cm^3

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO TDR No. 5543
DATE 8/17/60
PAGE 8 OF 20

The presence of 620 cm^3 is much more than is to be expected from calculations of void from the experimental transients. In fact, the calculations (see Fig. 2) indicate very little void at the onset of inertial pressure.

The following values of $N_s V_s(t=0)$ will be used in the calculations

$$N_s V_s(t=0) = \begin{matrix} 75 \text{ cm}^3 & 150 & 300 \end{matrix}$$

$$R_{Hmax}(t) = \begin{matrix} 1.51 \times 10^{-5} / t^{1/3}_{ms} & 1.90 \times 10^{-5} t^{1/3}_{ms} & 240 \times 10^{-5} / t^{1/3}_{ms} \end{matrix}$$

Calculation of $V_H(t)$:

The problem of the diffusion of radiolytic gas into a bubble of fixed radius has been solved⁷, a constant source of gas in the solution being assumed. The concentration at the bubble surface is

$$c(R,t) = c_0 + St \left[1 - \frac{1}{Ktq^2} \dots \right]$$

$$\dots 1 + \frac{q_R}{q_x} V(-q_I \sqrt{Kt}, q_R \sqrt{Kt}) - u(-q_I \sqrt{Kt}, q_R \sqrt{Kt}) \quad (12)$$

where

C_0 = concentration at $t=0$ = constant in space

S = rate of gas production in solution

K = diffusion constant

$$q_R = \frac{aR^2}{2K} ; \quad q_I = \sqrt{\frac{4aR}{K} \left(1 - \frac{aR^3}{4K} \right)}$$

$$a = \frac{3K_B T}{R^3} \frac{K}{K_H}$$

K_B = Boltzmann's Constant

R = radius of bubble

K_H = Henry's Constant

$$q^2 = q_R^2 + q_I^2$$

u, V = functions describing error function of complex argument. These functions are tabulated in Carslaw and Jaeger (7) C. Warner, TDR 547).

ATOMICS INTERNATIONAL

A Division of North American Aviation Inc

NO TDR No. 5543
 DATE 8/17/60
 PAGE 9 OF 20

p. 484. Second Edition. Substitution into this equation (12) shows that to a good approximation (a few %):

$$\eta(t) = \frac{c_o + St}{c_o} \quad \eta_o = \frac{c_o + St}{c_o} \quad \frac{P_{Go} V_c}{K_S T}$$

$$= (1 + \frac{St}{c_o}) (39.4 \times 10^6 E_c) \frac{V_c}{K_c T} \quad (13)$$

$$S = 1.02 \times 10^{19} \times (\text{Power in Mw}) = 3.06 \times 10^{21}$$

$$c_o = 1.02 \times 10^{19} \quad E_c = 1.02 \times 10^{14} (.4) = 4.0 \times 10^{18}$$

$$K_B T = 4.45 \times 10^{-14} \quad T = 322K$$

$$V_c = 2.6 \times 10^{-15} \quad (\text{See p.7})$$

$$\eta(t) = (1 + .75 t_{ms})(.92 \times 10^6) \quad (13')$$

In the table below $\eta(t)$ is calculated from (13'); $R_{Hmax}(t)$ is calculated for $N_s V_s(t=0) = 75, 150$ and 300 cm^3 . The inertial pressure P is interpolated from Fig. 4:

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO TDR No. 5543
 DATE 3/17/60
 PAGE 10 OF 20

t_{ms}	0	.33	.67	1.00	1.33	1.67	2.00	2.50	3.00	3.50	4.00
$\eta(t)$	$.92 \times 10^6$	1.15x	1.38x	1.61x	1.84x	2.07x	2.30x	2.65x	2.99x	3.33x	3.68x
$R_{Hmax/75}$	2.18×10^{-5}	1.73x	1.51x	1.37x	1.27x	1.20x	1.11x	1.05x	.99x	.95x	
P(Atm).50	.55	.68	.87	1.5	2.5	4.75	10.0				
$R_{Hmax/150}$	2.75×10^{-5}	2.18x	1.90x	1.73x	1.60x	1.51x	1.40x	1.32x	1.25x		
P(Atm)	.50	.55	.67	.77	.97	1.5	2.6	5.4	9.0		
$R_{Hmax/300}$	3.47×10^{-5}	2.75x	2.40x	2.18x	2.02x	1.90x	1.76x	1.66x	1.57x	1.52x	
P(Atm)			.55	.64	.71	.81	1.00	1.61	2.86	4.10	

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc

NO TDR No. 5543

DATE 8/17/60

PAGE 11 OF 20

The pressure traces calculated above are graphed in Figure 5. The experimental trace agrees fairly well with the trace calculated for $N_s V_s(t=0) = 150 \text{ cm}^3$.

It must be remembered that the expansion waves from the free surface will alter the traces calculated above and in fact cause the pressure to turn over. An approximate treatment of this pressure relief now follows.

The compressibility of a medium containing two types of bubbles is given by a generalization of (1):

$$\bar{K} = (1-f_s-f_H)k_0 + \frac{f_s}{p+\frac{4\sigma}{3R_s}} + \frac{f_H}{p+\frac{4\sigma}{3R_H}} \quad (14)$$

$$\approx \frac{f_s}{p} + \frac{f_H}{p+\frac{4\sigma}{3R_H}} \quad \text{if} \quad \frac{4\sigma}{3R_s} \ll p \quad (14')$$

where

$$f_s = \frac{N_s V_s(t)}{11.4 \times 10^3} ; \quad f_H = \frac{N_H(t) V_H(t)}{11.4 \times 10^3}$$

The velocity of sound at the core bottom can be computed from

the compressibility; i.e., $c = \sqrt{\frac{1}{\rho \bar{K}}} \approx \sqrt{\frac{1}{\bar{K}}}$. The velocity of

sound has been computed for the two cases $N_s V_s(t=0) = 75$ and 150 cm^3 , and the results are shown in Figure 6. The distance $r(t) =$

$$\int_0^t c(t) dt \text{ is shown in Figure 7.}$$

If the velocity of sound throughout the core is assumed to be given by $c(t)$, then by the Green's function approach outlined in TDR 5318 (e.g. p.8):

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. TDR No. 5543

DATE 3/17/60

PAGE 12 OF 20

$$P_{\text{bottom}}(t_2) - P_{\text{bottom}}(t=0) \cong [\bar{P}(t_2) - P(t_1)] - 2[\bar{P}(t_1) - P(0)]$$

$$\cong P(t_2) - 3P(t_1) + 2P(0)$$

or (15)

$$P_{\text{bottom}}(t_2) \cong P(t_2) - 3[\bar{P}(t_1) - P(0)]$$

where $\tau(t_1) + H = \tau(t_2)$

$P(t)$ = pressure trace with no expansion

waves e.g. Fig. 5.

Use of (15) with Fig. 5 and 7 yields the following traces:

$$N_s V_s(0) = 75 \text{ cm}^3$$

t =	= 0	1.75 ms	2.00	2.13	2.25
P_{bottom} =	$P(t)$		4.00Atm	3.28	2.50

$$N_s V_s(0) = 150 \text{ cm}^3$$

t	= 0ms	2.50	2.75	3.00	3.25	3.50
P_{bottom} =	$P(t)$		3.25	3.21	2.45	0

This approximate treatment yields maximum inertial pressures of approximately 4 and 3.25 Atmospheres. The experimentally observed peak pressure is 10 Atmospheres. As previously indicated, the treatment of the pressure relief assumes that the velocity of sound $c(t)$ is constant in space and given by the velocity of sound computed (with no expansion) for the core bottom. Actually, the expansion wave traversing the core decreases the sound velocity. The sound velocity will then be a minimum at the top of the core.

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc

NO TDR No. 5543

DATE 8/17/60

PAGE 13 OF 20

This decrease in sound velocity would slow up the pressure relief and certainly increase the agreement between the calculations and experiment.

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PREPARED BY:	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC.	PAGE NO. 14 OF 20
CHECKED BY:		REPORT NO. TDR 5543
DATE: 8/17/60		MODEL NO.

Fig 1 Pressure vs Energy (Experimental traces)

PREPARED BY:	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC.	PAGE NO. 15 OF 20
CHECKED BY:		REPORT NO. TDR 5543
DATE: 8/17/60		MODEL NO.

Fig 2 Transient 1420 7-208mz

PREPARED BY:	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC.	PAGE NO. 16 OF 20
CHECKED BY:		REPORT NO. TDR 5543
DATE: 8/17/60		MODEL NO.

Fig 3 Transient 158 B $\tau = 5.78$ ms

PREPARED BY:	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC.	PAGE NO. 17 OF 20
CHECKED BY:		REPORT NO. TDR 5543
DATE: 8/17/60		MODEL NO.

Fig 4 Molecules, η_H , vs R_{Hmax} for pressure P
 See equation (10) of text.

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CHECKED BY:		REPORT NO. TDR 5543
DATE: 8/17/60		MODEL NO.

Fig 5 Calculated inertial pressures vs time. See text on page 18. Time origin taken at $t = 14 \text{ ms}$.

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PREPARED BY:	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC.	PAGE NO. 19 OF 20
CHECKED BY:		REPORT NO. TDR 5543
DATE: 8/17/60		MODEL NO.

Fig. 6. Calculated velocity of sound c vs. time for two initial void volumes. See text p 11.

PREPARED BY:	ATOMICS INTERNATIONAL A DIVISION OF NORTH AMERICAN AVIATION, INC.	PAGE NO. 20 OF 20
CHECKED BY:		REPORT NO. TDR 5543
DATE: 8/17/60		MODEL NO

Fig 7. The distance $Z = \int_0^t c dt$ vs time