Evaluating the Performance of Pile Driving Hammers

by Garland E. Likins, Jr.

Engineers have for years attempted to relate the static capacity of a pile to its dynamic penetration during driving. This has led to a variety of dynamic formula based on energy considerations. More recently, attention has been given to the wave equation as a means of relating capacity with blow count. In either case, assumptions regarding the performance of the hammer must be made and capacity results are then often accepted as accurate without any further testing. Perhaps in no other finished installation does the acceptance of the final product depend so heavily on the proper performance of the installing equipment.

In the past, testing has usually meant a static load test. In many cases, these tests were not performed in sufficient quantity for many projects due t[illegible]st limitations. In some cases, such as offshor[illegible]lations, the large loads required effectively pr[illegible] serious attempts at load testing. If soil conditi[illegible] the hammer is modified or even replaced, an adequa[illegible] confirm that the driving criteria is still approp[illegible]n not included. To meet this testing void, dynam[illegible]s have become increasingly commonplace during the [illegible] years as both measuring equipment and analysis [illegible] have been developed and improved.

For projects where dynamic measurements are available, a surprisingly large percentage indicate inadequate hammer performance. When the hammer is not performing properly, other problems often occur such as inadequate bearing capacity. It has been estimated by the author's consulting experience that about sixty percent of the problems encountered on pile construction sites can be directly related to inadequate hammer performance (other problems are caused by poor pile material quality, unexpected soil behavior such as high quakes, low resistance in dense soils, setup or relaxation, etc.)

Since the hammer plays such an critical role, it is important to understand the operational characteristics of hammers. Conventional impact hammers generally fall into one of three general categories: drop, air/steam or diesel. A brief operation description follows for each type.

The predominate hammer type prior to this century, the drop hammer uses a mass which is raised mechanically to some height and then released. The most common method is to raise the ram using a winch cable system. As the ram is dropped, some of the available potential energy must be used to accelerate the cable winch system, therby reducing the overall efficiency. Further losses occur in friction of the ram on the guides. Another potential energy loss occurs when the crane operator, in order to speed up this relatively slow method, attempts to raise the ram too soon. What happens then is that he in effect often "catches" the ram either before or during impact thereby reducing the energy input to the pile. A more efficient system is where the mass is raised hydraulically and then left to free fall as the lifting mechanism is hydraulically retracted faster than the ram fall.

The basic operation of air/steam hammers, as can be seen in Figure 1, consists of two parts. Air or steam is input into a pressure cylinder. The pressure exerts an upward force on the ram. At some point in the upward motion, usually when the ram reaches about half its maximum stroke, the excess pressure is released. At this time, the ram still has some upward velocity. Under the action of gravity and friction, the ram continues to rise until the fall height, h, has been reached and the ram velocity is then zero. The ram then begins to fall under the action of gravity, g. This fall is not fully efficient in converting the potential energy, Wh, to kinetic energy due to the presence of friction. Typically two inches (5 cm) above impact, a tripping mechanism is activated which injects the pressure for the ram lifting process. During impact, the pile may also return some energy to the ram due to rebound in harder driving situation. This rebound energy gives the ram some initial upward velocity. Unless the air pressure/volume is adjusted, this rebound velocity will result in a higher total stroke, h.

In order to increase operating speed, this hammer is sometimes modified to be double acting. In this case, air pressure is also added to the top of the ram during the downstroke to increase the velocity at impact. The ram stroke is then usually shortened to speed up the cycle. Under ideal conditions, the hammer obtains the same kinetic energy at impact.

Consideration of these air/steam operating principles will lead to several potential sources of problems. If excessive friction is present in the system, the impacting velocity will be reduced. Typically assumed normal efficiencies are only 67 percent for this "free" drop with the reduction due primarily to friction. The second problem is an inadequate air source. If either the pressure and volume supplied to the pressure chamber (excessive hose length or losses or blockages in the air hose system must be considered) then the ram will not achieve the specified stroke. This problem is doubly important for the double acting hammers since their downward velocity is also dependent upon the air pressure. A third problem is perhaps more subtle but nevertheless real. Consider what happens as the hammer cushion (also called capblock) becomes worn. As its thickness reduces, the ram must travel this extra distance before actually striking and delivering its energy to the pile. However, since the lifting pressure is applied at a constant location, this actually means that as the capblock becomes thinner, this pressure is applied for a longer distance and contributes to excessive slowing of the ram and ultimate extra energy losses not usually accounted for; this is commonly called preadmission.

The third major hammer type employs a typical diesel cycle as show in Figure 2. The falling ram, as it nears the bottom of its stroke, closes the exhaust ports. As the ram continues downward, the gases in the enclosed chamber are compressed. At some point, a fuel charge is introduced. The ram finally collides with the anvil (impact block). At some point, usually just after impact, the fuel air mixture ignites and the pressure in the chamber increases. After impact, the gases begin to expand, pushing the ram upward. As the upward moving ram clears the ports, the excess pressure from the combustion is exhausted. The ram continues its upward motions creating a scavenging process until the ram achieves its full stroke. The ram then starts falling and the next cycle begins. Double acting diesel hammer systems have also been developed by creating either a pressure chamber above or a vaccuum chamber below the ram. The double acting pressure chamber essentially limits the maximum energy since further strokes then result in hammer lift off or racking on the pile top. If racking occurs, the fuel charge is reduced and the stroke decreases until the system is again in equilibrium. For the basic open end, single acting hammer, the stroke and hence impact velocity depend on the resistance of the pile. Thus, as more energy is required, more energy is applied. To some extent, the stroke can be controlled by the fuel charge used per cycle.

Problems also exist with diesel hammers. Naturally excessive friction between cylinder and piston can cause many problems; proper lubrication is important. More typical problems occur in the combustion process and can occur in these ways. If the fuel pump does not deliver the correct amount of fuel (blocked supply lines, faulty pump, etc.) the hammer will not be able to develop its full energy and in the worst case will not run at all. This does not present a rating problem if the assumed energy per blow is the observed potential energy, Wh. A more difficult problem is that of so called "preignition". In this case the fuel combusts prior to impact. The energy then goes into slowing the ram before impact instead of going into the pile. Preignition is difficult at best to detect without electronic measurements during actual hammer operation. Another problem centers around the initial compression of the gases; the pressure rings on the ram and anvil must be adequate to prevent excessive losses.

The comparisons of the three hamer types are usually done on the basis of energy comparisons. Each of the hammers is capable of developing some maximum potential energy, PE

$$PE = Wh \qquad (1)$$

or equivalent rated energy, Er, in the case of double acting hammers. However, potential energy in and by itself does not install the pile. The potential energy is first transferred into kinetic energy, KE, as the ram velocity increases prior to impact

$$KE = 1/2\ M_R\ V_R^2 \qquad (2)$$

where MR is the ram mass, VR is the ram velocity and is usually computed from

$$V_R = \sqrt{2\ g\ h\ e} \qquad (3)$$

where e is the efficiency of the system and includes among other factors, the friction losses. Comparing hammers on their maximum developed kinetic energy appears to be a better method than potential energy ratings, however it is a much more difficult quantity to determine and could vary even among otherwise physically identical hammers due to different friction losses, etc.

In reality, the only energy which is truely useful is that which is actually transferred to the pile. This energy is referred to as ENTHRU. The difference between that transferred to the pile and that available as kinetic energy is stored or consumed by the other driving system components as kinetic or strain energies of the anvil (if present), capblock, helmet, pile top cushion (where present for concrete piles), inelastic collisions as represented by coefficients of restitution and in the compression of gases in the case of diesel hammers. Changes in these components affect the actual transmitted energy. As these accessories can be and are frequently varied by the contractor, it would appear that each hammer system should be judged according to its actual ENTHRU and that the transfer efficiency of the system can then be computed from

$$T_p = ENTHRU/PE \qquad (4a)$$

for efficiency from potential energy, or

$$T_k = ENTHRU/KE \qquad (4b)$$

for transfer efficiency from kinetic energy. The actual hammer efficiency, e, can be computed from

$$e = KE/PE \tag{5}$$

The energy transferred to the pile top can be computed from the work-energy theorem as the amount of work, W, done on the pile top.

$$\begin{aligned} ENTHRU = W &= \int F \, du \qquad (6) \\ &= \int F \, du/dt \, dt \\ &= \int F \, v \, dt \end{aligned}$$

Since the pile top force, F, and velocity, v, are functions of time, the energy ENTHRU is also a funtion of time. Two values of ENTHRU are of importance: the maximum value EMAX is the amount of energy available in the pile to actually do work. The final value EFIN after the interaction impact forces terminate is the residual value remaining in the pile/soil system and is that portion of the ENTHRU which actually did the work. The difference between these values (EMAX-EFIN) is a rebound energy, EREB, which was returned to the driving system.

This energy transfer/rebound can also be found using other principles. Consider that the force, F, and velocity, v, are proportional by the pile impedance, I, (= EA/c where E, A and c are the pile material modulus, cross-sectional area and wavespeed, respectively)

$$F = Iv = (EA/c)v \tag{7}$$

as long as the pile is uniform and no reflections occur from soil resistance or the pile end. Using this concept, the downward travelling force waves can be computed as

$$Wd = (F + Iv)/2 \tag{8}$$

and the upward travelling force waves as

$$Wu = (F - Iv)/2 \tag{9}$$

and the wave velocities from

$$vd = Wd/I \tag{10}$$

and

$$vu = Wu/I \qquad (11)$$

Substitution of Equations 8 through 11 into Equation 6 leads to the energies of the upward and downward travelling waves

$$Ed = \int Wd\ vd\ dt \qquad (12)$$

$$= 1/4I \int (F + Iv)^2\ dt$$

$$Eu = \int Wu\ vu\ dt \qquad (13)$$

$$= 1/4I \int (F - Iv)^2\ dt$$

It then follows that the energy which remains below the location of the known F and v is then the difference between the upward and downward energy

$$ENTHRU = Ed - Eu \qquad (14a)$$

$$= 1/4I \left(\int \{(F + Iv)^2 - (F - Iv)^2\}\ dt \right. \qquad (14b)$$

which then reduces to

$$ENTHRU = \int F\ v\ dt \qquad (14c)$$

That the downward energy, Ed, is not the correct energy evaluation can be clearly demonstrated in the free pile case. For a pile with no resistance, the force and velocity are proportional for the first 2L/c time period, where L is the pile length. Afterward the top velocity for every subsequent 2L/c cycle will be twice the input velocity and the force will be forever zero. Since the force is then zero, the pile and hammer system are not in contact and no further energy transfer can occur as correctly shown by Equation 6. However, the upward and downward waves are non-zero (since v is always positive and F is zero) and of equal magnitude, although by definition of opposite direction. The upward and downward energies reduce to

$$Ed = Eu = I/4 \int v^2\ dt$$

Thus, at the free end pile top, the upward travelling energy reflects perfectly and then travels down the pile.

Other proposed definitions of energy transferred which use consideration of Equation 7 and 6 such as

$$E = 1/I \int F^2 \, dt$$

or

$$E = I \int v^2 \, dt$$

are equally incorrect except in the case of infinitely long, uniform piles which have no skin friction or internal damping forces. These cases obviously have no practical importance.

The task of obtaining the actual kinetic energy of the ram just prior to impact has been a difficult task using energy considerations. If the actual impact velocity cannot be measured, either the potential energy <u>and</u> losses to friction, etc. must be known or the ENTHRU must be measured and energy stored and lost in the other hammer components must be calculated. The actual hammer efficiency from Equation 5 is important since two otherwise identical hammers with equivalent potential energies will actually have different striking energies if the friction present in the hammers is different. Therefore, to obtain the correct kinetic energy, we must obtain the ram velocity.

Newton, in his famous "Principia", expressed the second law of motion in terms of momentum. The momentum of a mass, m (=W/g) with velocity, v, is

$$p = mv \qquad (15)$$

and since v is a vector (directionally oriented), momentum is also a vector. Newton's law reads: "The rate of change of momentum of a body is proportional to the resultant force acting on the body and is in the direction of that force". Therefore

$$Fe = dp/dt \qquad (16)$$

More importantly, if the resultant <u>external</u> force, Fe, acting on a system is zero, then

$$dp/dt = 0 \qquad (17)$$

or

$$p = \text{constant}$$

and the total momentum of that system remains constant. This general result, the conservation of linear momentum, is applicable to all pile driving since even the combustion of diesel hammers is an <u>internal</u> force which acts between particles and therefore cancels in pairs because of Newton's third law.

The only external force for the system is gravity. The time during impact over which gravity acts is small for air/steam or drop hammers and the momentum changes may be safely ignored. Optionally, gravity's effect on momentum can be calculated since the gravitational force is known. This change of momentum can alternatively be included as in the case of diesel hammers where the time between port closure and exhaust is generally between 0.1 and 0.2 seconds.

The momentum of the hammer system at any time is easily computed using Equation 15 and the element masses and velocities. However, the momentum of the entire system includes that contained in the pile/soil system. To compute the momentum of the pile/soil portion is an impossible task using Equation 15. However, if we use Equation 16 and the concept of impulse, we can find the change in momentum, dp from

$$dp = p_1 - p_0 = \int_0^t F\,dt \qquad (18)$$

The total impulse applied by the hammer to the pile is then equal to the integral over the entire hammer blow of the measured force with time. The rebound energy could be used to compute the rebound velocity of the ram for air/steam and drop hammers

$$EREB = 1/2(MR + MH)V_{R,reb}^2 \qquad (19)$$

where MH is the mass of the helmet and it is assumed that the ram and helmet both reach a velocity equal to VR,reb, the velocity of the ram at rebound. The rebound momentum of the hammer can then be computed from

$$p_{reb} = (MR + MH)\,V_{R,reb} \qquad (20)$$

and the input momentum from the ram

$$p_{input} = \int_0^{end} F\,dt + p_{reb} - pg \qquad (21)$$

where pg is the correction due to gravity (pg = M g dt where dt is the time duration during impact, typically 0.020 seconds for air/steam or drop hammers). Of course, once the input momentum is known, the ram velocity and therefore the ram's kinetic energy can be calculated from Equations 15 and 2.

To test this hypothesis, a series of wave equation simulations

$$p_{reb} = \int_{v=0}^{end} F\ dt = (M_R + M_H)\ V_{R,rebound} \qquad (22d)$$

The input momentum as calculated by Equation 22c is given in Table 3. In general, this method gives reasonable results, but with a larger scatter than by the rebound techniques. The reason for this extra variability can be seen by inspection of Figure 4. In this example, it is clear that the time of ram and pile top zero velocity are not identical. The force at this time is near its maximum value and hence the force impulse is changing rapidly. Small changes in timing lead to relatively large changes in momentum.

In this case, the pile top zero velocity was late and the computed impulse momentum was 14 percent too large. Further inspection of this case shows a relative minimum in the pile velocity (which has only a slightly positive magnitude) occuring before the correct ram zero time. Small changes in hammer performance, pile nonuniformities or skin friction distributions could easily cause the velocity to be negative at that time and the momentum would then be too small. The conclusion is that this method gives good results but with significant scatter due to the sensitivity of the force impulse to small changes in the time of zero pile top velocity.

The impulse can also be computed with consideration of Equation 8 and 9 from

$$dp = \int_0^t F\ dt = 1/2 \int_0^t (F + Iv)dt + 1/2 \int_0^t (F - IV)\ dt \qquad (23a)$$

$$= \int_0^t Wd\ dt + \int_0^t Wu\ dt \qquad (23b)$$

$$= p_{down} + p_{up} \qquad (23c)$$

or the sum of the momentum of the upward and downward travelling wave. As long as the downward wave, Wd, is positive, the pile is receiving input from the hammer. At the time Wd becomes zero, all of the initial hammer momentum has been transferred to the pile. Calculation of the input momentum can then be made from the downward wave, Wd

$$p_{down} = \int_0^{Wd=0} Wd\ dt \qquad (24)$$

with only one condition. Note in Equation 23a that if the force F is zero (indicating hammer-pile separation as shown earlier), there is then no change in momentum. Actually in that case Wd=-Wu and dpdown equals - dpup and no net transfer is actually occurring. Therefore equation 24 was used subject to the condition that F be positive. These results are shown in Table 3 for calculations at the pile top and at a distance of ten feet below the top. Results for the pile top computation are excellent and exhibit little scatter. Results are similar for the location below the top when blow counts and resistances are of reasonable magnitudes. Using this wave approach eliminates the sensitivity to changes in time since the rate of change is smaller as Wd approaches zero.

These studies were performed using two different coefficients of restitution for the hammer cushion. The coefficients chosen cover the range of values commonly used for cushion materials. No noticeable changes in the calculated input hammer momentums are observed indicating the insensitivity of the method to changes in hammer accessories. The effect of different capblock coefficents of restitution can however be observed in the ENTHRU values (Table 2) since they then "absorb" different amounts of energy in inelastic collisions (by definition). This does not play a major role except in hard driving. Notice that until refusal conditions are encountered that the blow count-capacity relationship is very similar.

Energy and momentum for two cases as a function of time during impact are shown graphically in Figures 6 and 7.

It is apparent that the input momentum of air steam or drop hammers may be determined to within five percent accuracy using pile impulse considerations. Since the ram mass is known, direct calculation gives ram impact velocity and kinetic energy without having to resort to elaborate transducer systems to monitor ram motion.

A similar energy momentum study was performed for a diesel hammer using the WEAP program. The hammer was used assuming both a normal combustion and also preignition of the gasses. Results are given in Tables 4 and 5. Computed force velocity time relations are given in Figures 8 and 9 for the normally operating hammer. Inspection of Table 4 reveals several features concerning the use of momentum for diesel hammers.

A) The momentum in the system increases substantially (by 1/3) during the relatively long time between port closure and exhaust.

B) The input momentum at the time of impact can be accurately obtained by either of Equations 22c or 24.

C) Since the downward and upward ram velocity (momentum) are roughly equal as the ram passes the ports, the input momentum can be calculated from half the total force impulse (Equation 18).

D) While momentum calculations are acurate they do not allow cases of preignition and normal combustion to be distinguished. This is obvious because the compression and combustion gas pressures are forces which are completely internal to the system.

Since momentum cannot be used to identify hammers which have preignition other inspection is required. The hammer could be judged by observing the maximum stroke either visually or by blow rate from

$$h[ft] = 4.01\ T^2 - 0.3 \qquad (25)$$

where T is the time in seconds between hammer blows. This equation, based on the principle of free fall under gravity, has been compared with actual stroke measurements and is judged accurate for all single acting, open end diesel hammers. An electronic device, the Saximeter, has been previously developed to perform this computation using only accoustic input from the hammer impacts.

Inspection of Table 5 shows that the stroke for a preigniting hammer is practically identical to that of one operating with normal combustion. A hammer may then develop the same potential energy but still have a different performance as seen by the blow count-capacity differences. Table 5 does demonstrate that the actual ram velocity (kinetic energy) at impact is dramatically affected by preignition although the velocity at the ports and maximum velocity before impact are not significantly different. The result of preignition is then to use much of the combustion energy to slow the ram prior to impact. This is reflected in reducing the actual energy ENTHRU entering and remaining in the pile. A diagram of the energy in the various system elements is shown in Figures 10 and 11 for normal and preignition cases. It can be seen that the gases store energy which is recovered by the ram prior to exhaust. In the presented examples, the amount of energy used in compressing the gas prior to impact is about twice as large in the preignition case. The reduced performance can also be observed in the pile top measurements of force and velocity; not only are the magnitudes reduced but the shapes are changed.

The wave equation soil model has elastic plastic springs and linear viscous damping. The static and damping soil forces were integrated with time. The resulting momentum was equal to the total input impulse from Equation 18. Thus all momentum input to the pile was then transferred to the soil. It would be ideal to be able to compute the pile capacity from the momentum. For the diesel WEAP cases (capacities 200 to 800 kips), the best capacities obtained from momentum ranged from 277 to 558 kips. Unfortunately, it does not appear reasonable to compute capacity from momentum techniques.

Conclusions

The three major hammer types have been summarized with respect to both operational characteristics and potential problems. Computational procedures for evaluating the effectiveness or efficiency of energy as transferred to the pile are reviewed and discussed. A method for computation of the actual ram kinetic energy at impact was derived and presented. This method uses the principle of conservation of momentum and the standard Case-Goble measurements of force and velocity at the pile top. Comparison of this kinetic energy with the available potential energy will give a good indication of the efficiency of drop or air/steam hammers. It appears that combustion energy or actual energy transferred to the pile is a better measure for diesel hammer.

Table 1: Input Parameters for WEAP Runs

	English	Metric
Air Steam - Hammer Vulcan 010		
Ram Weight	10 kip	44.5 kn
Stroke	3.3 ft	1.0 m
Efficiency	67%	67%
Impact Velocity	11.93 ft/sec.	3.64 m/sec.
Input Momentum	3.70 k-sec.	16.5 kn-sec.
Max. Ram Kinetic Energy	22.1 k-ft.	30 kJ
Max. Potential Energy	33 k-ft.	44.8 kJ
Diesel - Hammer Delmag D22		
Ram Weight	4.86 kip	21.6 kn
Anvil Weight	1.60 kip	7.1 kn
Efficiency	90%	90%
Helmet - Airsteam and Diesel		
Helmet Weight	2.5 kip	11.1 kn
Helmet Stillness	30,000 k/inch	
Coefficient of Restitution		
Air Steam	1.0 and 0.6	1.0 and 0.6
Diesel	0.8	0.8
Pile Description		
Length	50 ft.	15.25 m
Material	Steel	Steel
Area	30 in^2	194 m^2
Soil Description		
Percent Toe Bearing	50%	50%
Skin Friction Distribution	Triangular	Triangular
Quake	0.1 inch	2.5 mm
Skin Damping (Smith type)	0.1 sec/ft	.33 sec/m
Toe Damping (Smith type)	0.1 sec/ft	.33 sec/m

Table 2

CAP	Bl Ft.	MAX ENERGY (K-Ft)			ENTHRU (K-Ft)			RAM VELOCITY AT TIME OF V_p=MIN (ft/sec)		
		$E_{available}$	Ed	E_u	EFIN	EMAX	EREB	ACTUAL	PILE	REBOUND
50	5	24.7	40.7	18.1	22.6	22.6	0	+2.71	POS	---
100	10	23.5	28.1	6.5	21.6	21.6	0	+3.28	-2.12	---
200	20	22.9	22.9	3.1	19.8	20.9	1.1	-2.26	-1.98	-2.35
300	32	22.7	22.6	4.1	18.5	20.6	2.1	-3.21	-3.08	-3.30
400	50	22.6	23.6	6.8	16.8	20.2	3.4	-4.24	-3.85	-4.21
500	84	22.6	25.0	10.4	14.6	19.7	5.1	-4.91	-5.42	-5.16
600	173	22.6	26.8	14.1	12.7	19.7	7.0	-6.08	-6.29	-6.01
700	415	22.6	27.9	16.4	11.5	19.4	7.9	-6.71	-6.73	-6.40
800	1714	22.5	28.1	17.8	10.3	18.8	8.5	-7.17	-6.20	-6.64
300	32	22.7	21.7	4.0	17.7	19.7	2.0	-3.17	-3.05	-3.25
500	86	22.6	24.2	10.5	13.7	18.8	5.1	-5.43	-4.79	-5.13
700	814	22.6	26.8	17.1	9.7	18.2	8.5	-6.99	-6.06	-6.60

Table 3

Capacity	Blows foot	MOMENTUM - MSD IN PILE					INPUT MOMENTUM			
		Force @V=0	Wd top	Wd 10' below		Force End	Actual	From Rebound Pile Velocity*	From Rebound Energy*	
50	5	NA	(3.54)**	6.12			NA			
100	10	2.92	3.89	4.55		4.09	3.99			
200	20	3.71	3.69	3.90		4.92	4.05	3.90	3.76	
300	32	3.73	3.64	3.64		5.23	3.98	3.78	3.70	
400	50	4.22	3.60			5.58	3.93	3.84	3.70	
500	84	3.62	3.64	3.64		5.88	3.92	3.53	3.63	
600	173	3.76	3.71	3.71		6.32	3.91	3.63	3.74	
700	415	3.93	3.73	3.73		6.54	3.90	3.67	3.80	
800	1714	3.33	3.73	3.73		6.61	3.89	3.95	3.78	
300	32	3.73	3.63	NA	3.70	5.21	3.97	3.78	3.70	COR=.6
500	86	3.57	3.63	NA	3.70	6.01	3.92	3.90	3,77	
700	814	3.76	3.74	NA	3.70	6.59	3.90	3.99	3.78	

NOTES:

COR=1.0

IMPACT MOMENTUM = 3.70

* Includes a 0.25 correction for gravity effects

** Input not yet complete

Table 5

Capacity	Blows/foot	Stroke	Velocity (ft/sec) Port	Velocity (ft/sec) from WH	Velocity (ft/sec) Actual	Actual Ram Velocity At Impact ft/sec.	Actual Ram Velocity At Pile Top ft/sec.	Max Top Pile Force kips	Energy (k-ft) Max	Energy (k-ft) End
200 N	19	5.80	16.78	18.33	17.29	15.37	13.9	772	19.94	19.17
400 N	55	6.97	18.70	20.09	19.15	17.52	15.6	876	19.57	16.95
600 N	134	7.62	19.68	21.01	20.11	18.55	16.5	929	20.60	15.73
800 N	403	7.96	20.17	21.47	20.60	19.03	16.9	959	21.36	14.75
400 P	68	7.03	19.03	20.18	19.64	13.00	10.9	737	14.13	11.61
600 P	238	7.54	19.34	20.90	19.93	13.50	11.1	791	14.09	9.19

Table 4

Cap.	Com-bus-tion	Bl. ft.	Stroke	MOMENTUM - RAM Port	From WH	Actual	HAMMER & PILE Impact	End	COMPUTED MOMENTUM Force (v=0)	WAVD (w=0)	WAVD COR	Force End/2
200	N	19	5.80	2.51	2.77	2.61	3.00	3.63	2.91	2.74	2.96	3.09
400	N	55	6.97	2.80	3.04	2.89	3.24	3.85	3.55	3.37	3.56	3.45
600	N	134	7.67	2.95	3.17	3.04	3.37	3.95	3.41	3.18	3.36	3.54
800	N	403	7.96	3.03	3.24	3.11	3.44	3.97	3.49	3.16	3.35	3.50
400	P	68	7.03	2.89	3.05	2.97	3.30	3.90	NA	3.30	3.45	3.51
600	P	238	7.54	2.93	3.15	3.01	3.34	3.90	NA	3.15	3.30	3.38

Note * N - Normal 0.002 second duration beginning 0.002 second after impact

P - Preignition 0.004 second duration beginning 0.008 second before impact.

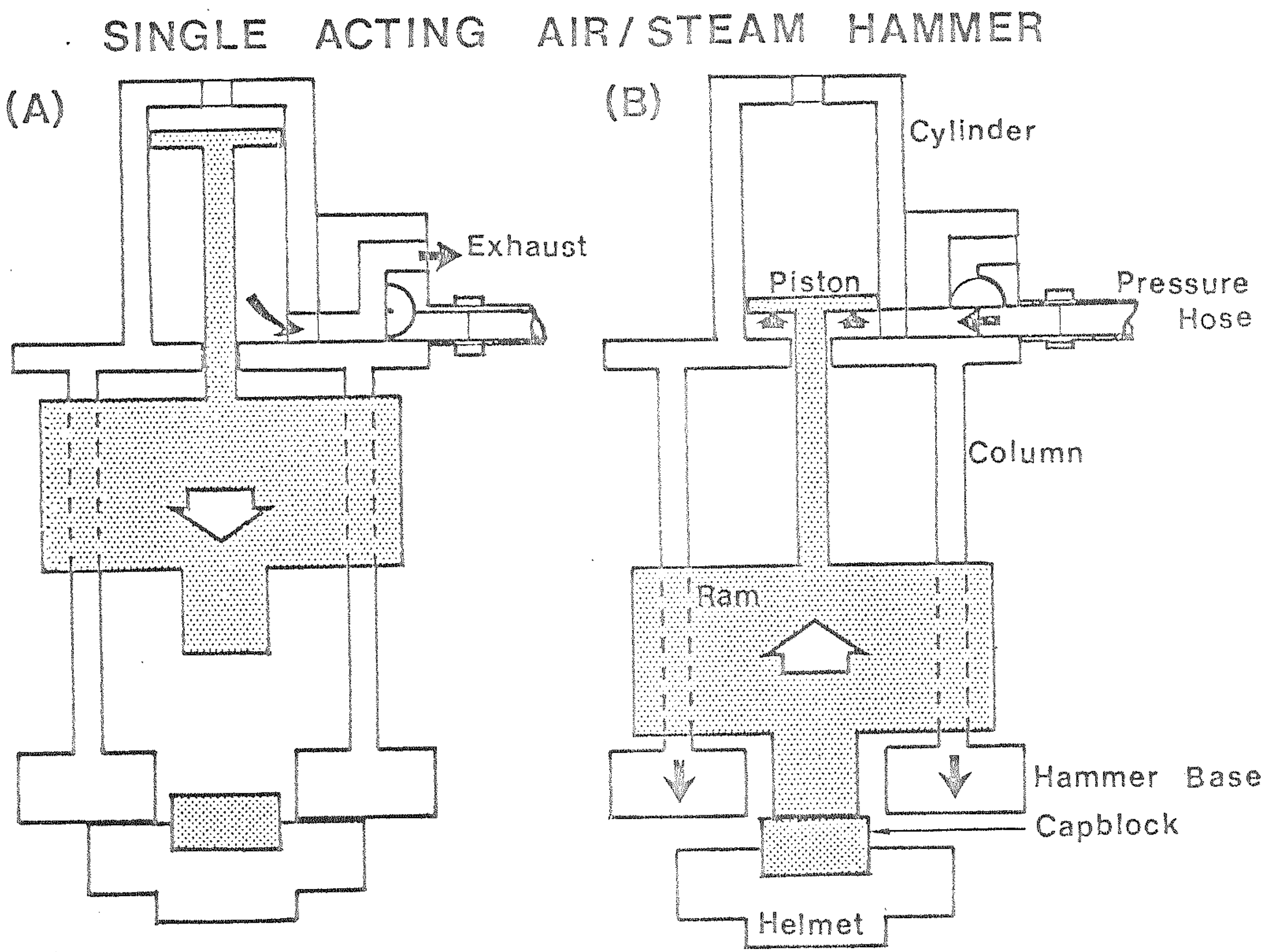


FIGURE 1: SIMPLE ACTING AIR/STEAM HAMMER
(A) DURING FALL (B) AFTER IMPACT

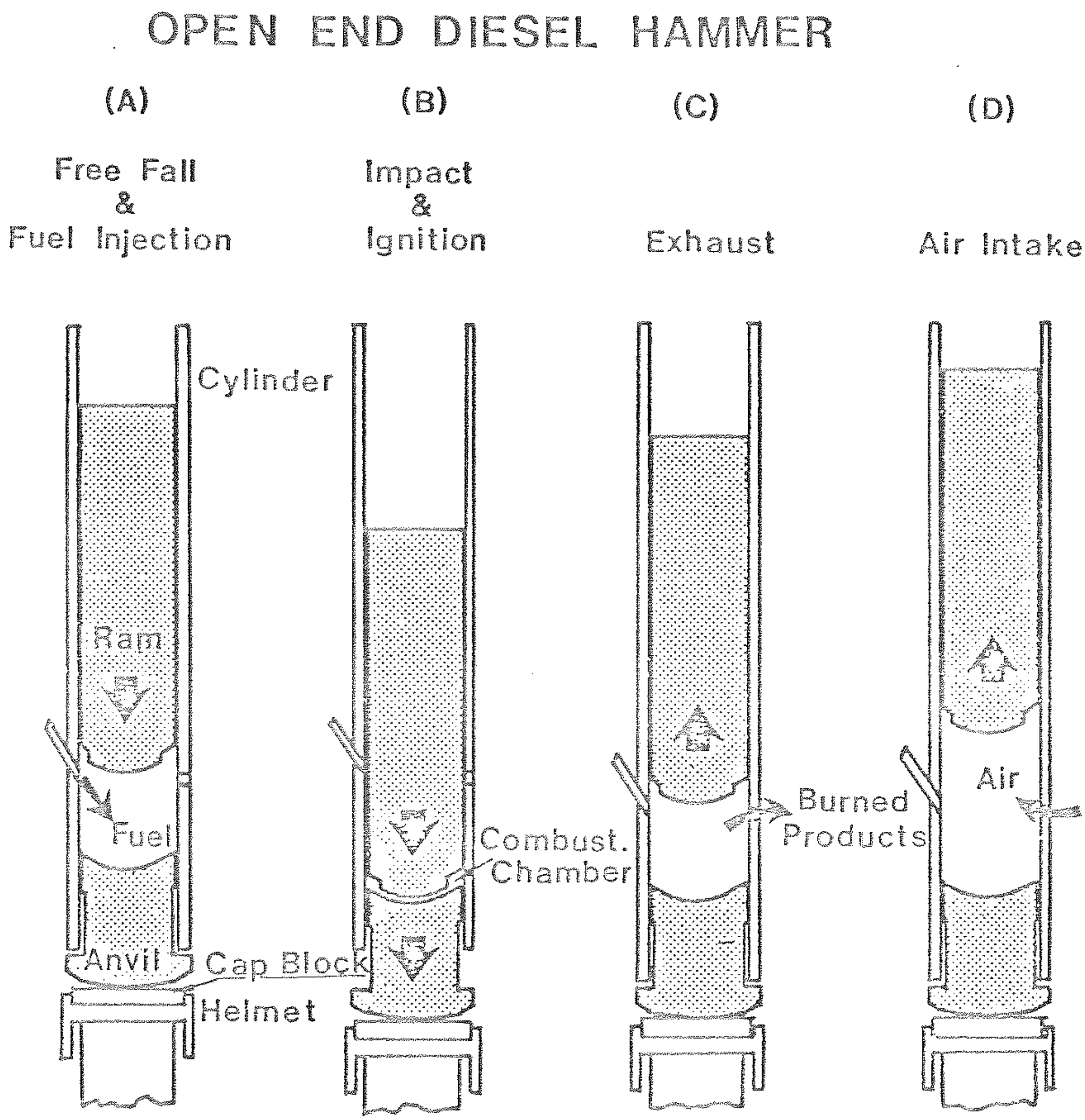


FIGURE 2: WORKING PRINCIPLE OF THE OPEN END DIESEL HAMMER

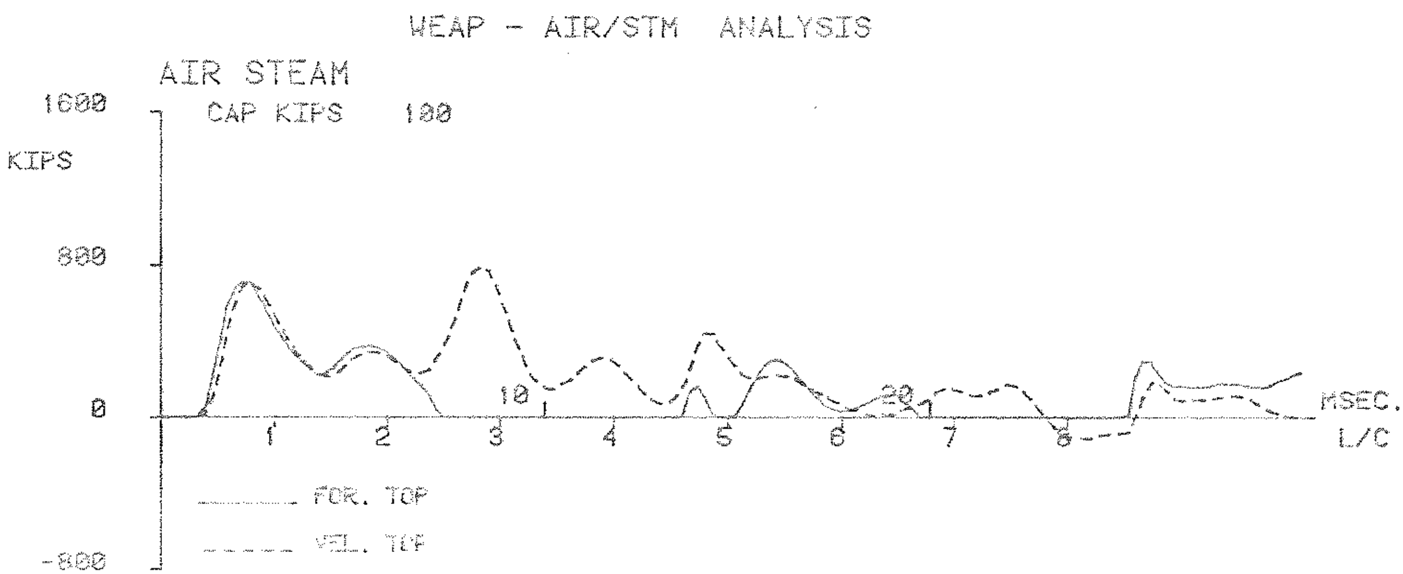


Figure 3 (A): Pile Top Force and Proportional Velocity from Air/Steam Analysis with Vulcan 010 and R_u = 100 k

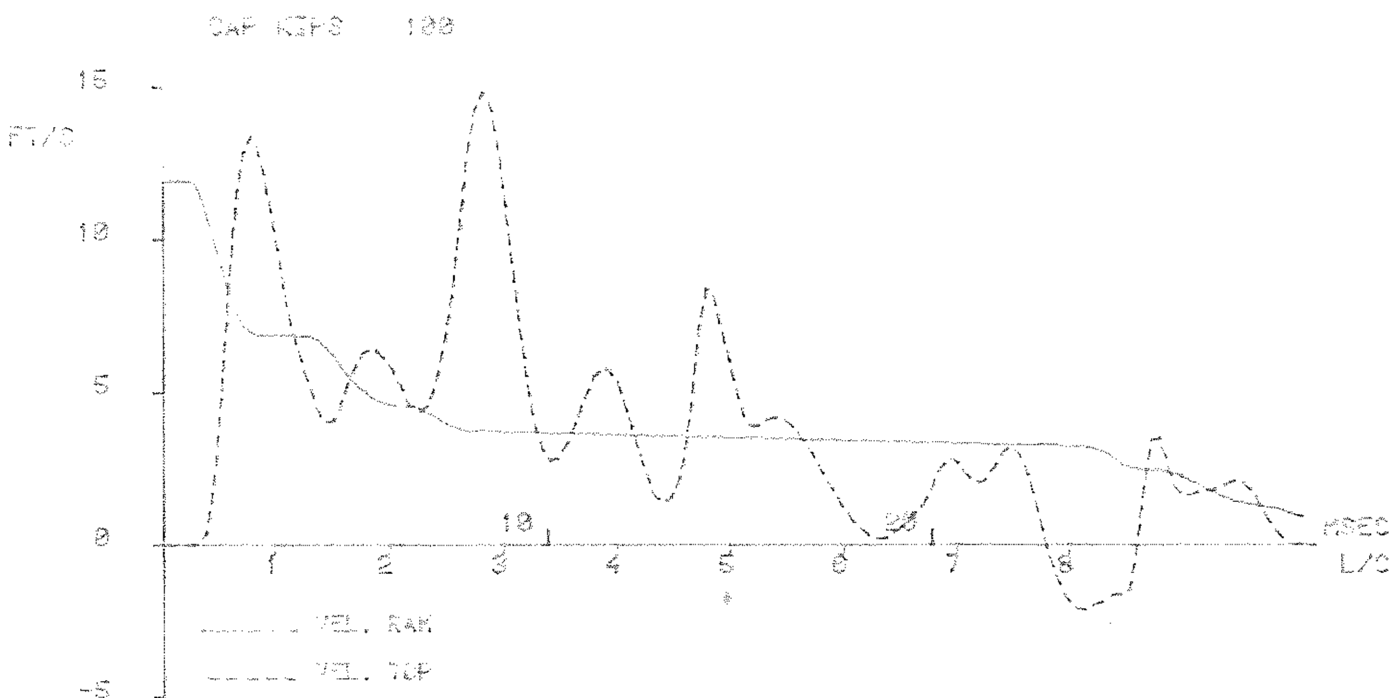


Figure 3 (B): Ram Velocity and Pile Top Velocity as Function of Time

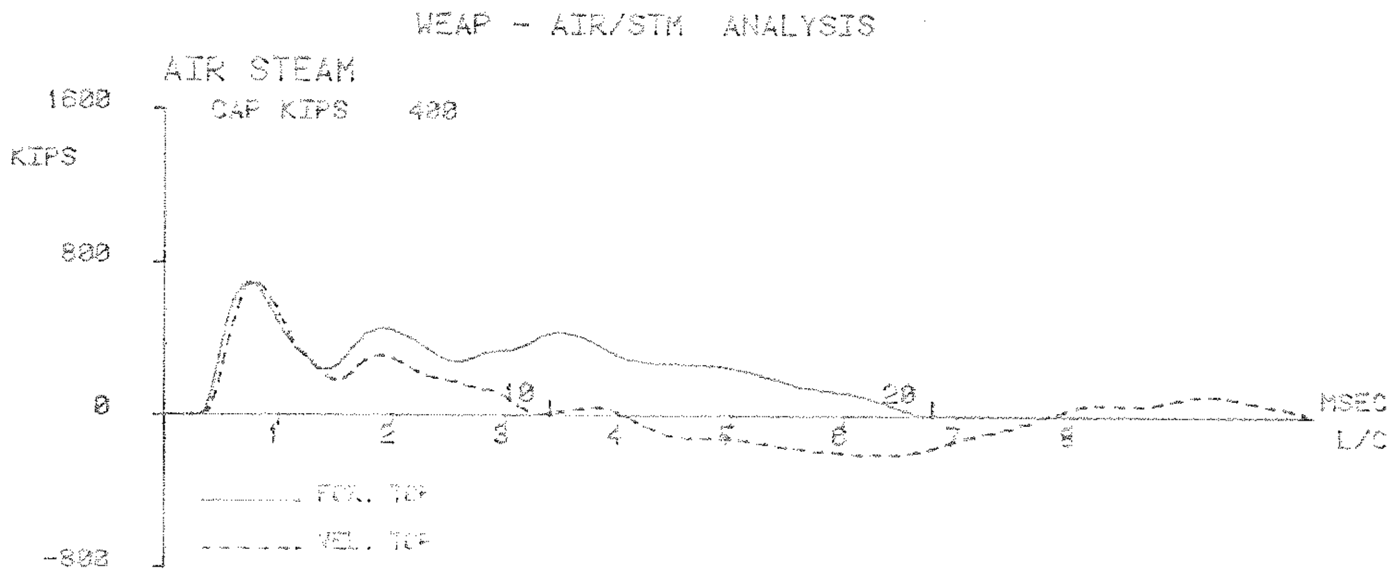


Figure 4 (A): Pile Top Force and Proportional Velocity for Air/Steam Analysis with Vulcan 010 and R_u = 400 k

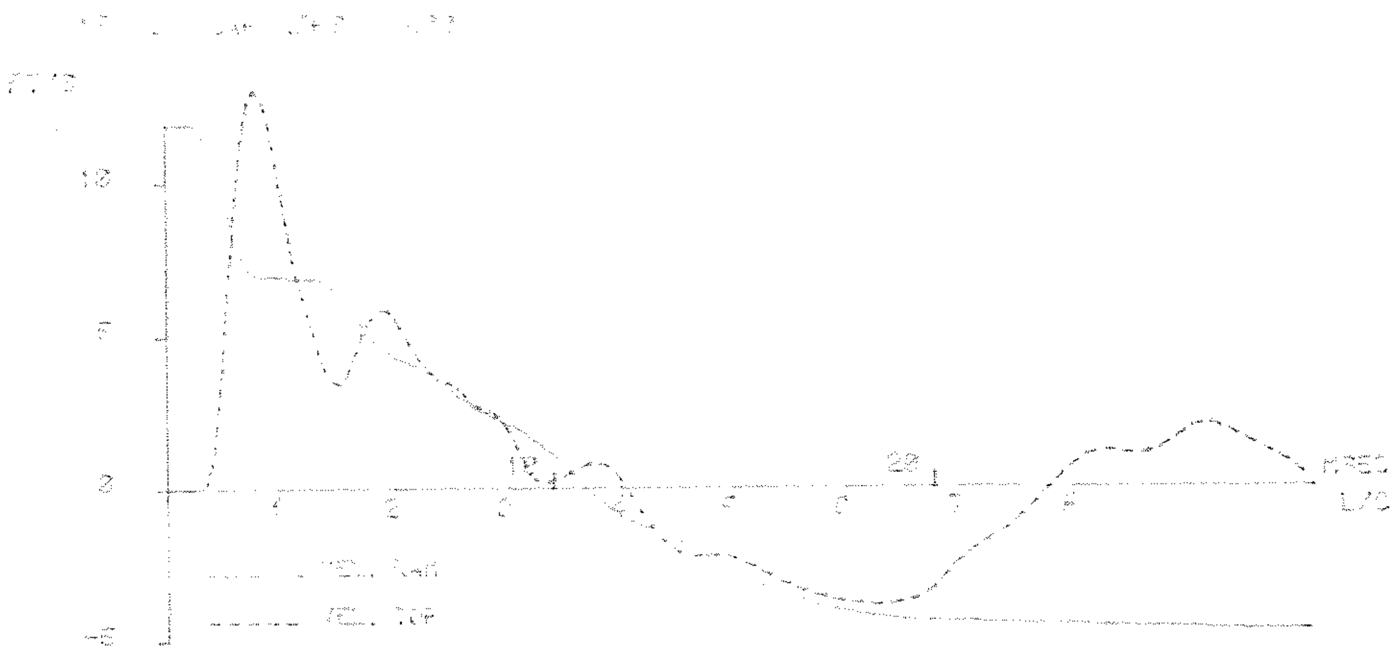


Figure 4 (B): Ram Velocity and Pile Top Velocity as Function of Time

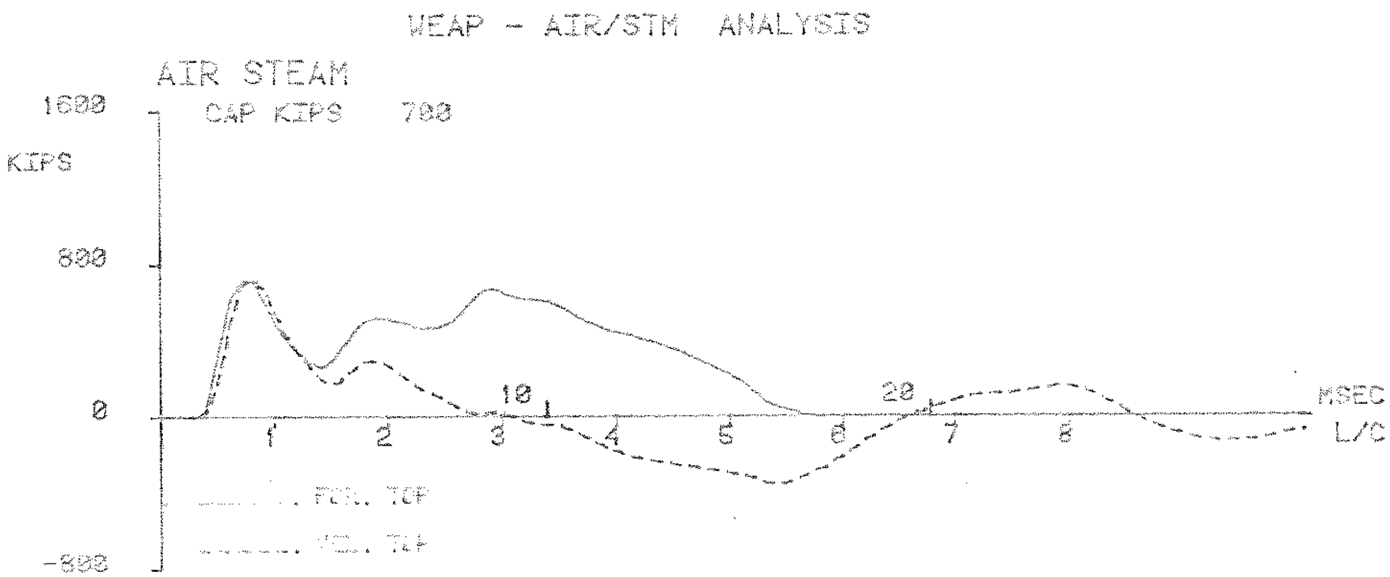


Figure 5 (A): Pile Top Force and Proportional Velocity for Air/Steam Analysis with Vulcan 010 and R_u = 700 k

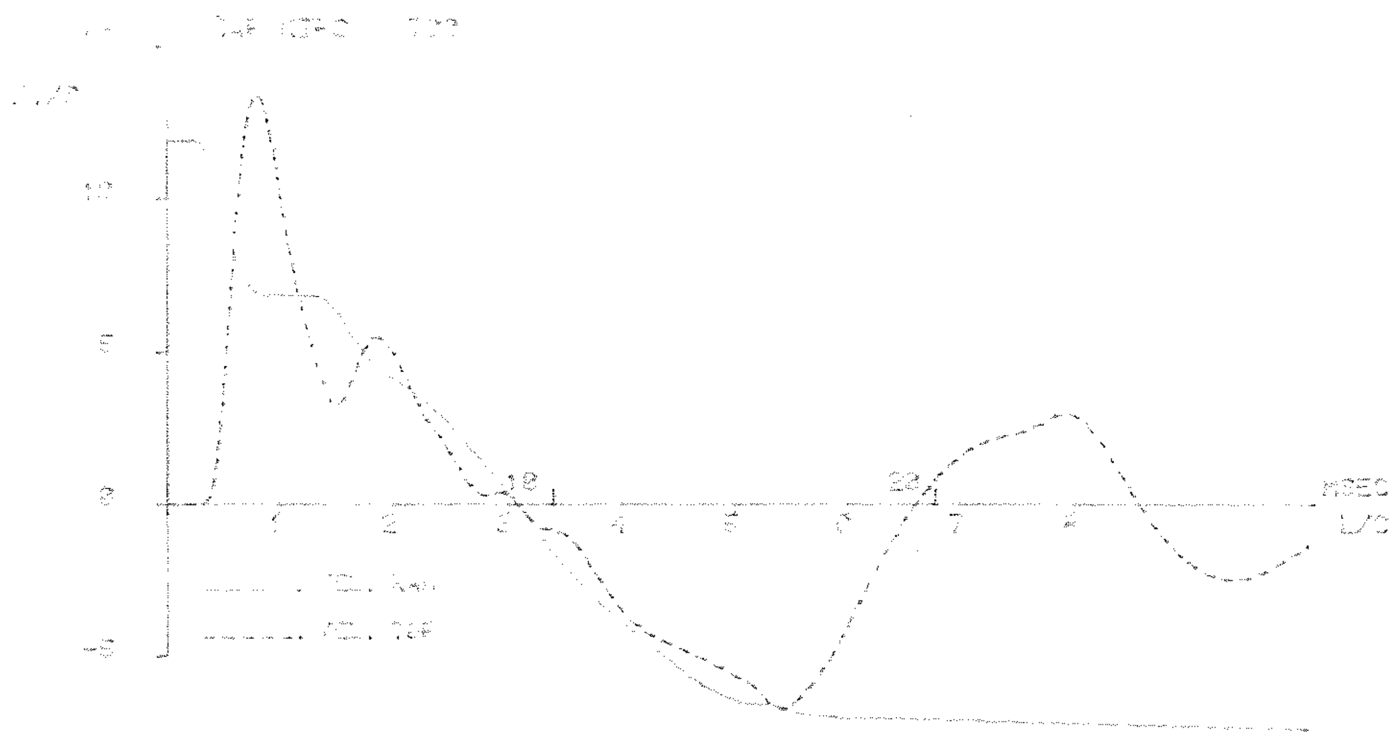


Figure 5 (B): Ram Velocity and Pile Top Velocity as Function of Time

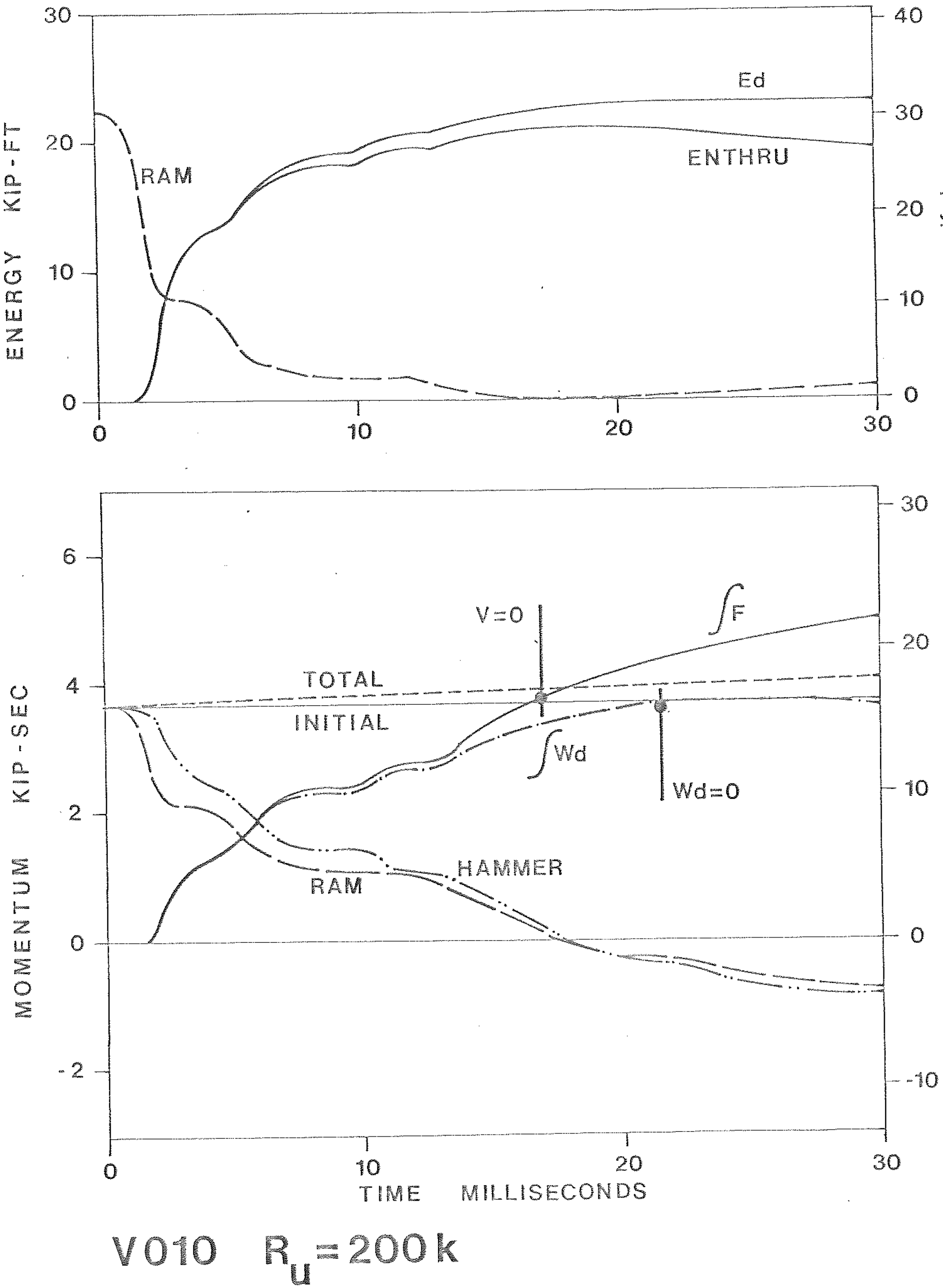
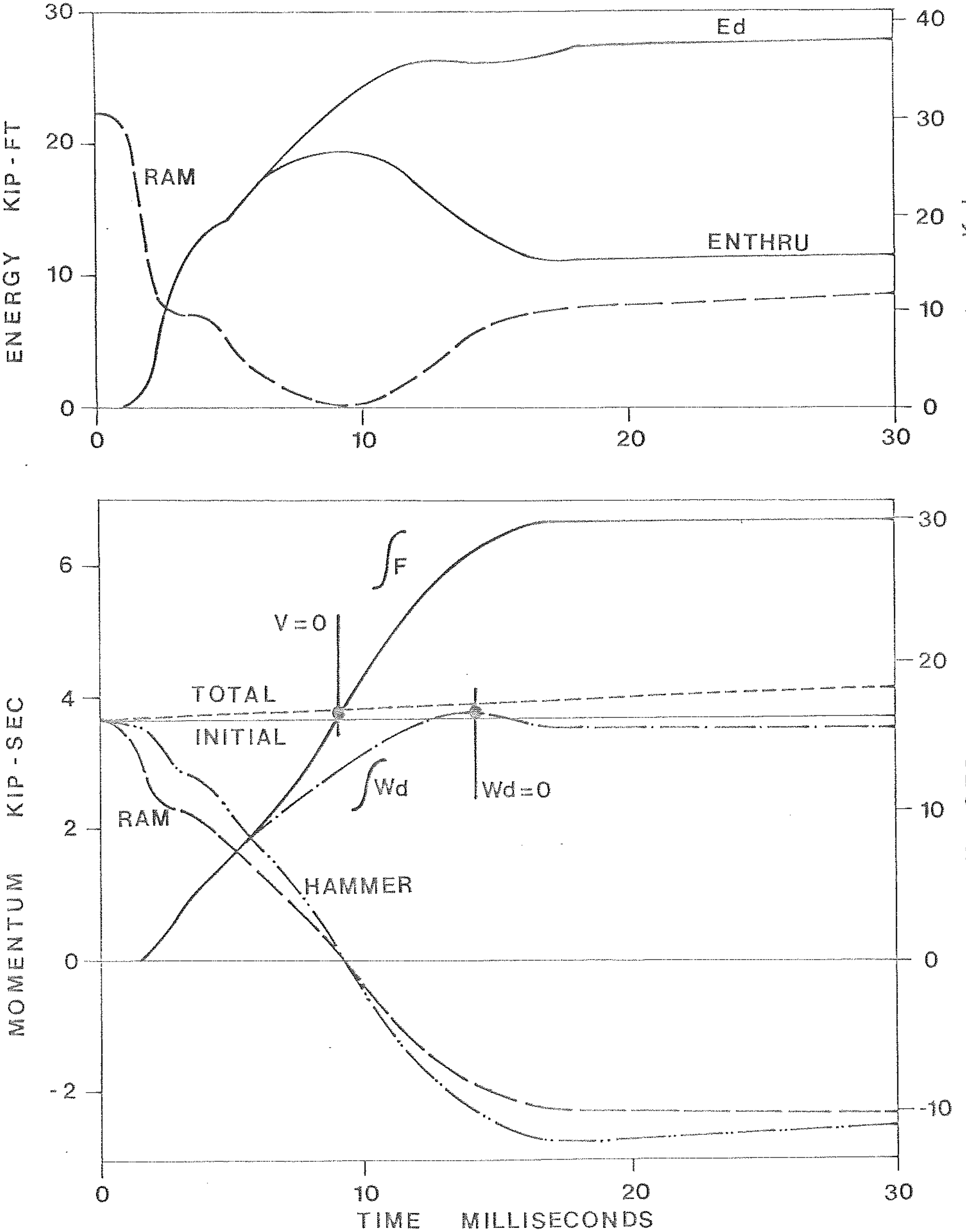


Figure 6: Energy and Momentum Transfer with Time for Air/Steam Analysis



V010 R_u=700k

Figure 7: Energy and Momentum Transfer with Time for Air/Steam Analysis

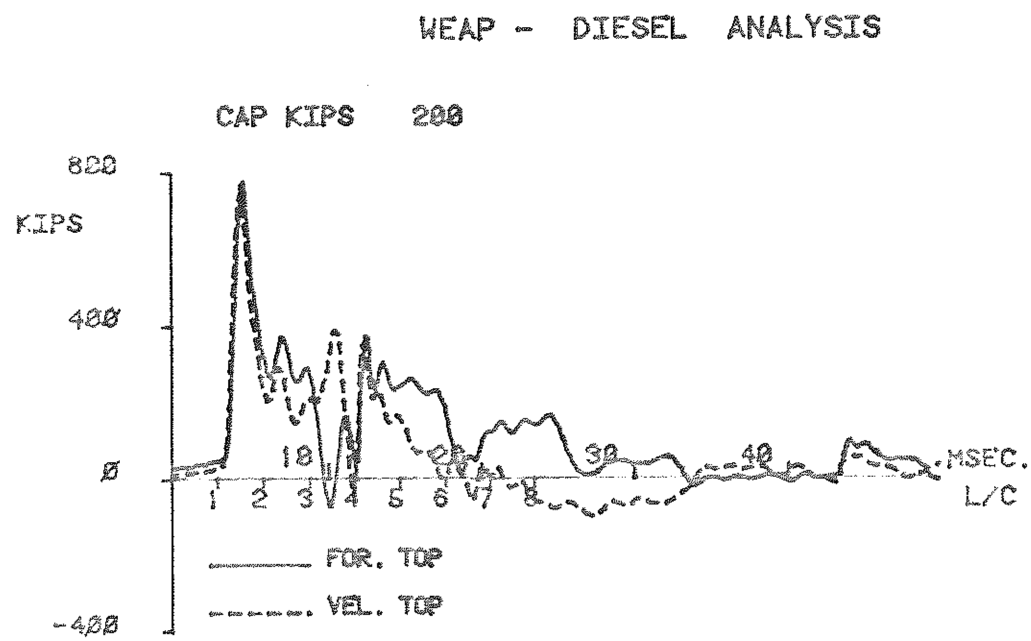


Figure 8 (A): Pile Top Force and Proportional Velocity for Diesel Analysis with Vulcan 010 and R_u = 200 k

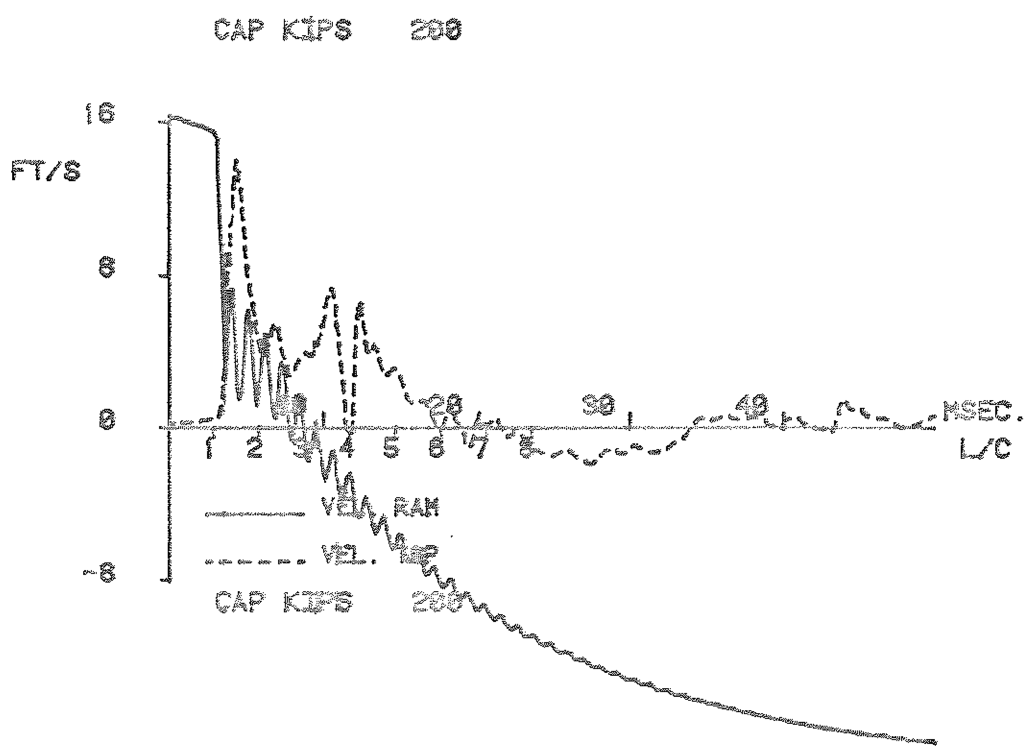


Figure 8 (B): Ram Velocity and Pile Top Velocity as Function of Time

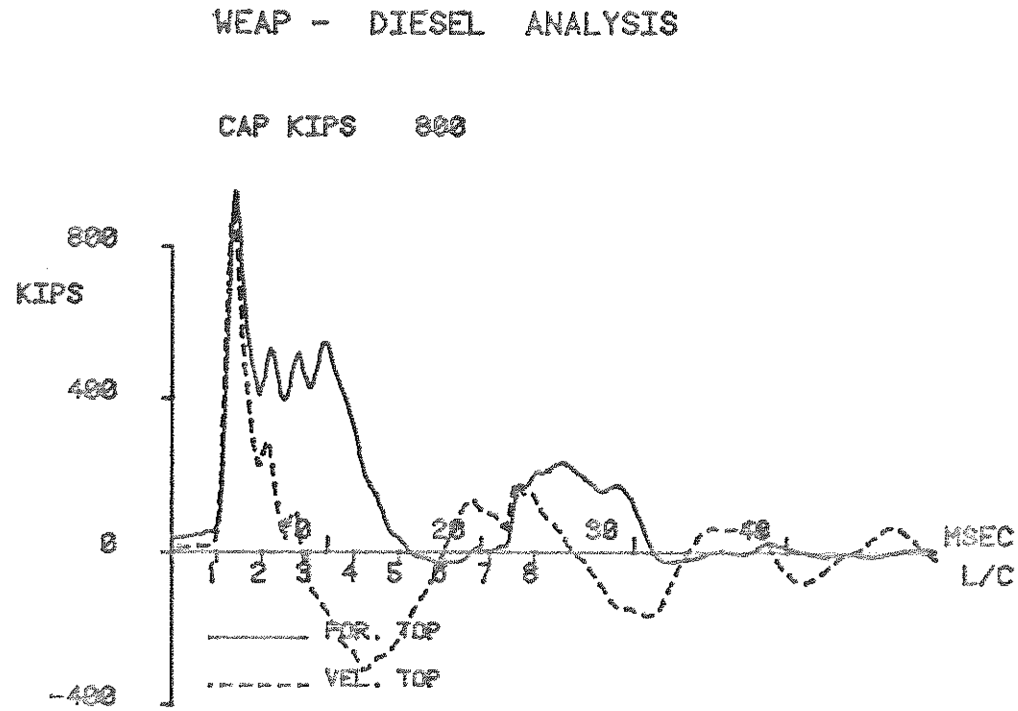


Figure 9 (A): Pile Top Force and Proportional Velocity for Diesel Analysis with Vulcan 010 and R_u = 800 k

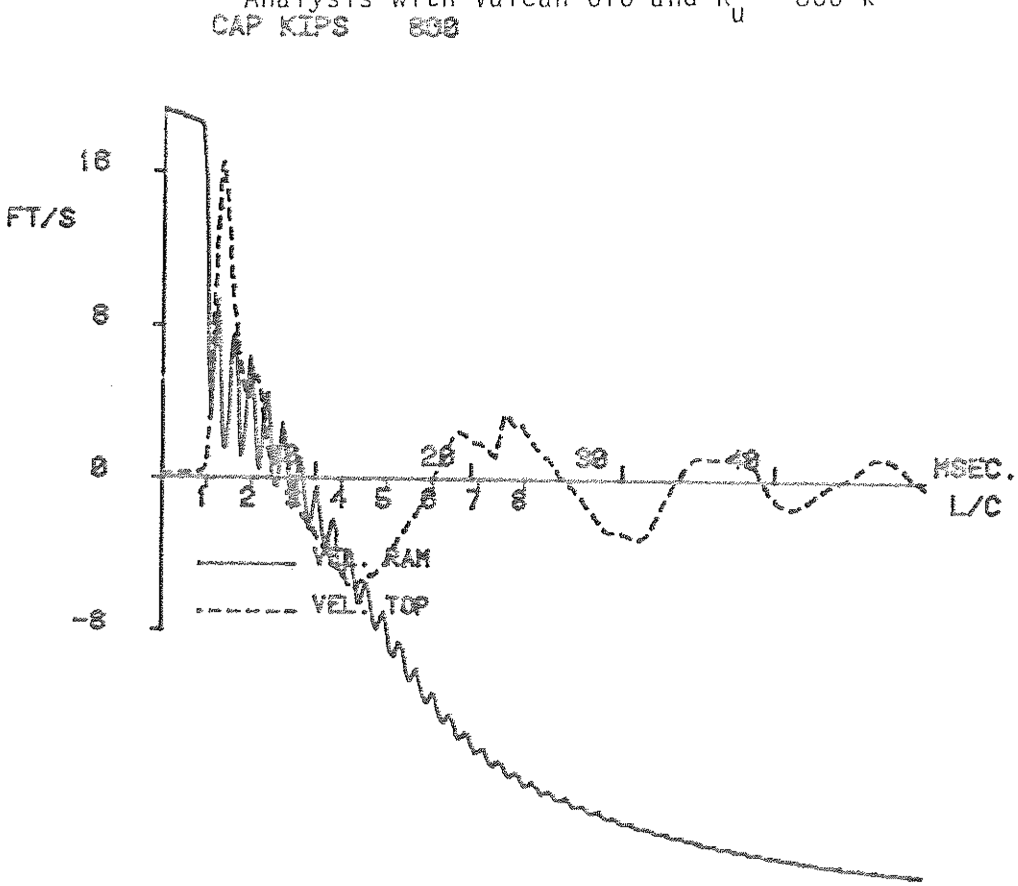


Figure 9 (B): Ram Velocity and Pile Top Velocity as Function of Time

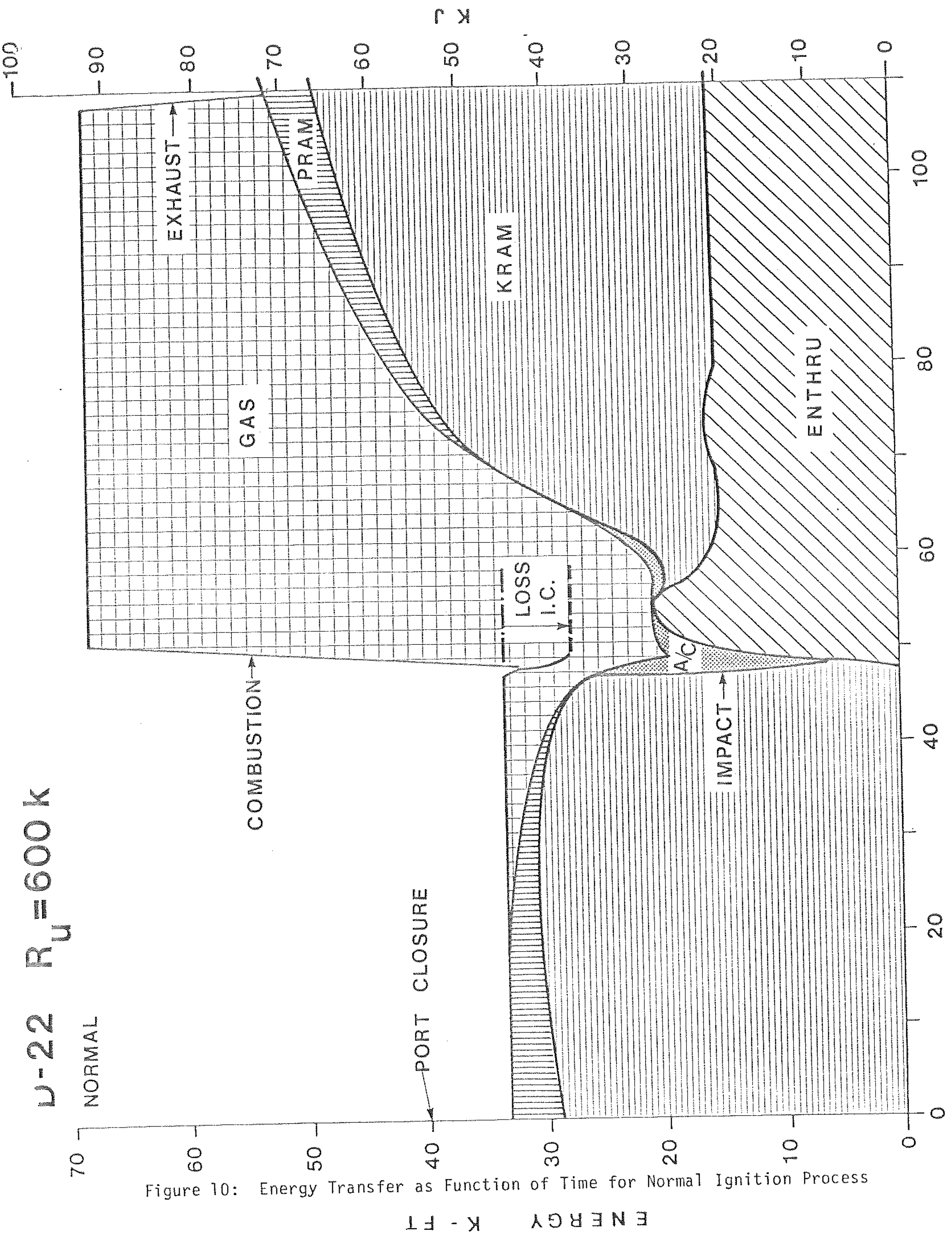


Figure 10: Energy Transfer as Function of Time for Normal Ignition Process

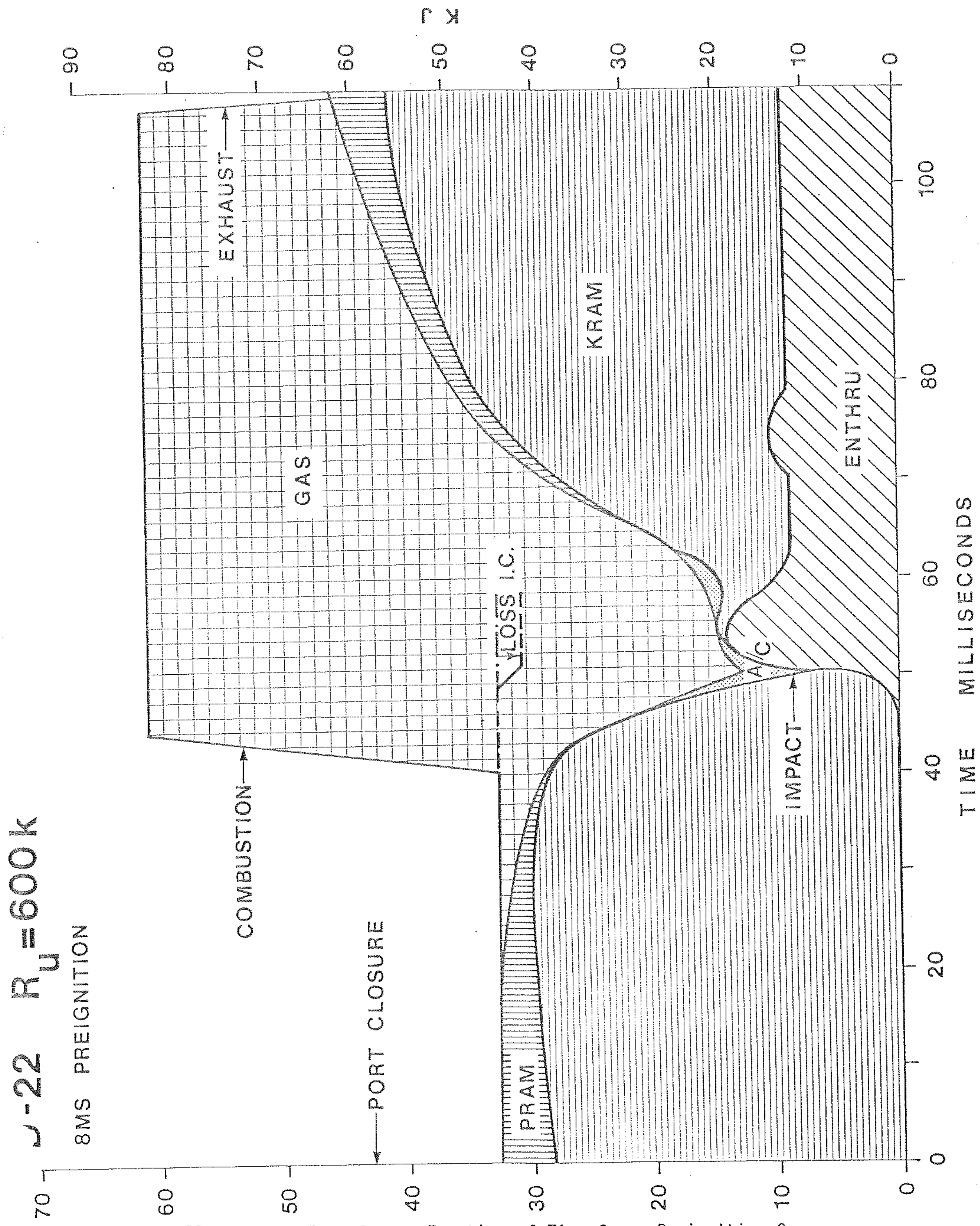


Figure 11: Energy Transfer as Function of Time for a Preignition Case

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