DEC 3 1962

UCRL 6919

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ONE-DIMENSIONAL HYDRODYNAMIC FLOW:
KO CODE

Livermore, California

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Lawrence Radiation Laboratory
Livermore, California

Contract No. W-7405-eng-48

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HYDRODYNAMIC FLOW: KO CODE

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PART I. GENERAL DISCUSSION

INTRODUCTION

For a number of years the Lawrence Radiation Laboratory has solved 1-D shock hydrodynamic problems using the artificial viscosity method ("Q" method) of von Neumann and Richtmyer.^{1,2} The equations have been organized into a program where a wide variety of problems can be solved without requiring an experienced programmer.* The program requires an IBM 7090 with a 32-K memory and the following input-output devices:

1. Two channels A and B for input and output tapes.
2. A card reader that reads columns 1 to 72.
3. An on-line printer that prints 120 columns.
4. A BCD off-line printer to process the output tape.

Since the difference equations are essentially those described in the references they will not be discussed. The program will solve shock, detonation, and spall problems for 1-D linear, cylindrical, or spherical flow. In addition, there is an option to calculate the flow through an arbitrary cross section (Flume option). The time step is automatically calculated to insure stability in the shock region and in the flow behind the shock region. All of the problem input, including material properties, boundary conditions, edit times, etc., is entered from an input sheet. Any number of problems may be set up at a time and the program will automatically solve them in sequence.

*A card deck may be obtained by writing to Mark Wilkins, Bldg. 162, Lawrence Radiation Laboratory, P. O. Box 808, Livermore, California.

¹Von Neumann and Richtmyer, "A Method for the Numerical Calculations of Hydrodynamical Shocks," J. Appl. Phys. 21 page (1950).

²R. D. Richtmyer, Difference Method for Initial Value Problems, (Interscience Publishers Inc., New York, 1957).

I. INPUT

A. Zoning

The fluid is divided into regions where the equation of state is constant and the regions in turn are divided into mass zones. There may also be voids between any two regions. A total of 25 regions and 298 mass zones are provided. One of the requirements of the "Q" method is that sufficient zones be used. The "Q" occupies 3 to 4 zones, usually a region should have 2 to 3 times this number of zones. If the problem has sharp gradients or if high space definition of a parameter is required, a larger number of zones will be needed. Energy and momentum will be conserved by the equations of motion independent of any reasonable zoning, however, the actual value of a parameter at a specific point can be in error if insufficient zones are used. For a shock crossing two zones where the mass changes, as happens at material interfaces, an error can result because the equations will not be centered in mass at this point. Actually, it is not the mass mismatch that is the real source of error, but rather it is the change in zone thickness which effects the "Q" such that an error is introduced. Usually, this error is localized at one or two zones at the point of mismatch. The pressure will probably be correct, but the internal energy and compression of a zone can be in error. A similar difficulty arises when a shock reaches a free surface. The equations can be improved to treat these contact discontinuities in a more elegant way, however, it has been our experience that the results never warranted the extra complication. The inference is that in Lagrange coordinates this type of error is localized and does not effect the overall problem.

When a problem is started with a moving piston suddenly applied at a boundary, or when a high explosive is ignited from a boundary, the "Q" must build up to form the shock or detonation front. It will be necessary for the "Q" to travel several times its own zonal thickness before the correct state of the fluid will be reached.

The 298 zones available in this program are more than enough to do most problems. To allow for higher zone density in some parts of the problem, but not have a sudden transition in zone thickness, a geometrical progression zone generator is provided. Also, a problem may be automatically rezoned at a specific position in the calculation.

B. Equations of State

The equations of state used are in the form:

$$P = a_0 + a_1\mu + a_2\mu^2 + a_3\mu^3 + (b_0 + b_1\mu + b_2\mu^2 + b_3\mu^3)E \quad (1)$$

$$P = (\gamma - 1)(1 + \mu)E \quad (2)$$

where

E = internal energy

$\mu = \rho/\rho_0 - 1$ (here ρ_0 is the reference density and ρ the actual density)

$a, b, \dots$, and γ are constants.

The equations numbered 10 through 20 have the form (1) above and the equations numbered 21 through 25 have the form (2). The constants are entered in the appropriate locations on the input sheet as well as the initial relative volume, $V^0 = \rho_0/\rho$ and the initial energy E^0 . The high-explosive equations of state are numbered 1 through 5 for form (1) and 6 through 9 for form (2). For H. E. that is to be detonated, the chemical energy E^0 and the quantity $\beta = 1/1 - V_{CJ}$ (V_{CJ} = Chapman-Jouguet volume relative to the initial volume) must be entered.

The equations numbered 10 through 20 are considered to be metals and have the built-in logic that for $\mu < 0$ the term μ^2 is omitted. Also, there is a preset minimum value of pressure $P_{min} = -0.030$ mb. This value can be changed on the input sheet.

If the pressure in zones on each side of a regional interface J are each less than 0 and if the sum of these pressures is less than $P_S = -0.002$, then the interface will split into two free surfaces with one free surface keeping the same Lagrange coordinate J and the other labeled V . This allows two materials to come apart. The preset value $P_S = -0.002$ is used instead of $P_S = 0$ to prevent numerical difficulties of voids opening and closing (this routine can also operate on a test on volume instead of pressure). To calculate spall, the material is divided into several regions with the same equation of state and P_S set equal to the spall tension for the material (a slight change in the internal logic will provide for spalling between all 298 zones, but for practical considerations the spall is allowed only at a regional interface giving a total of 25 spalls possible).

C. Boundary Conditions

In plane geometry a fixed boundary, where the fluid velocity is always zero, may be applied anywhere in the grid. For cylinders and spheres it will automatically be at the point of symmetry. For any geometry a pressure profile or a fixed velocity may be applied at either end of the fluid. Unless stated otherwise, the ends of the fluid will be treated as free surfaces.

D. Initial Conditions

Initial values for velocity, relative volume, pressure, and internal energy may be given to any zone.

E. Edits

Printouts may be obtained at any desired frequency starting from a given time or from a time when a specified boundary arrives at a certain point. Several combinations of the above are provided on the input sheet. Also interface edits may be called for instead of a full edit of all of the zone parameters.

F. Stability

The initial time step to begin a problem is 10^{-4} μ sec; this will build up to the maximum value for stability. The maximum time step is the time required for a sound signal to traverse $2/3$ of a zone. When a void is closing, the program will calculate the exact time step to close the void and then set the time step to 10^{-4} as though a new problem were being calculated.

G. Options

The program is arranged such that the calculations start from the maximum Lagrange coordinate and proceed to the first Lagrange coordinate. If three consecutive zones are found to have zero velocity, the program will end this cycle and start the next. To defeat this activity test, the word "sweep" is entered in the appropriate location on the input sheet.

Each time step the change in energy, $E - E^0/E^0$, is calculated where E is the total energy of the cycle and E^0 is the initial total energy. If the energy change becomes larger than 10%, the program will stop and print out

"energy check." For some types of problems this stop must be taken out and is done by entering BPE (by-pass-energy) on the input sheet.

Two forms of "Q" are available:

1. $Q = C_0^2 \frac{\rho_0}{V} \left(\frac{\partial U}{\partial X} \right)^2 (\Delta X)^2$ (Quadratic Q) $C_0 = \text{constant}$
2. $Q = \frac{1}{4} C_0 \frac{\rho_0}{V} a \left(\frac{\partial U}{\partial X} \right) (\Delta X)$ (Linear Q) $a = \text{sound speed.}$

The value of $C_0 = 2$ is built into the code, but it may be changed on the input sheet.

The Flume option requires additional input (the cross-sectional area as a function of distance) to be entered on the input sheet.

Typical detonation and shock calculations are shown in Figs. 1-3.

Part II. INSTRUCTIONS FOR KO INPUT

1. Starting with L\$ on the top left corner of the input sheet, in column 8 enter 1, 2, or 3 for linear, cylindrical, or spherical geometry, respectively. The remaining columns on this line are for the problem identification, date, and options.

Problem number: Locations 8 through 18

Date: Locations 25 through 30

BPE: Locations 37 through 42

If any entry is made in these locations, the 10% error stop will be bypassed.

Sweep: Locations 43 through 48. An entry in these locations will instruct the program to calculate all of the zones regardless of activity.

Ignite: Locations 49 through 54. An entry here will set the outside boundary of H. E. equal to -0.2 and start the H. E. detonation calculation.

R-input: Locations 55 through 60. An entry in these locations instructs the program that an input by zone is to follow.

Wall: The word "out" entered in locations 61 through 63 will place a fixed boundary at the Lagrange point initially at the largest (outside) X position. The word "in" entered in locations 64 and 65 will place a fixed boundary

Fig. 1. Plot of pressure vs distance for a high explosive after the detonation has proceeded 11 μ sec.

schematic at
t=0

H. E.

← detonate

Fig. 3. Plot of pressure vs distance for an aluminum plate that has collided with a magnesium plate.

schematic at
time of impact

at the Lagrange point situated at the smallest X (inside) position.

Profile: Locations 67 through 69. An entry here instructs the program that a pressure profile is to be applied to the boundary located at the largest (outside) X position. Locations 70 and 71. An entry here will place a pressure profile at boundary of the lowest (inside) X position. [See also (8) below.]

2. The line starting with L40D is for the number designating the equation of state to be used. The equations of state are listed from the largest X value to the smallest X value in the problem. Each equation of state number must be preceded by "D.". If there is a void between two equations of state, enter "0" for the equation of state number.
3. The line starting with L40A is for the number of zones in each region listed in the same order as the equations of state. Each entry is preceded by "A." If there is a void, enter 0 for the number of zones.
4. The line starting with L80 is for initial positions of equation of state boundaries. For cylindrical (2KO) or spherical (3KO) problems, the entry must be preceded by a plus sign, + . For linear (1KO) or Flume problems (4KO) the entries may be preceded by either a plus sign + and/or a minus sign - . The entries are listed in the same order as (2) above.
5. Lines L030 through L047 are to be used for the KO edits.

Example 1.

Print-out every 2 μ sec until region 3 reaches 2.05 cm, then every 0.01 μ sec for 2 μ sec, then every 0.05 μ sec for 1 μ sec.

L030 + 2 A03 + 2.05

L034 + 0.01 + 2 + 0.05 + 1

Example 2.

Print-out every 5 μ sec for 20 μ sec, then every 1 μ sec for 5 μ sec, then every 2 μ sec for 10 μ sec; at t = 35 μ sec edit every 0.01 μ sec for 1 μ sec, then every 0.1 μ sec for 10 μ sec.

L030 + 5 A0 + 0 + 20

L034 + 1 + 5 + 2 + 10

L040 A100 A0 + 0 + 35

L044 + 0.01 + 0.1 + 0.1 + 10

NOTE: A region is defined as any portion of the fluid that has the same equation of state. A particular region is designated by its right-hand boundary. Regions are counted from right to left.

6. The line starting with L120 is for the $(\rho)^0$, E^0 , and V^0 for the equation of state used.
7. The line starting with L01025 is for a velocity input by zone which must be listed starting from the largest (outside) X position.
8. The line starting with L0774 is for the pressure profile equation.

$$(a) P = P^0 + C(X)^a \text{ or } (b) P = P^0 + C(t)^a$$

P^0 , C , and a are input constants. The pressure profile is applied to either the outside or inside boundary of the fluid (see 1 above). Form (a) of the pressure profile is selected by placing "-" in front of the number 1 under the box labeled X or t. Form (b) is selected by placing "+" in front of the number 1 (X is the outside or inside boundary at any time, t is the time).

If a profile has been selected for an outside boundary, it will begin at $t = 0$ and stop at a specified time (test t) or when the boundary has reached a specified position (test X). If the profile is for an inside boundary, it will start at a specified time (test t) or a specified position (test X) and continue to act until the end of the problem.

Example 1.

To apply the pressure profile: $P = 6.2210^{-3} - 1.244 \cdot 10^{-4} t^2$ for a period of 50 μsec :

L0774 + 0.00622 - 0.001244 IO 2 + 1 + 50

(The number -0.0001244 may also be written -0.1244E-3)

Example 2.

To apply the inside pressure profile $P = +0.4 + 0.006X^{-3}$ starting when $X = 9$:

L0774 + 0.4 + 0.006 IO - 3 - 1 + 0 + 0.9

SUPPLEMENTARY INPUT

Octal Location:

L0633 Linear "Q." An entry in this location will replace the quadratic "Q" by the linear "Q."

- L0634 Geometric Zoning. If a region is to be zoned where one end has a zone thickness $\Delta X = a$ and the other end is to have a zone thickness $\Delta X = l$,
- L0665 where a and l are the first and last terms in a geometric progression, put the value of ΔX that is to be at the lower boundary of the fluid in L0634. The ΔX for the upper boundary is placed in L0665. All regions with normal zoning and voids must have plus zero (+0) entered starting from the outside region. Also, in the number of zone column, the regions with geometric zoning must have zeros entered. (See sample input problem 3K0176.)
- L0716 To place a fixed boundary at a position X , enter the value of X in this location.
- L0717 Rezone Routine. The number of zones in any region can be
- L0720 doubled at a specified point in the calculation. The letter "D" is
- L0732 placed after L0717 followed by the region number that is to be the sentinel to rezone the problem. When the above region reaches a specified ratio of its present position to its initial position, the regions listed in L0732 will be rezoned. The ratio is entered in L0720 and up to 10 successive ratios may be entered. Ten different regions to be rezoned can be listed in L0732; each region number must be preceded by the letter "D".

Example:

Start the rezone when region I is half-way to zero, one-third, and one-fourth. Rezone regions 1, 2, and 3

L0717 D1

L0720 + 0.5 + 0.33 + 0.25

L0732 D3 D2 D1

- L01006 A limit of 6500 cycles (time steps) for any problem is included in the program. If it is desired to stop a problem after a different number of cycles have been calculated, enter the number in this location.
- L01021 Piston on the Outside Boundary. The number (+1) entered here will cause the outside velocity to remain at its initial value for the entire problem.
- L01021 H. E. Detonation. To start the H. E. detonation calculation from any zone in the H. E. region, place the zone number preceded by "D" in this location.
- Example:

L01021 D25

Also enter "sweep" on the name card (see 1 above).

- L01507 Interface Edits. To specify interface edits, enter +1 after L01507.
- L01510 If a full edit is desired for some of the regions, enter the region numbers in L01510, each preceded by the letter "D" (up to four regions).
- L01522 Time Step. To reduce the time step calculated by the program, enter the reduction factor in this location.
- Example: Reduce the calculated Δt by $3/4$. L01522 +0.75
- L02000 Flume Option. The input is the same as for KO except in column 8 of the name card. The number 4 must be entered instead of 1, 2, or 3. In addition the cross-sectional area as a function of the X coordinate must be entered on the Flume area input sheet.

CONSTANTS FOR THE EQUATION OF STATE:

- L01517 - Con 1 $P = a_0 + a_1\mu^1 + a_2\mu^2 + a_3\mu^3 + (b_0 + b_1\mu^1 + b_2\mu^2 + b_3\mu^3)E$
- L01527 - Con 2
- L01537 - Con 3
- L01547 - Con 4

L01557 - Con 5
 L01567 - Con 6 $P = (\gamma - 1)(1 + \mu) E$
 L01570 - Con 7
 L01571 - Con 8
 L01572 - Con 9
 L01573 - Con 10 $P = a_0 + a_1\mu^1 + a_2\mu^2 + a_3\mu^3 + (b_0 + b_1\mu^1 + b_2\mu^2 + b_3\mu^3) E$
 L01603 - Con 11
 L01613 - Con 12
 L01623 - Con 13
 L01633 - Con 14
 L01643 - Con 15
 L01653 - Con 16
 L01663 - Con 17
 L01673 - Con 18
 L01703 - Con 19
 L01713 - Con 20
 L01723 - Con 21 $P = (\gamma - 1)(1 + \mu) E$
 L01724 - Con 22
 L01725 - Con 23
 L01726 - Con 24
 L01727 - Con 25

The "Q" constant C_0 is entered by region number. The octal location for each region number is listed below. The value $C_0 = 2$ is already in all of these locations. To change the value, simply enter the desired value in the proper location.

Octal Location:

L04250	Region 1	L04237	Region 10
L04247	2	L04236	11
L04246	3	L04235	12
L04245	4	L04234	13
L04244	5	L04233	14
L04243	6	L04232	15
L04242	7	L04231	16
L04241	8	L04230	17
L04240	9	L04227	18

L04226	Region	19	L04222	Region	23
L04225		20	L04221		24
L04224		21	L04220		25
L04223		22			

To enter the constant, β , in the H. E. equation of state, enter the desired value in the octal location for each equation of state number.

L07254	Equation of state	1
L07253		2
L07252		3
L07251		4
L07250		5
L07247		6
L07246		7
L07245		8
L07244		9

PART III. MACHINE OPERATION

I. TAPES REQUIRED TO RUN THE "KO" PROGRAM

1. Tape No. 1A = Generator and Main Code Tape

This tape is written automatically by placing the generator and main code binary deck of cards into the 7090 card reader and pushing the load card button on the console. After the binary deck has been read into memory, it will then write on Tape No. 1A, and print "Tape 1A Made" on the on-line printer. The tape will then automatically rewind. More than one Tape 1A can be made by switching another tape to position 1A and pushing the start bar on the console. This can be repeated as many times as necessary.

2. Tape No. 4A = Problem Restart Tape

This tape is preset for an initial production run by placing the card labeled "9 KO sent" in the card reader and pushing the load card button on the console. A blank record of 1000 words and a one-word sentinel record will be written on Tape 4A. As production problems are run, they will write restart records on Tape 4A. The one-word sentinel "Record" will

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always be the last record on the tape. This sentinel record allows the tape 4A to be used for several production runs or until it becomes full.

3. Tape No. 9B = Time Edits Written in BCD

II. SENSE SWITCHES NEEDED TO RUN "KO"

1. S. S. No. 1 = down - consecutive cycle edits.
2. S. S. No. 2 = down - a restart record will be written on Tape 4A. The problem can then be taken off the machine or continued by pushing the start bar on the console.
3. S. S. No. 3 = down will end and rewind - unload tape 9B. If start bar is pushed, problem identification is written on next page 9B and problem continued.
4. S. S. No. 4 = down - interface edits will print on-line. If a negative number is entered by the console keys, the program will print a full edit on-line.
5. S. S. No. 5 - not used.
6. S. S. No. 6 - not used.

III. PROBLEM DECK NEEDED TO RUN "KO"

- *1. Name card.
- *2. Material number for each region.
- *3. Number of zones for each region.
- *4. Radii for each region.
- *5. Edit times.
- *6. Initial RHO - E - V input for each material.
 7. Velocity input if required by problem, starting from outside surface and continuing inward.
- *8. Equation of state constants.
 9. Pressure profile input if required.
10. Any other options or pregenerator decimal changes.
- *11. Pregenerator decimal input end card.
 - a) pregenerator binary changes.
- *12. Pregenerator binary input transition card.
 - a) Decimal input for changing the generated radii. (R-input)

- *13. R-input. Decimal input end card.
 - a) Main code binary changes.
- *14. Main code binary input transition card.
 - a) Main code decimal changes.
- *15. Main code decimal input end card.
- *16. Final end card for each problem.

There is no limit on the number of problem decks that can be put together for a single production run. The cards marked with an (*) must be in each problem deck in the order listed.

IV. INPUT - OUTPUT SEQUENCE AND GENERAL OPERATION OF KO PRODUCTION RUN

A. Input

1. Tape 1A will read into memory and rewind.
2. Problem name card will be read into memory and problem identification written on Tape 9B.
3. The cards up to and including the "pregenerator binary input transition card" will be read into memory.
4. Tape 4A will be positioned at the beginning of the one-word sentinel record.
5. First part of the generator will be completed.
6. The cards, if any, up to and including the "R-input decimal input end card" will be read into memory.
7. The final part of the generator will be completed.
8. The cards up to and including the "final end card for each problem" will be read into memory.

The input has now been read and generated and the problem calculations have started.

B. Output

1. Problem name and regional masses printed on-line.
2. A full off-line edit on Tape 9B and a single line, (cycle, time, time step, energy change, total energy, pressure profile) will be printed on the on-line printer at the end of the generator.

3. Step 2 will be repeated as specified by the KO edit times included in the problem input.
4. A restart record will be written every 1000 cycles during the running of a problem.
5. When a problem is completed (final edit time is reached), or cycle limit is exceeded, (to insure against a problem runaway, a cycle limit of 6500 cycles is preset in the code), Tape 4A will be searched back until the last restart record of the previous problem is found, and then the last restart record of the running problem will be written. Either "problem finished" or "cycle limit exceeded and problem finished" will be printed on the on-line printer.

The main code will then return to IV A-1 above and start the next problem. If there are no more problems, the card reader will be selected and "all KO problems completed" will be printed on the on-line printer.

6. If sense switch 2 is used to terminate a production run, a restart record will be written on Tape 4A for the problem that is running and the machine will stop at an "HPR" instruction. The problem can now be taken off, or if the start bar on the console is pushed, the problem will continue to run if sense switch 2 is in the up position.
7. If during a problem run, an "overflow" or "energy check" develops, the problem will go back to the last restart record and run from there until three cycles before the trouble occurred and then edit cycle by cycle for four cycles. If the error still persists (indicating it is not a machine error) the main code will return to IV A-1 above and go on to the next problem.

The same sequence will be followed for any program stop if the machine is manually transferred to location (2) in the memory.

C. Restart Procedure

1. The last problem run, but not completed on a Tape 4A, can be restarted from the last restart record on the tape by placing an "operator's restart card" in the card reader and pushing the load tape button on the console.
2. If a problem that was not the last one on a Tape 4A is to be restarted, a problem restart deck can be used. This deck consists of the following cards:

- a. Name card of problem.
 - b. Old problem card.
 1. Location octal 1005 non-zero.
 2. Location octal 1004; if zero, the problem will start from its last restart record. If a cycle number is entered, the last restart record with a smaller or equal cycle will be selected to restart the problem.
 - c. Main code binary transition card.
 - d. Main code decimal input end card.
 - e. Final end card for each problem.
3. If a restart record(s) of a problem(s) is desired on another Tape 4A, the Tape 4A containing the record(s) must be hung on Tape 4B, the other Tape 4A will be on Tape 4A. Tape 1A will be hung and the following cards placed in the card reader:
- a. Binary restart record transfer deck.
 - b. Decimal input card with location octal zero, may either be zero or non-zero. If zero, all restart records of the problem will be transferred to the new Tape 4A. If non-zero, the cycle number of the restart record of the problem that is to be transferred must be entered.
 - c. Name card of problem.

A total of 24 problems to transfer can be handled at one time by placing cards (IV-C-3-b and c) after the binary restart record transfer deck and pushing the load card button on the console. All records on Tape 4B will print on the on-line printer with those being transferred so marked. If a new Tape 4A is being transferred onto, then sense switch 3 should be down. If Tape 4A already has some restart records, then no sense switches are required.

V. BINARY OR DECIMAL CHANGES FOR TAPE NO. 1A

An alter Tape 1A deck is used for this purpose. It consists of the following cards:

1. Three binary load cards.
2. Binary changes to be made.
3. Main code binary transition card.
4. Decimal changes to be made.

5. Main code decimal end card.

6. Two blank cards.

With sense switch 1 down, push the load card button on the console.

Tape 2A will be read into the memory and changes will be read from the card reader, then the contents in the memory will be written on Tape 1A. To make additional Tape 1A's, push the start bar on the console.

If no sense switches are down, Tape 1A will be read instead of Tape 2A and memory written on Tape 1A.