UCRL-ID--106104

DE91 001080

KDYNA User's Manual

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September 28, 1990

MASTER

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PRELIMINARIES

ABSTRACT

This report is a complete user's manual for KDYNA, the Earth Sciences version of DYNA2D. Because most features of DYNA2D have been retained in KDYNA much of this manual is identical to the DYNA2D user's manual.

INTRODUCTION

DYNA2D is a vectorized, explicit, two-dimensional, axisymmetric and plane strain finite element code for analyzing the large deformation dynamic and hydrodynamic response of inelastic solids. A contact-impact algorithm permits gaps and sliding with friction along material interfaces. A specialization of this algorithm can handle the case of zones of different sizes rigidly joined at a material interface with no need for transition regions. Spatial discretization is achieved with 4-node solid elements, and the equations of motions are integrated by the central difference method. An interactive rezoner eliminates the need to terminate the calculation when the mesh becomes too distorted. Instead the mesh can be rezoned during the run and the calculation continued. The command structure for the rezoner is described and illustrated with an example.

KDYNA is a version of DYNA2D specially adapted for simulating explosions in homogeneous or layered geological media. First, these simulations require modeling of the pressure cavity region where very hot gasses are expanding and heating the rock around them. Second, they require equations of state for rock in shocked states spanning solid, liquid, and gaseous phases and for rock of diverse compositions. Special material models are required to address pore collapse, cracking, frictional failure, and plastic flow of rock which remains solid at distances far from the high energy source. Shock effects in partially saturated porous media require modeling of interactions among air, water, and solid substrate. Finally, static overburden loading must be considered in modeling the response of rock buried deeply underground.

KDYNA fulfills the requirements of these simulation problems. Cavity pressure is specified for the small central region where rock is vaporized during the explosion. A "p-α" material model, which addresses the compaction of hot rock through molten and vaporized stages, utilizes a three-phase equation of state which accesses an external data base. Rock fracture is predicted with a constitutive

model which treats in continuum fashion up to three orthogonal fractures in each element and which takes into account friction along a fracture surface. A new yield model employs a unified approach to triaxial compression, triaxial extension, and torsion. An effective stress model permits separate equations of state to be used for compaction of wet (solid-water) and dry matrices. In this model the rock matrix interacts with the water only when the pores are fully saturated, and the rock shear strength is allowed to vary with saturation level. A rock overburden model defines the direction of gravity in the problem mesh and addresses water table elevation for the effective stress model.

Material models can be isolated for study using a "driver" mode, which allows the user to evaluate the constitutive and volumetric response of a single zone for a given strain path.

The Benson-Christensen-Margolin artificial viscosity model, added recently, provides sharper definition of shocks.

The rezoning capabilities of DYNA2D have been extended to permit deletion of logically connected zones along k-lines (circumferential) and l-lines (radial) so that the radial structure of the mesh is preserved. The deletion of zones when zone size limits time step size can lead to a dramatic reduction in problem running time. KDYNA also can execute periodic dezoning instructions read from a command file during production runs.

A remapping capability has also been added to allow a complete remeshing when some portion of material has to removed from the problem region because of severe mesh distortion.

HISTORY OF SOLUTION METHOD

DYNA2D [1] was developed ten years ago and has since been applied in the analysis of a large number of problems. Originally, DYNA2D had a variety of elements including nine-node Lagrange elements, constant-pressure variable-node elements with four integration points, and constant-stress quadrilaterals with single-point integration. Three solution schemes were available:

- o finite element (Galerkin)
- o finite element (Petrov-Galerkin)
- o finite difference [2].

The first scheme, which included the variable-node elements, was eliminated because the radial weighting in axisymmetry caused difficulties at the centerline in large-deformation, hydrodynamic calculations. Furthermore, variable-node elements proved to be very expensive relative to the constant-stress four-node elements, and, consequently, were seldom exercised. The finite difference scheme was eliminated because the second method gave comparable results with a smaller storage requirement.

Early in the development of DYNA2D the third author, reinforced by conversations with Goudreau [3] and experiences with the finite difference method, attempted to overcome difficulties with the Galerkin method at the axis in axisymmetric problems by weighting the discretized momentum equations by the product of the basis functions and the reciprocal of the radius, i.e., r^{-1}. The attempt worked so well that the resulting scheme remains the sole option in DYNA2D. Originally referred to as the "area Galerkin" method, since it eliminated the radial weighting, it was found by Hughes [4] to be what is correctly called the "Petrov-Galerkin" method. Although a time-dependent mass vector is obtained the penalty for it has proven to be small. The method is identical to the finite difference method [2] in plane strain, but in axisymmetric problems the method is the same only if material strength is neglected. Another method of overcoming the axis problem while preserving the radial weighting was developed by Hancock [5] for the PISCES2D-ELK code. The latter method was tested in a version of DYNA2D and discovered to be very effective on several test problems.

FEATURES OF KDYNA

SPATIAL DISCRETIZATION

Fig. 1 shows the two types of elements available in KDYNA. One element-centered stress state is stored for each element in addition to any material parameters. An hourglass viscosity is used to control the zero energy modes.

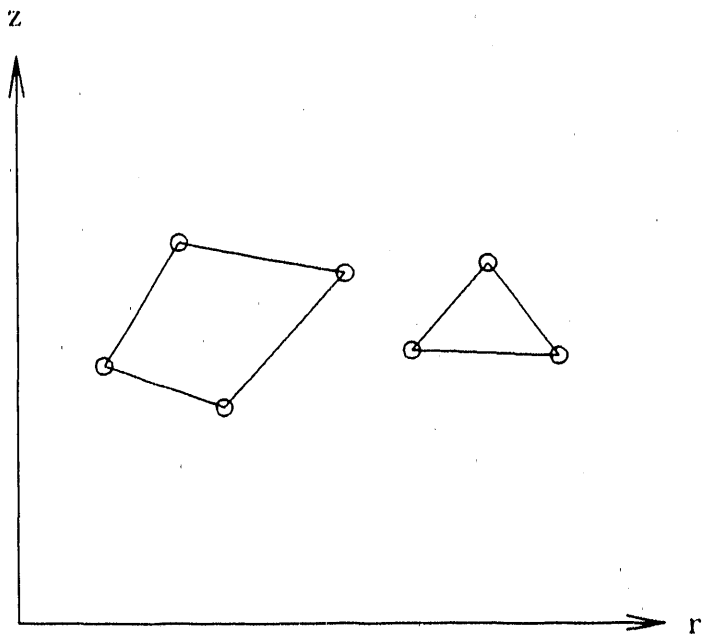

Fig. 1. Solid elements available in KDYNA.

MATERIAL MODELS

The material models presently implemented are:

1. elastic
2. orthotropic elastic
3. kinematic/isotropic plastic
4. thermo-elastic-plastic
5. soil and crushable foam
6. linear viscoelastic
7. rubber
8. high explosive burn
9. fluid
10. elastic-plastic hydrodynamic
11. temperature dependent plasticity with 3d cracking

12. Johnson/Cook plasticity
13. power law plasticity
16. pseudo TENSOR concrete/geological model
19. rock volumetric crack model
22. rock 3D crack model
23. Rubin-Attia rock failure model

Models numbered greater than 9 determine only the deviatoric stress. Pressure is determined by one of the equations of state listed below, compatibility between material models and equations of state being described in Appendix B.

1. linear polynomial
2. JWL high explosive
3. Sack "Tuesday" high explosive [10]
4. Gruneisen
5. ratio of polynomials
6. linear polynomial with energy deposition
7. ignition and growth of reaction in HE [11,12]
8. tabulated-compaction
9. tabulated
11. TENSOR pore collapse
13. TENSOR pore collapse with H-Division $p(\rho,E)$ tabular EOS
14. cavity pressure
15. H-Division $p(\rho,E)$ tabular EOS only
16. TENSOR pore collapse with cracking
17. p-α with EOS tables
18. effective stress model without gas tables
19. effective stress model with gas tables
24. Gruneisen with piecewise linear u_s-u_p curve

The soil and crushable foam, the linear viscoelastic, and the rubber subroutines were adapted from HONDO and recoded for vectorization; the ignition and growth EOS was adapted from KOVEC [13]; the other subroutines, coded by the authors, are based in part on the cited references and are nearly 100 percent vectorized. The forms of the first five equations of state are given in the KOVEC user's manual and are reproduced in this manual.

With the exception of the orthotropic elastic and the rubber material subroutines, a Jaumann stress rate formulation is used; these two use Green-St. Venant strains to compute second Piola-Kirchoff stresses, which are subsequently transformed to Cauchy stresses. The Green-Naghdi stress rate, suggested by Johnson and Bammann [14], is implemented for the elastic-plastic model with kinematic hardening. The implementation of this rate is similar to that used in NIKE2D.

KDYNA is organized to accept new material models and equations of state of any complexity. The organization permits different material and EOS types to use different amounts of storage. All history variables except the stress tensor and the effective plastic strain are packed in a one-dimensional storage vector to ensure that no space is wasted. New models can be added by the procedure outlined in the DYNA3D Theoretical Manual [15].

HE BURNS

Two burn models are presently available. One is the beta burn model used by KOVEC, and the other is the programmed burn model used by HEMP [16]. Both models permit detonations from points and lines.

ARTIFICIAL VISCOSITIES

The linear-quadratic bulk viscosity is used to smear shock fronts over several elements and to damp numerical oscillations. Three such formulations are implemented.

- standard DYNA2D
- Richards-Wilkins [17,18]
- Benson-Christensen-Margolin [36]

The first differs from the second in that the strain rate and characteristic length used in the viscosity calculation are the volumetric strain rate and minimum thickness, respectively. In the second formulation directional properties of the shock wave are considered. For most engineering problems the least expensive DYNA2D formulation is usually sufficient.

Four viscosities are available for resisting zero energy deformation modes in constant stress elements. These are

- standard DYNA2D [3]
- rotational [19,16]
- Flanagan-Belytschko [20]
- Hancock [21]

Hourglass viscosity should always be used to prevent instabilities. All four formulations work well, although one sometimes seems better than another on a problem by problem basis. The default, standard DYNA2D formulation is very inexpensive and can be recommended for most problems. Hancock's hourglass control is similar in many respects to the default formulation, but because we were unaware of his work, we failed to reference it in [3].

LOADING FUNCTIONS

A variety of loading functions may be used including

- o geometry-dependent pressure loadings
- o geometry-dependent shear loadings
- o body force loads due to spinning
- o body force loads due to base accelerations
- o concentrated nodal loads
- o follower forces
- o nodal velocity time histories

An unlimited number of time histories may be defined and may be referenced by any loading function.

SLIDELINES

Four slideline options are available:

- o sliding only [22]
- o tied [23]
- o sliding with voids (no-tension interfaces) [22]
- o sliding with voids and friction (NIKE2D penalty formulation)

All slideline types admit arbitrary zoning along interfaces, and, with the exception of the first two options, gaps may exist in the initial configuration. Slidelines are permitted to intersect. When voids close, momentum is conserved. It should be noted that the current slideline references are not up to date. For most structural problems not involving hydrodynamics, the fourth slideline option is the most reliable. Appendix A discusses precautions to be taken in using slidelines. Note that slidelines are not compatible with overburden.

REZONING

A mesh rezoner has been embedded in DYNA2D. All element and nodal variables are remapped to the new mesh defined by the user. Internal energy, kinetic energy, r-momentum, z-momentum, and mass are computed and printed for each material before and after rezoning to enable the user to determine if the rezoned mesh is acceptable.

Rezoner commands may be given in one of three ways: interactively

from the terminal, periodically from an ascii file, or aperiodically from an ascii file. For a complete description of the use of the rezoner with a simple example, see the chapter "REZONING".

CAPACITY

Presently the capacity of KDYNA is limited to betwwen 40000 and 60000 elements on the two-million-word Crays. Storage allocation is dynamic, so that the only true limit that exists on the number of boundary condition cards, number of material cards, number of pressure cards, etc. is the capacity of the computer.

PROGRAMMER INFORMATION

KDYNA consists of one ANSI FORTRAN77 source that compiles with CFT [24] on Cray computers. This version of KDYNA also compiles and executes on Vax computers with the VMS operating system and Sun and Stellar workstations with the UNIX operating system.

EXECUTION TIMES

The approximate speed of KDYNA for different computers in shown in the table below:

Machine	Time (μsec/zone-cycle)
Cray XMP	50-100
Stellar 2000	200-2000
Sun SPARC	500-5000

with variations due to complexity of material models used in the problem.

EXECUTION

KDYNA is a public file on the Cray computers at LLNL. The execute line is:

KDYNA I=*inf* O=*otf* G=*ptf* D=*dpf* T=*tpf* F=*thf* C=*cfr* P=*pmf*

where

inf = input file
otf = ascii output file
ptf = binary global plot file
dpf = restart dump file
tpf = temperature file (TOPAZ2D plotfile)
thf = binary time history plot file containing data for selected nodes and elements only
cfr = command file for periodic noninteractive rezoning
pmf = PAMPERS output file (see "driver mode", Appendix C)

Output files names must not exceed six characters because of family naming conventions. If the time history file (*thf*) is not named on the execute line, time history data is written to the ascii output file (*otf*).

For restarting from a dump the execute line is:

KDYNA R=*rtf* I=*inf* O=*otf* G=*ptf* D=*dpf*

where

rtf = restart dump file from previous run

Special execute lines for starting or restarting with the intent of rezoning or remapping are described in the chapters "REZONING" and "REMAPPING", respectively.

File name dropouts are permitted, for example

KDYNA I=*inf*
KDYNA R=*rtf*

Default names for the ascii output file, binary global plot file, and restart dump file respectively are D2HSP, D2PLOT, and D2DUMP. On Vax computers the execute line is:

RUN KDYNA

KDYNA will then prompt for the file assignment part of the execute line. When specifying file names for the Vax under VMS do not give the suffix ".DAT" as it is understood.

On UNIX machines the execute line is just:

KDYNA

KDYNA will prompt for the file assignment part of the execute line. Suffixes are not used in UNIX file names.

SENSE SWITCH CONTROLS

While KDYNA is running it can be interrupted and commanded by typing one of the following messages:

Message	Response
SW1.	Write a restart dump file and terminate KDYNA.
SW2.	Print time and cycle number and continue.
SW3.	Write a restart dump file and continue running.
SW4.	Dump global plot data for the current state and continue
SW5.	Exit solution phase and enter rezoner.
SW6.	For each cycle print time, cycle number, step size, and controlling element number to the ascii output file. Type message again to stop printing.

When KDYNA terminates, all scratch files are destroyed. The restart file, plot files, and ascii output files remain on disk. Of these only the restart dump file is needed to continue the interrupted analysis.

AUTOMATED INPUT GENERATION

Complete input files for KDYNA may be generated with MAZE [26]. MAZE input is format free and can be given interactively, with a command file, or interactively after starting with a command file. MAZE output corresponds to the input described in this manual.

POST-PROCESSING

The main post-processor for KDYNA is ORION [27], although TAURUS [28] may be used to obtain special three-dimensional plots. These programs read the binary plot files that KDYNA generates and plot contours, time histories, and deformed shapes. Contours of nearly 100 different quantities may be plotted on meshes consisting of triangular and quadrilateral elements. They can compute a variety of strain measures, momentum by material, reaction forces along constrained boundaries, and interface pressures along sliding interfaces. ORION and TAURUS are fully interactive.

STARTING INPUT DECK

1. Title Card

Columns	Quantity	Format
1-72	Heading to appear on output	12a6

2. Control Cards

Card 1

Columns	Quantity	Format
1-2	IDV flag EQ.0: no dumping, default EQ.87: dump history & peak variables (Card 3b)	i2
3-5	Number of materials, NUMMAT	i3
6-10	Number of nodal points	i5
11-15	Number of elements	i5
16-20	Number of nodal printout blocks	i5
21-25	Number of element printout blocks	i5
26-30	Number of load curves	i5
31-35	Number of concentrated nodal loads and follower forces	i5
36-45	* Time to begin periodic noninteractive rezoning, RIO1	e10.0
46-55	* Time to end periodic rezoning, RIO2 (default 1.e20)	e10.0
56-65	* Time interval between rezoning, RIOD (default 1.e20)	e10.0
66-75	Scale factor for computed time step size, SFCT (default .67)	e10.0
76-80	Brode function flag, IBRODE EQ. 1: Brode parameters are defined	i5

* Parameters in columns 36-65 apply only if an input file is defined (C=cfr on the execute line). Otherwise they are ignored.

Card 2

Columns	Quantity	Format
1-5	Number of element sides having either pressure or shear loadings applied	i5
6-10	Number of velocity boundary condition cards	i5
11-15	Base acceleration in r-direction flag (see Fig. 2) EQ.0: no r-acceleration EQ.1: r-acceleration	i5
16-20	Base acceleration in z-direction flag (see Fig. 2) EQ.0: no z-acceleration EQ.1: z-acceleration	i5
21-25	Angular velocity about z-axis flag EQ.0: no angular velocity EQ.1: angular velocity	i5
26-30	Initial condition parameter flag EQ.0: initialize velocities to zero EQ.1: read in initial velocities	i5
31-35	Number of stonewalls	i5

(continued on next page)

(Continuation of Card 2)

Columns	Quantity	Format
36-40	Number of slidelines	i5
41-45	Number of slideline intersections, NUMSLI	i5
46-50	Analysis type EQ.0: axisymmetric EQ.1: plane strain	i5
51-65	Reduction factor, RF, to determine minimum permissable time-step (<1.0). If nonzero then calculation terminates when DT ≤ RF * DTINIT where DTINIT is the initial time-step size.	e15.0
66-70	Number of nodal constraint sets	i5
71-75	Number of non-reflecting boundary definitions	i5
76	* Overburden calculation flag. May be set only for equations-of-state using overburden: 11, 13, 16, 18, and 19. (See also Gravity Definition Card 5a.) EQ. "T": TENSOR overburden, no iteration EQ. " ": no overburden calculation	a1

* Note: If overburden has not been used in the initial run it cannot be invoked later in restart runs with remapping!!!!

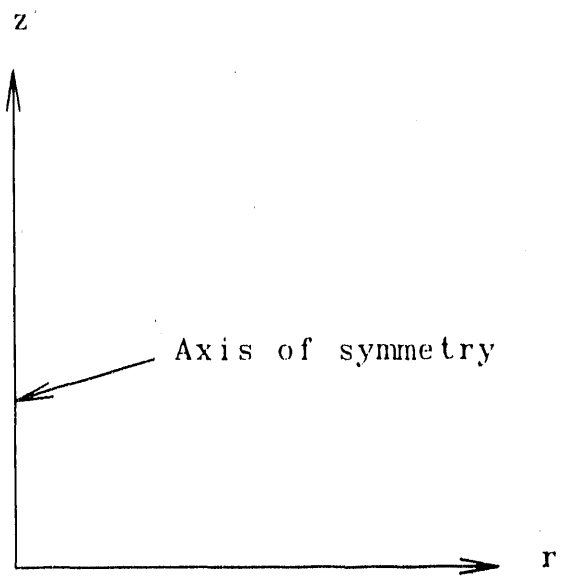

Fig. 2: Coordinate system with symmetry about z-axis.

Card 3

Columns	Quantity	Format
1-10	Termination time	e10.0
11-20	Time interval between high-speed printouts	e10.0
21-30	Time interval between dumps of plot data	e10.0
31-40	Initial time-step size. If 0, then the initial time-step is computed.	e10.0
41-45	HE burn option, IBURN EQ.0: beta burn EQ.1: programmed burn - elements that are lit at time zero are flagged in element data EQ.2: programmed burn - lighting is defined in Section 6 EQ.3: volume burn-lighting times are given on element cards	i5
46-50	Number of time steps between restart dumps EQ.0: restart dump is written only upon normal termination	i5
51-55	Thermal effects option EQ.0: no thermal effects EQ.n: temperature-time history is defined by load curve n LT.0: nodal temperatures are defined in TOPAZ2D output plot files	i5
56-60	Dump option for internal energy EQ.0: internal energy is not written into data base EQ.1: internal energy is written into data base	i5
61-65	Special dump for Chemistry Department, component 20	i5
66-70	Reset default viscosities, IRQ EQ.1: new defaults are read on Card 4	i5
71-75	Discrete element input option, INPSD EQ.0: no input EQ.1: discrete elements are defined	i5

Card 3a

(used only if IDV=87 on card 1)

Columns	Quantity	Format
1-5	IHDMP, flag to dump history variables EQ.0: do not dump EQ.1: dump	i5
6-10	IPDMP, flag to dump peak variables EQ.0: do not dump EQ.1: dump	i5
11-25	TSTART, initial time	e15.0

Card 4 (define if IRQ=1)

Columns	Quantity	Format
1-5	Hourglass control, IHQ EQ.0: default set to 1 EQ.1: standard DYNA2D (1) EQ.2: rotational (2) EQ.3: Flanagan-Belytschko (3) EQ.4: Hancock	i5
6-15	Hourglass viscosity coefficient, QH (default .1) IHQ.EQ.1: QH ≤ .15 IHQ.EQ.2: QH ≤ .20 IHQ.EQ.3: QH ≤ .40 IHQ.EQ.4: QH ≤ .40	e10.0
16-20	Bulk viscosity type, IBQ EQ.0: default set to 1 EQ.1: standard DYNA2D EQ.2: Richards-Wilkins EQ.5: Benson-Christensen-Margolin (4)	i5
21-30	Quadratic viscosity coefficients, Q1 default value is 1.3 for IBQ = 5 default value is 1.5 otherwise	e10.0
31-40	Linear viscosity coefficient, Q2 default value is 1.0 for IBQ = 5 default value is .06 otherwise	e10.0

These are defaults that can be overridden for each material defined below.

---

(1) Recommended for 1D.

(2) Not recommended for problems using quads that have degenerated into triangles along material interfaces.

(3) Recommended for 2D but not for 1D.

(4) Note: for Benson-Christensen-Margolin viscosities:
(a) Defaults may only be overridden with this card
(b) ADDITIONAL DATA MUST BE SUPPLIED with a card placed at the end of the deck. See Section 25.

3. Material Cards

Repeat the following cards for each material model:

Card 1

Columns	Quantity	Format
1-5	Material identification number (≤ NUMMAT)	i5
6-10	Material type, MT:	i5
	EQ. 1: elastic	
	EQ. 2: orthotropic elastic	
	EQ. 3: kinematic/isotropic plasticity	
	EQ. 4: thermo-elastic-plastic	
	EQ. 5: soil and crushable foam	
	EQ. 6: linear viscoelastic	
	EQ. 7: rubber	
	EQ. 8: high explosive burn	
	EQ. 9: fluid	
	EQ.10: elastic-plastic hydrodynamic	
	EQ.11: temperature dependent plasticity with 3d cracking	
	EQ.12: Johnson/Cook plasticity	
	EQ.13: power law plasticity	
	EQ.16: pseudo TENSOR concrete/geological model	
	EQ.19: rock volumetric crack model	
	EQ.22: rock 3D crack model	
	EQ.23: Rubin-Attia rock failure model	
11-20	Density ρ_0 (porous reference state for solid, expanded reference state for iron gas source)	e10.0
21-25	Equation-of-state type. Define if MT > 7.	
	EQ. 1: linear polynomial	
	EQ. 2: JWL high explosive	
	EQ. 3: Sack "Tuesday" high explosive	
	EQ. 4: Gruneisen	
	EQ. 5: ratio of polynomials	
	EQ. 6: linear polynomial with energy deposition	
	EQ. 7: ignition and growth of reaction in HE	
	EQ. 8: tabulated compaction	
	EQ. 9: tabulated	
	EQ.11: TENSOR pore collapse	
	EQ.13: TENSOR pore collapse ∝ H-Div. $p(\rho,E)$ tabular EOS	
	EQ.14: cavity pressure	
	EQ.15: H-Division $p(\rho,E)$ tabular EOS only	
	EQ.16: TENSOR pore collapse with cracking	
	EQ.17: p-α with EOP Tables	
	EQ.18: effective stress model without gas tables	
	EQ.19: effective stress model with gas tables	
	EQ.24: Gruneisen with piecewise linear u_s-u_p curve	

If not defined, the following quantities are set to their default values

(Continuation of Card 1)

Columns	Quantity	Format
26-30	Hourglass control, IHQ EQ.1: standard DYNA2D EQ.2: rotational EQ.3: Flanagan-Belytschko viscosity form EQ.4: Hancock	I5
31-40	Hourglass viscosity coefficient	e10.0
41-45	Bulk viscosity type, IBQ* EQ.1: standard DYNA2D EQ.2: Richards-Wilkins	I5
46-55	Quadratic viscosity coefficient, Q1*	e10.0
56-65	Linear viscosity coefficient, Q2*	e10.0

Card 2

Columns	Quantity	Format
1-72	Material identification	12a6

* If IBQ = 5 on Control Card 4 the last three entries have no effect. In this (BCM) case the viscosity parameters specified on Control Card 4 apply to all the materials in the problem. The BCM viscosity cannot be mixed with other types of of bulk viscosity.

Material Type 1
(Elastic)

Card 3

Columns	Quantity	Format
1-10	Young's modulus	e10.0

Card 4

Columns	Quantity	Format
1-10	Poisson's ratio	e10.0

Cards 5,6,7,8

Blank

Material Type 2
(Orthotropic Elastic)

Card 3

Columns	Quantity	Format
1-10	E_a	e10.0
11-20	E_b	e10.0
21-30	E_c	e10.0

Card 4

Columns	Quantity	Format
1-10	ν_{ba}	e10.0
11-20	ν_{ca}	e10.0
21-30	ν_{cb}	e10.0

Card 5

Columns	Quantity	Format
1-10	G_{ab}	e10.0

Card 6

Columns	Quantity	Format
1-10	AOPT, material axes option (see Fig. 3) EQ.0.: locally orthotropic with material axes determined by angle ψ, specified on each element card, and element nodes n_1 and n_2 EQ.1.: locally orthotropic with material axes determined by a point in space and global location of element center EQ.2.: globally orthotropic with material axes determined by ψ_G	e10.0

Card 7

Columns	Quantity	Format
1-10	y_p, define for AOPT = 1.	e10.0
11-20	z_p, define for AOPT = 1.	e10.0

Card 8

Columns	Quantity	Format
1-10	ψ_G, define for AOPT = 2.	e10.0

The material law that relates stresses to strains is: $\underset{\sim}{C} = \underset{\sim}{T}\,\underset{\sim}{C}_L\,\underset{\sim}{T}$, where $\underset{\sim}{T}$ is a transformation matrix, and $\underset{\sim}{C}_L$ is the constitutive matrix defined in terms of the material constants of the orthogonal material axes, a and b.

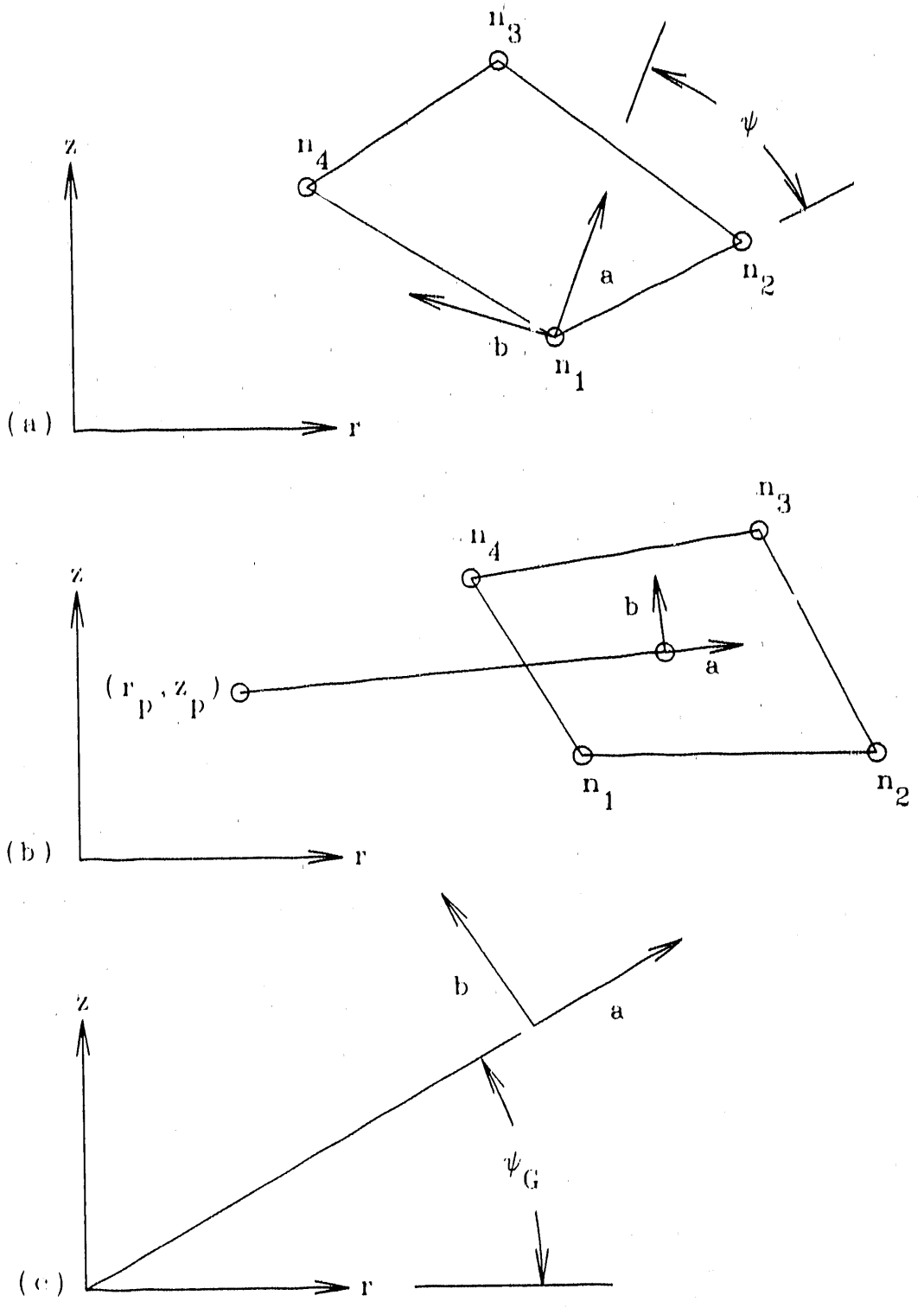

Fig. 3 Options for determining principal material axes: (a) AOPT = 0.0, (b) AOPT = 1.0, and (c) AOPT = 2.0

$$\underset{\sim}{C}_L^{-1} = \begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ba}}{E_b} & -\frac{\nu_{ca}}{E_c} & 0 \\ -\frac{\nu_{ab}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{cb}}{E_c} & 0 \\ -\frac{\nu_{ac}}{E_a} & -\frac{\nu_{bc}}{E_b} & \frac{1}{E_c} & 0 \\ 0 & 0 & 0 & \frac{1}{G_{ab}} \end{bmatrix}$$

Note that this matrix is symmetric.

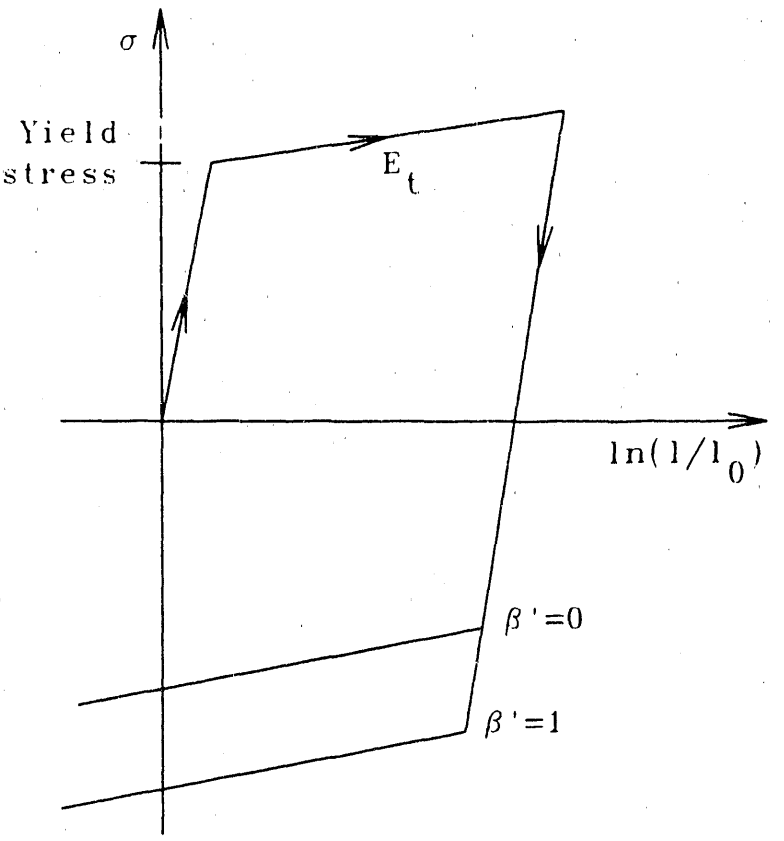

Fig. 4 Elastic-plastic behavior with isotropic and kinematic hardening where l_0 and l are undeformed and deformed lengths of uniaxial tension specimen.

Material Type 3
(Kinematic/Isotropic Elastic-Plastic)

Card 3

Columns	Quantity	Format
1-10	Young's modulus	e10.0

Card 4

Columns	Quantity	Format
1-10	Poisson's ratio	e10.0

Card 5

Columns	Quantity	Format
1-10	Yield stress	e10.0

Card 6

Columns	Quantity	Format
1-10	Hardening modulus, E_t	e10.0

Card 7

Columns	Quantity	Format
1-10	Hardening parameter, $0 < \beta' < 1$	e10.0

Card 8

Blank

Kinematic, isotropic, or a combination of kinematic and isotropic hardening may be specified by varying β' between 0 and 1. For $\beta' = 0$ hardening is entirely kinematic, for $\beta' = 1$ entirely isotropic. See Fig. 4 on previous page.

Material Type 4
(Thermo-Elastic-Plastic)

Card 3

Columns	Quantity	Format
1-10	T_1, temperature	e10.0
11-20	T_2	e10.0
.	.	.
.	.	.
.	.	.
71-80	T_8	e10.0

Card 4

Columns	Quantity	Format
1-10	E_1, Young's modulus at T_1	e10.0
11-20	E_2	e10.0
.	.	.
.	.	.
.	.	.
71-80	E_8	e10.0

Card 5

Columns	Quantity	Format
1-10	ν_1, Poisson's ratio at T_1	e10.0
11-20	ν_2	e10.0
.	.	.
.	.	.
.	.	.
71-80	ν_8	e10.0

Card 6

Columns	Quantity	Format
1-10	α_1 coefficient of thermal expansion at T_1	e10.0
11-20	α_2	e10.0
.	.	.
.	.	.
.	.	.
71-80	α_8	e10.0

(continued next page)

Card 7

Columns	Quantity	Format
1-10	σ_{y1}, yield stress at T_1	e10.0
11-20	σ_{y2}	e10.0
.	.	.
.	.	.
.	.	.
71-80	σ_{y8}	e10.0

Card 8

Columns	Quantity	Format
1-10	E_1^p, plastic hardening modulus at T_1	e10.0
.	.	.
.	.	.
.	.	.
71-80	E_8^p	e10.0

At least two temperatures and their corresponding material properties must be specified. The analysis will be terminated if a material temperature falls outside the range defined in input. If a thermoelastic expansion is considered, leave cards 7 and 8 blank. The coefficient of thermal expansion is defined with respect to a reference temperature.

Material Type 5
(Soil and Crushable Foam)

Card 3

Columns	Quantity	Format
1-10	Shear modulus	e10.0
11-20	Bulk unloading modulus	e10.0
21-30	Yield function constant a_0	e10.0
31-40	Yield function constant a_1	e10.0
41-50	Yield function constant a_2	e10.0
51-60	Pressure cutoff for tensile fracture	e10.0

Cards 4, 5, 6, 7, and 8

Columns	Quantity	Format
1-10	Volumetric strain (see Fig. 5)	e10.0
11-20	Pressure	e10.0
21-30	Volumetric strain	e10.0
31-40	Pressure	e10.0

The deviatoric yield function, φ, is described in terms of the second invariant J_2,

$$J_2 = \frac{1}{2} s_{ij} s_{ij}$$

pressure, p, and constants a_0, a_1, and a_2 as:

$$\varphi = J_2 - [a_0 + a_1 p + a_2 p^2].$$

On the yield surface $J_2 = 1/3\ \sigma_y^2$ where σ_y is the yield stress, i.e.,

$$\sigma_y = [3(a_0 + a_1 p + a_2 p^2)]^{1/2}$$

For elastic-perfectly plastic behavior $a_1 = a_2 = 0$, and $(3a_0)^{1/2}$ defines the yield strength.

The volumetric strain is given by the natural logarithm of the relative volume, V.

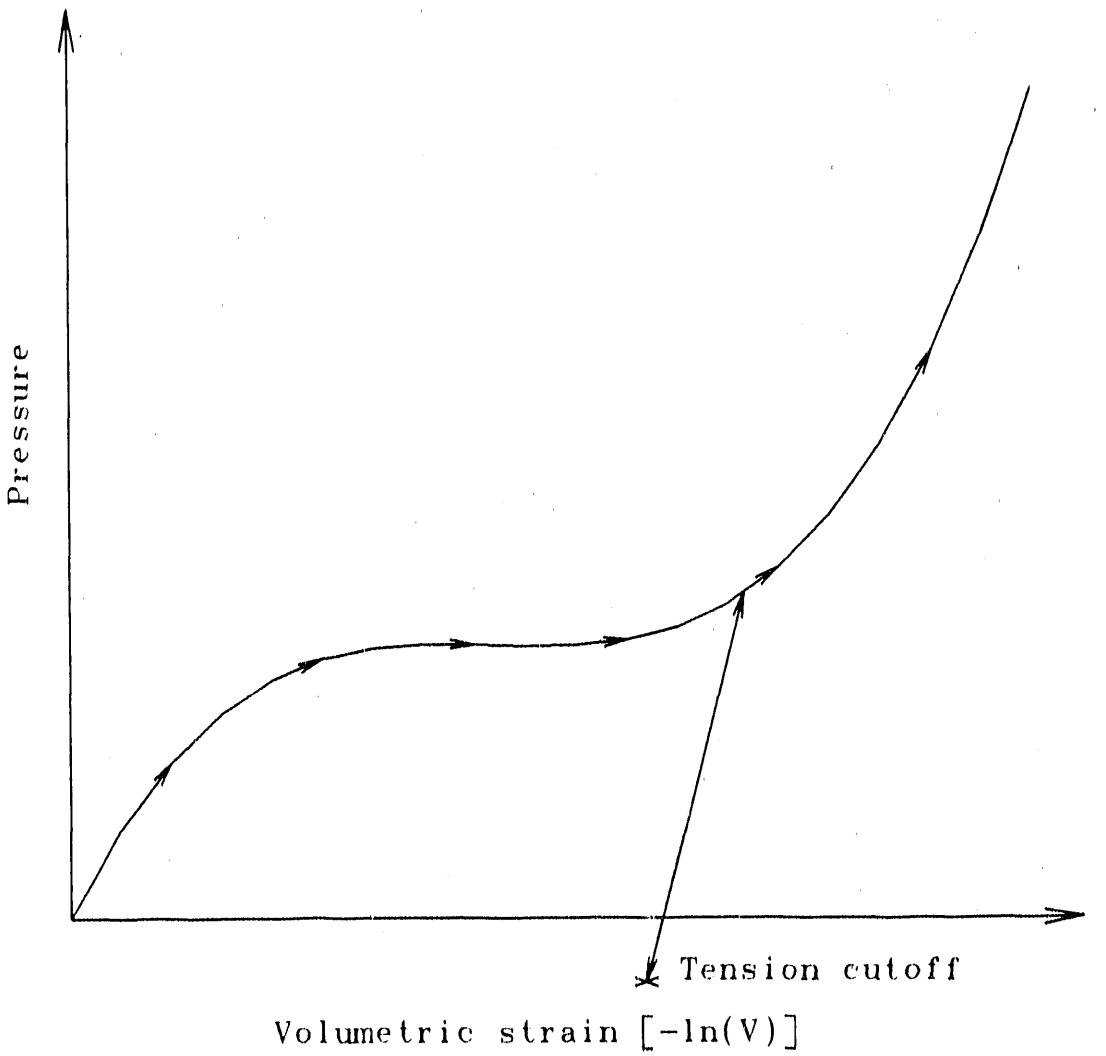

Fig. 5. Volumetric strain vs pressure curve for soil and crushable foam.

Material Type 6
(Viscoelastic)

Card 3

Columns	Quantity	Format
1-10	Bulk modulus (elastic)	e10.0

Card 4

Columns	Quantity	Format
1-10	Short-time shear modulus, G_0	e10.0

Card 5

Columns	Quantity	Format
1-10	Long-time shear modulus, G_∞	e10.0

Card 6

Columns	Quantity	Format
1-10	Decay constant, β	e10.0

Cards 7,8
Blank

The shear relaxation behavior is described by:

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$$

Material Type 7
(Rubber)

Card 3

Columns	Quantity	Format
1-10	Shear modulus	e10.0

Cards 4,5,6,7,8
Blank

Material Type 8
(High Explosive Burn)

Card 3

Columns	Quantity	Format
1-10	D, Detonation velocity	e10.0
11-20	P_{CJ}, Chapman-Jouget pressure	e10.0

Cards 4,5,6,7,8

Blank

Material Type 9
(Fluid)

Card 3

Columns	Quantity	Format
1-10	Pressure cutoff	e10.0

Cards 4,5,6,7,8
Blank

The fluid material may be used with an equation-of-state. No deviatoric stress is permitted with this material type.

Material Type 10
(Isotropic-Elastic-Plastic-Hydrodynamic)

Card 3

Columns	Quantity	Format
1-10	Shear modulus	e10.0
11-20	Yield strength, σ_0	e10.0
21-30	Plastic hardening modulus, E_h	e10.0
31-40	Pressure cutoff, less than 0. EQ.0.: a negative infinity cutoff is assumed	e10.0
41-50	Yield function constant, a_1	e10.0
51-60	Yield function constant, a_2	e10.0

Card 4

Blank

Card 5

Columns	Quantity	Format
1-10	ε_1, effective plastic strain	e10.0
11-20	ε_2	e10.0
21-30	ε_3	e10.0
31-40	ε_4	e10.0
41-50	ε_5	e10.0
51-60	ε_6	e10.0
61-70	ε_7	e10.0
71-80	ε_8	e10.0

Card 6

Columns	Quantity	Format
1-10	ε_9, effective plastic strain	e10.0
11-20	ε_{10}	e10.0
21-30	ε_{11}	e10.0
31-40	ε_{12}	e10.0
41-50	ε_{13}	e10.0
51-60	ε_{14}	e10.0
61-70	ε_{15}	e10.0
71-80	ε_{16}	e10.0

Card 7

Columns	Quantity	Format
1-10	σ_1, effective stress	e10.0
11-20	σ_2	e10.0
21-30	σ_3	e10.0
31-40	σ_4	e10.0
41-50	σ_5	e10.0
51-60	σ_6	e10.0
61-70	σ_7	e10.0
71-80	σ_8	e10.0

Card 8

Columns	Quantity	Format
1-10	σ_9, effective stress	e10.0
11-20	σ_{10}	e10.0
21-30	σ_{11}	e10.0
31-40	σ_{12}	e10.0
41-50	σ_{13}	e10.0
51-60	σ_{14}	e10.0
61-70	σ_{15}	e10.0
71-80	σ_{16}	e10.0

Whenever Cards 5-8 are blank, the yield stress and plastic hardening modulus are taken from Card 3. In this case assuming $a_1 = a_2 = 0$, the bilinear stress-strain curve shown in Fig. 4 is obtained with $\beta = 1$. The yield strength is calculated as

$$\sigma_y = \sigma_0 + E_h \bar{\varepsilon}^p + (a_1 + a_2 p)\max(0,p)$$

where p is the pressure. The quantity E_h is the plastic hardening modulus defined in terms of Young's modulus, E, and the tangent modulus, E_t, as follows:

$$E_h = \frac{E_t E}{E - E_t}.$$

If cards 5-8 are used, a curve like that in Fig. 6 is defined. In this case, the yield stress and plastic hardening modulus, a_1 and a_2 on Card 3 are ignored. Effective stress is defined in terms of the

deviatoric stress tensor, s_{ij}, as:

$$\bar{\sigma} \equiv \left(\frac{3}{2} s_{ij} s_{ij}\right)^{1/2} \tag{1}$$

and effective plastic strain as:

$$\bar{\varepsilon}^p \equiv \int_0^t \left(\frac{2}{3} D^p_{ij} D^p_{ij}\right)^{1/2} dt, \tag{2}$$

where t denotes time and D^p_{ij} is the plastic component of the rate-of-deformation vector.

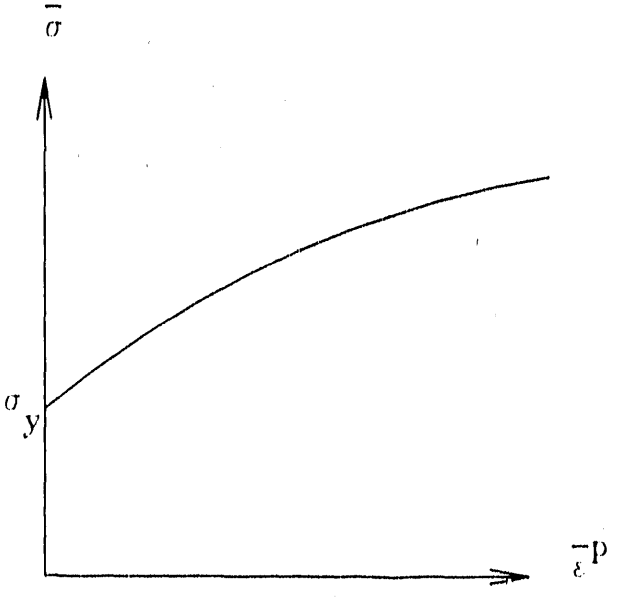

Fig. 6: Effective stress vs effective plastic strain.

Material Type 11
(Temperature Dependent, Elastic-Plastic, Hydrodynamic with 3D Cracking)

Card 3

Columns	Quantity	Format
1-10	G_0	e10.0
11-20	σ_0	e10.0
21-30	β^0	e10.0
31-40	n	e10.0
41-50	γ_1	e10.0

Card 4

Columns	Quantity	Format
1-10	σ_m	e10.0
11-20	b^m	e10.0
21-30	b'	e10.0
31-40	h	e10.0
41-50	f	e10.0

Card 5

Columns	Quantity	Format
1-10	A (if 0. then R' must be defined)	e10.0
11-20	T_{m0}	e10.0
21-30	γ_0	e10.0
31-40	a	e10.0
41-50	p_{min} or failure stress, $\sigma_f \geq 0$	e10.0

Card 6

Columns	Quantity	Format
1-10	Spall type EQ.0.: default set to 2. EQ.1.: $p > p_{min}$ EQ.2.: $\sigma_{max} > \sigma_f$ element spalls and tension, $p < 0$, is not allowed EQ.3.: $p < p_{min}$ element spalls and tension, $p < 0$, is not allowed EQ.4.: principal stress > σ_f, use 3d-crack tensile failure	e10.0
11-20	R' (if R' $\neq$ 0, A is not defined)	e10.0

(continued next page)

Card 7

Columns	Quantity	Format
1-16	EC_0	e16.0
17-32	EC_1	e16.0
33-48	EC_2	e16.0
49-64	EC_3	e16.0
65-80	EC_4	e16.0

Card 8

Columns	Quantity	Format
1-16	EC_5	e16.0
17-32	EC_6	e16.0
33-48	EC_7	e16.0
49-64	EC_8	e16.0
65-80	EC_9	e16.0

Users who have an interest in this model are encouraged to read the paper by Steinberg and Guinan [9] which provides the theoretical basis for it. Another useful reference is the KOVEC user manual.

The shear modulus, G, is defined, before melting, by the formula

$$G = G_0 \left[1 + bpV^{1/3} - h\left(\frac{E_i - E_c}{3R'} - 300\right)\right] e^{-\frac{fE}{E_m - E_i}}$$

where p is the pressure, V is the relative volume, E_c is the cold compression energy:

$$E_c(x) = \int_0^x pdx - \frac{900\, R'\, \exp(ax)}{(1-x)^{2(\gamma_0 - a - 1/2)}} \quad \text{with } x = 1-V,$$

and E_m is the melting energy:

$$E_m(x) = E_c(x) + 3R'T_m(x)$$

which is in terms of the melting temperature $T_m(x)$:

$$T_m(x) = \frac{T_{m0}\exp(2ax)}{V^{2(\gamma_0 - a - 1/3)}}$$

and the melting temperature at $\rho = \rho_0$, T_{m0}.

In the above equation, R' is defined by

$$R' = R\rho/A$$

where R is the gas constant and A is the atomic weight. If R' is not defined, KDYNA computes it with R in the cm-gram-microsecond system of units.

The yield strength σ_y is given by:

$$\sigma_y = \sigma_0' \left[1 + b'pV^{1/3} - h\left(\frac{E_i - E_c}{3R'} - 300\right)\right] e^{-\frac{fE}{E_m - E_i}}$$

if E_m exceeds E_i. Here, σ_0' is given by:

$$\sigma_0' = \sigma_0 \left[1 + \beta(\gamma_i + \varepsilon^{-p})\right]^n$$

where γ_i is the initial plastic strain. Whenever σ_0' exceeds σ_m, σ_0' is set equal to σ_m. After the material melts, σ_y and G are set to zero.

If the coefficients EC_0, ... , EC_9 are not defined, KDYNA will fit the cold compression energy to the ten term polynomial expansion:

$$E_c = \sum_{i=0}^{9} EC_i \eta^i$$

where EC_i is the ith coefficient and $\eta = \rho/\rho_0$. The least squares method is used to perform the fit.

Material Type 12
(Johnson/Cook Strain and Temperature Sensitive Plasticity)

Card 3

Columns	Quantity	Format
1-10	G	e10.0
11-20	A	e10.0
21-30	B	e10.0
31-40	n	e10.0
41-50	C	e10.0
51-60	m	e10.0
61-70	T_m, melt temperature	e10.0
71-80	T_r, room temperature	e10.0

Card 4

Columns	Quantity	Format
1-10	$\dot{\varepsilon}_0$	e10.0
11-20	Specific heat	e10.0
21-30	p_{min} or failure stress σ_f	e10.0
31-40	Spall type EQ.0.: default set to 2. EQ.1.: $p \geq p_{min}$ EQ.2.: $\sigma_{max} \geq \sigma_f$ element spalls and tension, $p < 0$, is not allowed EQ.3.: $p < p_{min}$ element spalls and tension, $p < 0$, is not allowed	e10.0
41-50	Plastic strain iteration flag EQ.1: accurate iterative solution for plastic strain. Much more expensive than default.	e10.0

Card 5

Columns	Quantity	Format
1-10	D_1, failure parameter	e10.0
.	.	.
.	.	.
.	.	.
41-50	D_5	e10.0

(continued next page)

Cards 6,7,8
Blank

Johnson and Cook express the flow stress as

$$\sigma_y = (A + B\bar{\varepsilon}^{p\,n})(1 + C \ln \dot{\varepsilon}^*)(1 - (T^*)^m)$$

for A, B, C, n, and m = input constants

$\bar{\varepsilon}^p$ = effective plastic strain

$\dot{\varepsilon}^* = \dot{\bar{\varepsilon}}^p / \dot{\varepsilon}_0$

= effective plastic strain rate for $\dot{\varepsilon}_0 = 1/\text{sec}$

T^* = homologous temperature

Constants for a variety of materials are supplied in the references cited.

Due to the nonlinearity in the dependence of flow stress on plastic strain, an accurate calculation of flow stress requires iteration for the increment in plastic strain. However, by using a Taylor series expansion with linearization about the current time we can solve for $\Delta\bar{\varepsilon}^p$ with sufficient accuracy to avoid iteration.

The strain at fracture is given by

$$\varepsilon^f = [D_1 + D_2 \exp D_3\sigma^*][1 + D_4 \ln \dot{\varepsilon}^*][1 + D_5 T^*]$$

where σ^* is the ratio of pressure to effective stress

$$\sigma^* = \frac{p}{\sigma_{eff}}$$

Fracture occurs when the damage parameter reaches 1, i.e.,

$$D = \Sigma \frac{\Delta\bar{\varepsilon}^p}{\varepsilon^f} = 1.$$

Material Type 13
(Power Law Isotropic Plasticity)

Card 3

Columns	Quantity	Format
1-10	Young's modulus	e10.0
11-20	Poisson's ratio	e10.0
21-30	k, strength coefficient	e10.0
31-40	n, hardening exponent	e10.0

Cards 4,5,6,7,8
Blank

Elastoplastic behavior with isotropic hardening is provided by this model. The yield stress, σ_y, is a function of plastic strain and obeys the equation:

$$\sigma_y = k\,\bar{\varepsilon}^{n}$$

where $\bar{\varepsilon}$ is the effective strain.

Material Type 16
(Pseudo TENSOR Concrete/Geological Model)

Card 3

Columns	Quantity	Format
1-10	ν for constant Poisson's ration model or -G for constant shear modulus model	e10.0
11-20	Tensile cutoff (maximum principal stress failure), sigf	e10.0
21-30	Cohesion, a_0	e10.0
31-40	Pressure hardening coefficient, a_1	e10.0
41-50	Pressure hardening coefficient, a_2	e10.0
51-60	Damage scaling factor, b_1	e10.0
61-70	Cohesion for failed material, a_{0f}	e10.0
71-80	Pressure hardening coefficient for failed material, a_{1f}	e10.0

Card 4

Columns	Quantity	Format
1-10	Percent reinforcement	e10.0
11-20	Elastic modulus for reinforcement	e10.0
21-30	Poisson's ratio for reinforcement	e10.0
31-40	Initial yield stress	e10.0
41-50	Tangent modulus	e10.0
51-60	Load curve of rate sensitivity for principal material	e10.0
61-70	Load curve of rate sensitivity for reinforcement	e10.0

Card 5

Columns	Quantity	Format
1-10	ε_1, effective plastic strain or pressure	e10.0
.	.	.
.	.	.
.	.	.
71-80	ε_8	e10.0

(continued next page)

Card 6

Columns	Quantity	Format
1-10	ε_9	e10.0
.	.	.
.	.	.
.	.	.
71-80	ε_{16}	e10.0

Card 7

Columns	Quantity	Format
1-10	σ_1, effective stress	e10.0
.	.	.
.	.	.
.	.	.
71-80	σ_8	e10.0

Card 8

Columns	Quantity	Format
1-10	σ_9	e10.0
.	.	.
.	.	.
.	.	.
71-80	σ_{16}	e10.0

For the constant Poisson's ratio model, the shear modulus is computed from the bulk modulus. For the constant shear modulus model, Poisson's ratio is computed from the bulk modulus. The bulk modulus is determined by the equation-of-state.

If zero values are specified for a_0 and a_1, the data on cards 5 and 6 are taken to be pressure values instead of values of effective plastic strain.

If a negative value is specified for a_0, the value given for sigf is assumed to be unconfined compressive strength of the principal material instead of the tensile cutoff value. In this case values for the tensile cutoff and pressure hardening coefficients are calculated internally as follows:

$$sigf = 1.7((f'c)^2/ucf)^{1/3}$$

$$a_0 = (1/4)(f'c)$$

$$a_1 = 1/3$$

$$a_2 = (1/3)/(f'c)$$

$$a_{0f} = 0$$

$$a_{1f} = 0.385$$

where $ucf = -a_0$ is a unit conversion factor for f'c, i.e., psi per DYNA pressure unit.

A zero equation-of-state number can also be specified in this case and data for a trilinear EOS8 model (good for pressures below about 5 kilobars) will be generated internally using the values given for Poisson's ratio and f'c. Otherwise, equation-of-state 8, 9, or 11 must be specified and the corresponding data provided in the user's material input.

Principal material and reinforcement properties are combined using a rule of mixtures as follows:

```
bulk = (1-fs)*bkm + fs*bkr
shrm = (1-fs)*gm + fs*gr
sigy = (1-fs)*sym + fs*syr
```

where

$$sym = \begin{cases} f(k1,edot)*(a_0 + p/(a_1+a_2p))*g(dmg) & \text{or} \\ f(k1,edot)*g(p) \end{cases}$$

and

$$syr = f(k2,edot)*qs + qh*epx.$$

f(k,edot) denotes the yield stress strain rate scaling factor obtained by linear interpolation from load curve k (if k=0, f=1.0), and g denotes either the damage or the pressure scaling factor obtained by linear interpolation from the yield stress table. dmg is an isotropic measure of damage defined as

$$dmg = \int_0^{\bar{\varepsilon}^p} \frac{d\bar{\varepsilon}^p}{\left(1 + \frac{p}{sigf}\right)^{b_1}}$$

fs is the percent reinforcement, which is treated isotropically.

If the maximum principal stress in an element exceeds the tensile cutoff, the matrix material in the element is assumed to have fractured. After fracture, the matrix material in an element can support only compressive loads and its shear strength is limited by the yield surface for failed material,

$$symf = a_{0f} + p/(a_{1f}+a_2 p)$$

Material Type 19 [37]
(Rock Volumetric Crack Model)

Card 3

Columns	Quantity	Format
1-10	Either ν for a constant Poisson's ratio or -G for a constant shear modulus model	e10.0
11-20	Tensile cutoff for maximum principal stress failure, SIGF	e10.0
21-30	Failure damage limit	e10.0
31-40	Number of points in virgin Y-P curve, NPV	e10.0
41-50	Number of points in failed Y-P curve, NPF	e10.0
51-60	Pressure abscissa for shear failure limit surface: 0 for Y(p), 1 for Y($\bar{p}$)	e10.0

Notes:

1) NPV + NPF ≤ 20
2) The entire virgin curve must be entered, but the failure curve need only be entered up to a brittle-ductile point.

Cards 4 through 8 maximum

Quantity
NPV virgin pressure values
NPV virgin yield stress values
NPF failed pressure values
NPF failed yield stress values

The four sets of data above are concatenated and written in format 8e10.0 for no more than 5 successive cards. Unused fields at the end are blank filled.

Material Type 22 [37]
(Rock 3D Crack Model)

Card 3

Columns	Quantity	Format
1-10	ν, a constant Poisson's ratio	e10.0
11-20	Tensile cutoff for maximum principal stress failure, SIGF	e10.0
21-30	Failure damage limit	e10.0
31-40	Number of points in virgin Y-P curve, NPV	e10.0
41-50	Number of points in failed Y-P curve, NPF	e10.0
51-60	Pressure abscissa for shear failure limit surface: EQ.0. for Y(p) EQ.1. for Y(p)	e10.0

Notes:

1) NPV + NPF < 20
2) The entire virgin curve must be entered, but the failure curve need only be entered up to a brittle-ductile point.

Cards 4 through 8 maximum

Quantity
NPV virgin pressure values
NPV virgin yield stress values
NPF failed pressure values
NPF failed yield stress values

The four sets of data above are concatenated and written in format 8e10.0 for no more than 5 successive cards. Unused fields at the end are blank filled.

Material Type 23 [33]
(Rubin-Attia Rock Failure Model)

Card 3

Columns	Quantity	Format
1-10	ν, a constant Poisson's ratio	e10.0
11-20	Tensile cutoff for maximum principal stress failure, SIGF	e10.0
21-30	Failure damage limit	e10.0
31-40	Number of points in virgin Y-P curve, NPV	e10.0
41-50	Number of points in failed Y-P curve, NPF	e10.0
51-60	Pressure abscissa for shear failure limit surface: EQ.0. for Y(p) EQ.1. for Y(p) EQ.2. for Rubin yield with triaxial compression data only	e10.0
61-70	Choice of stress deviator limited by shear failure EQ.0 for total stress EQ.1 for uncracked stress	e10.0
71-80	Friction coefficient for slip on closed crack	e10.0

Notes:

1) NPV + NPF ≤ 20
2) The entire virgin curve must be entered, but the failure curve need only be entered up to a brittle-ductile point.

Cards 4 through 8 maximum

Quantity
NPV virgin pressure values
NPV virgin yield stress values
NPF failed pressure values
NPF failed yield stress values

The four sets of data above are concatenated and written in format 8e10.0 for no more than 5 successive cards. Unused fields at the end are blank filled.

3a. Equation-of-State Cards

Supply equation-of-state cards only if the material type is greater than seven and is not 13. Each equation-of-state is only applicable to certain material models. A table of material model-eos compatibilities is found in Appendix B.

Every equation-of-state used in the problem must have a label, supplied with Card 9 as shown.

Card 9

Columns	Quantity	Format
1-72	Equation-of-state label	12a6

Cards 10 and up contain physical parameters describing the eos. An explanation of some of these parameters follows.

1. Density and Volume:

KDYNA requires the user to specify two densities: an initial density, $\rho(0)$ and a reference density ρ_0. The initial density and the initial volume V(0), obtained from nodal positions, are used to compute the mass in a zone as:

$$m = \rho(0)V(0) \tag{1}$$

The user is free to choose any state as a reference state for the density, ρ_0. However, this choice will have to be consistent with the meaning of energy per reference volume. (See Section 2, below.) Conservation of mass requires the reference volume to be given by:

$$V_0 = \rho(0)V(0)/\rho_0 \tag{2}$$

The initial density is calculated from either

$$\rho(0) = \rho_0(1+\mu(0)) \tag{3}$$

or

$$\rho(0) = \rho_0/x(0) \tag{4}$$

where the user specifies either the initial excess compression, $\mu(0)$, or the initial relative volume $x(0)$ given by:

$$x(0) = V(0)/V_0 \tag{5}$$

In planar symmetry, the volume of a zone is simply the area times a unit depth. In axisymmetry (about the z axis), the zonal volume, V, is calculated from:

$$V = V^{**}/2\pi = A_1\bar{r}_1 + A_2\bar{r}_2 \tag{6}$$

where V^{**} is the volume obtained by revolving the zone area, A, about the z axis, and $\bar{r}_1$ and $\bar{r}_2$ are the centroids of the triangular subregions A_1 and A_2, respectively.

2. Internal Energy:

Several equations-of-state require the user to specify E(0), the initial internal energy per unit reference volume, V_0. In general

$$E = E^*/V_0 \tag{7}$$

where E^* is the internal energy in a zone and V_0 was given in Section 1 by (2). Given E(0) and V_0, (7) provides KDYNA with the initial internal energy $E^*(0)$. We can relate E to ε, the internal energy per unit mass, since:

$$E^* = \varepsilon m \tag{8}$$

and

$$V_0 = m/\rho_0 \tag{9}$$

so that:

$$E = \rho_0\varepsilon \tag{10}$$

Note also that, in axisymmetry, the internal energy E^* in a zone with volume V is related to the internal energy E^{**} in the corresponding volume of revolution, V^{**}. Using (6) and (8) we obtain:

$$E^* = \varepsilon\rho V = \varepsilon\rho V^{**}/2\pi = E^{**}/2\pi \tag{11}$$

The cycle summary edits show total internal energy divided by 2π.

3. Guidelines for Setting x(0) and E(0):

There are two ways to set the initial relative volume, x(0), and the initial internal energy per reference volume, E(0). If x(0) and E(0) are uniform throughout the zones of a particular material, then these values should be assigned in Cards 10 and 11 of the Equation-of-State input set. If these initial values vary from zone to zone of the same material, then they must be assigned via the Element Cards, as shown in Section 5. Note that values assigned via the Element Cards will override values assigned via EOS Cards 10 and 11.

Equation-of-State Form 1
(Linear Polynomial)

Card 10

Columns	Quantity	Format
1-10	C_0	e10.0
11-20	C_1	e10.0
21-30	C_2	e10.0
31-40	C_3	e10.0
41-50	C_4	e10.0
51-60	C_5	e10.0
61-70	C_6	e10.0
71-80	E(0), initial internal energy per unit reference volume	e10.0

Card 11

Columns	Quantity	Format
1-10	x(0), initial relative volume	e10.0

The linear polynomial equation-of-state is linear in internal energy. The pressure is given by:

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E,$$

where terms $C_2\mu^2$ and $C_6\mu^2$ are set to zero if $\mu < 0$, $\mu = \rho/\rho_0 - 1$, and ρ/ρ_0 is the ratio of current density to reference density.

Equation-of-State Form 2
(JWL)

Card 10

Columns	Quantity	Format
1-10	A	e10.0
11-20	B	e10.0
21-30	R1	e10.0
31-40	R2	e10.0
41-50	ω	e10.0
51-60	E(0), initial internal energy per unit reference volume	e10.0
61-70	x(0), initial relative volume	e10.0

The JWL equation-of-state defines the pressure as

$$p = A\left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \frac{\omega E}{V} ,$$

and is usually used for detonation products of high explosives.

Equation-of-State Form 3
(Sack)

Card 10

Columns	Quantity	Format
1-10	A_1	e10.0
11-20	A_2	e10.0
21-30	A_3	e10.0
31-40	B_1	e10.0
41-50	B_2	e10.0
51-60	E(0), initial internal energy per unit reference volume	e10.0
61-70	x(0), initial relative volume	e10.0

The Sack equation-of-state defines pressure as

$$p = \frac{A_3}{V^{A_1}} e^{-A_2 V} \left(1 - \frac{B_1}{V}\right) + \frac{B_2}{V} E$$

and is used for detonation products of high explosives.

Equation-of-State Form 4
(Gruneisen)

Card 10

Columns	Quantity	Format
1-10	C	e10.0
11-20	S_1	e10.0
21-30	S_2	e10.0
31-40	S_3	e10.0
41-50	γ_0	e10.0
51-60	a	e10.0
61-70	E(0), initial internal energy per unit reference volume	e10.0
71-80	x(0), initial relative volume	e10.0

The Gruneisen equation-of-state with cubic shock velocity-particle velocity defines pressure for compressed materials as

$$p = \frac{\rho_0 C^2 \mu\left[1 + (1 - \gamma_0/2)\mu - \frac{a}{2}\mu^2\right]}{\left[1 - (S_1 - 1)\mu - S_2\frac{\mu^2}{\mu+1} - S_3\frac{\mu^3}{(\mu+1)^2}\right]^2} + (\gamma_0 + a\mu)E,$$

and for expanded materials as

$$p = \rho_0 C^2 \mu + (\gamma_0 + a\mu)E,$$

where C is the intercept of the u_s-u_p curve, S_1, S_2, and S_3 are the coefficients of the slope of the u_s-u_p curve, γ_0 is the Grueneisen gamma, and a is the first order volume correction to γ_0.

Equation-of-State Form 5
(Ratio of Polynomials)

Card 10

Columns	Quantity	Format
1-16	A10	e16.0
17-32	A11	e16.0
33-48	A12	e16.0
49-64	A13	e16.0

Card 11

Columns	Quantity	Format
1-16	A20	e16.0
17-32	A21	e16.0
33-48	A22	e16.0
49-64	A23	e16.0

Card 12

Columns	Quantity	Format
1-16	A30	e16.0
17-32	A31	e16.0
33-48	A32	e16.0
49-64	A33	e16.0

Card 13

Columns	Quantity	Format
1-16	A40	e16.0
17-32	A41	e16.0
33-48	A42	e16.0
49-64	A43	e16.0

Card 14

Columns	Quantity	Format
1-16	A50	e16.0
17-32	A51	e16.0
33-48	A52	e16.0
49-64	A53	e16.0

(continued next page)

Card 15

Columns	Quantity	Format
1-16	A60	e16.0
17-32	A61	e16.0
33-48	A62	e16.0
49-64	A63	e16.0

Card 16

Columns	Quantity	Format
1-16	A70	e16.0
17-32	A71	e16.0
33-48	A72	e16.0
49-64	A73	e16.0

Card 17

Columns	Quantity	Format
1-16	α	e16.0
17-32	β	e16.0
33-48	A14	e16.0
49-64	A24	e16.0

Card 18

Columns	Quantity	Format
1-16	E(0), initial internal energy per unit reference volume	e16.0
17-32	x(0), initial relative volume	e16.0

The ratio of polynomials equation-of-state defines the pressure as

$$p = \frac{F_1 + F_2E + F_3E^2 + F_4E^3}{F_5 + F_6E + F_7E^2}(1 + \alpha\mu)$$

where

$$F_i = \sum_{j=0}^{n} A_{ij}\mu^j \qquad \begin{array}{l} \text{for } n = 4 \text{ if } i < 3 \\ \text{for } n = 3 \text{ if } i \geq 3 \end{array}$$

$$\mu = \rho/\rho_0 - 1$$

In expanded zones F_1 is replaced by $F_1' = F_1 + \beta\mu^2$.

Equation-of-State Form 6
(Linear Polynomial with Energy Leak)

Card 10

Columns	Quantity	Format
1-10	C_0	e10.0
11-20	C_1	e10.0
21-30	C_2	e10.0
31-40	C_3	e10.0
41-50	C_4	e10.0
51-60	C_5	e10.0
61-70	C_6	e10.0
71-80	E(0), initial internal energy per unit reference volume	e10.0

Card 11

Columns	Quantity	Format
1-10	x(0), initial relative volume	e10.0
11-20	CN, number of time history curve giving energy deposition rate.	e10.0

Equation-of-State Form 7
(Ignition and Growth of Reaction in HE)

Card 10

Columns	Quantity	Format
1-10	a	e10.0
11-20	b	e10.0
21-30	xp_1	e10.0
31-40	xp_2	e10.0
41-50	frer	e10.0

Card 11

Columns	Quantity	Format
1-10	g	e10.0
11-20	r_1	e10.0
21-30	r_2	e10.0
31-40	r_3	e10.0
41-50	r_5	e10.0

Card 12

Columns	Quantity	Format
1-10	r_6	e10.0
11-20	fmxig	e10.0
21-30	freq	e10.0
31-40	$grow_1$	e10.0
41-50	em	e10.0

Card 13

Columns	Quantity	Format
1-10	ar_1	e10.0
11-20	es_1	e10.0
21-30	cvp, (heat capacity of products)	e10.0
31-40	cvr, (heat capacity of explosive reactants)	e10.0
41-50	eeta1	e10.0

(continued next page)

Card 14

Columns	Quantity	Format
1-10	ecrit	e10.0
11-20	Enq (heat of reaction)	e10.0
21-30	Tmp0 (initial temperature, generally 298°K)	e10.0
31-40	blank	
41-50	blank	

Card 15

Columns	Quantity	Format
1-10	$grow_2$	e10.0
11-20	ar_2	e10.0
21-30	es_2	e10.0
31-40	en_2	e10.0
41-50	fmxgr	e10.0
51-60	fmngr	e10.0

Equation-of-state form 7 is used to calculate the shock initiation (or failure to initiate) and detonation wave propagation of solid high explosives. It should be used instead of the ideal HE burn options in the following cases: when there is a question of whether the HE will react, when there is a finite time required for a shock wave to build up to detonation, or when there is a finite thickness of the chemical reaction zone in a detonation wave. At relatively low initial pressures (< 2-3 GPa), this equation-of-state should be used with material type 10 for accurate calculations of the unreacted HE behavior. At higher initial pressures, material type 9 can be used. A JWL equation-of-state defines the pressure in the unreacted explosive as

$$p_e = r_1 e^{-r_5 V_e} + r_2 e^{-r_6 V_e} + r_3 T_e / V_e$$

where V_e and T_e are the relative volume and temperature, respectively, of the unreacted explosive. Another JWL equation-of-state defines the pressure in the reaction products as

$$p_p = ae^{-xp_1 V_p} + be^{-xp_2 V_p} + gT_p / V_p$$

where V_p and T_p are the relative volume and temperature, respectively,

of the reaction products. As the chemical reaction converts unreacted explosive to reaction products, these JWL equations-of-state are used to calculate the mixture of unreacted explosives and reaction products as described by F, the reacted fraction. F = 0 for no reaction. F = 1 for a complete reaction. The temperatures and pressures for reactants and products are assumed equal, i.e., $T_e = T_p$ and $p_e = p_p$, and the relative volumes are additive, i.e.,

$$V = (1-F)V_e + FV_p .$$

The chemical reaction rate for conversion of unreacted explosive to reaction products consists of three physically realistic terms: an ignition term in which a small amount of explosive reacts soon after the shock wave compresses it; a slow growth of reaction as this initial reaction spreads; and a rapid completion of reaction at high pressure and temperature. The form of the reaction rate equation is

$$\delta F/\delta t = \text{freq}(1-F)^{\text{frer}}(V_e - 1 - \text{ecrit})^{\text{eetal}} \qquad \text{(Ignition)}$$

$$+ \text{grow}_1(1-F)^{\text{es}_1} F^{\text{ar}_1} p^{\text{em}} \qquad \text{(Growth)}$$

$$+ \text{grow}_2(1-F)^{\text{es}_2} F^{\text{ar}_2} p^{\text{en}} \qquad \text{(Completion)}$$

The ignition rate is set equal to zero when F ≥ fmxig, the growth rate is set equal to zero when F ≥ fmxgr, and the completion rate is set to zero when F ≤ fmngr.

Details of the computational methods and many examples of one- and two-dimensional shock initiation and detonation wave calculation can be found in References [1] - [7] and other references cited by these. Unfortunately, sufficient experimental data has been obtained for only two solid explosives to develop very reliable shock initiation models: PBX-9404, including related HMX-based explosives LX-14, LX-10, LX-04, etc., and LX-17, the insensitive TATB-based explosive. Reactive flow models have been developed for other explosives (TNT, PETN, Composition B, propellants, etc.) but are based on very limited experimental data. The details of material and eos input for PBX-9404 and LX-17 are given on the next page.

PBX-9404

Card 1 Material No., Material Type = 10, Density = 1.842, EOS Form = 7
Card 2 PBX-9404
Card 3 Shear modulus = 0.0454, Yield Strength = 0.002
Card 4 Blank
Card 5 Blank
Card 6 Blank
Card 7 Blank
Card 8 Blank
Card 9 PBX-9404 Ignition and Growth

Columns:	1-10	11-20	21-30	31-40	41-50	51-60
Card 10	8.524	0.1802	4.6	1.3	0.667	
Card 11	3.8e-6	9522.	-0.05944	2.4650e-5	14.1	
Card 12	1.41	0.3	7.43e+11	3.1	1.0	
Card 13	0.111	0.667	1.0e-5	2.7813e-5	20.0	
Card 14	0.0	0.102	298.0	-	-	
Card 15	400.0	1.0	0.333	2.0	0.5	0.0

LX-17

Card 1 Material No., Material Type = 10, Density = 1.90, EOS Form = 7
Card 2 LX-17
Card 3 Shear modulus = 0.0354, Yield Strength = 0.002
Card 4 Blank
Card 5 Blank
Card 6 Blank
Card 7 Blank
Card 8 Blank
Card 9 LX-17 Ignition and Growth

Columns:	1-10	11-20	21-30	31-40	41-50	51-60
Card 10	5.31396	0.0270309	4.1	1.1	0.667	
Card 11	4.60e-6	778.1	-0.05031	2.2229e-5	11.3	
Card 12	1.13	0.5	4.0e+6	0.6	1.0	
Card 13	0.111	0.667	1.0e-5	2.487e-5	7.0	
Card 14	0.22	0.069	290.0	-	-	
Card 15	400.0	1.0	0.333	3.0	0.5	0.0

A JWL equation-of-state defines the pressure in the unreacted HE as

$$P_e = A_e\left(1 - \frac{\omega_e}{R1_e V_e}\right)e^{-R1_e V_e} + B_e\left(1 - \frac{\omega_e}{R2_e V_e}\right)e^{-R2_e V_e} + \frac{\omega_e E_e}{V_e}$$

where V_e is the relative volume, E_e is the internal energy, and A_e, B_e, ω_e, $R1_e$, and $R2_e$ are input constants. Similarly, the pressure in the reaction products is defined by another JWL form:

$$P_p = A_p\left(1 - \frac{\omega_p}{R1_p V_p}\right)e^{-R1_p V_p} + B_p\left(1 - \frac{\omega_p}{R2_p V_p}\right)e^{-R2_p V_p} + \frac{\omega_p E_p}{V_p}$$

The mixture of unreacted explosive and reaction products is defined by the fraction reacted F (F=0 => no reaction, F=1 => complete conversion from explosive to products). The pressures and temperatures are assumed to be in equilibrium and the volumes are assumed to be additive, i.e.,

$$V = (1-F)V_e + FV_p,$$

The rate of reaction for material type 18 is

$$\delta F/\delta t = I(FCRIT-F)^y(V_e^{-1}-1)^3(1+G(V_e^{-1}-1)) + H(1-F)^y F^x P^z (V_p^{-1}-1)^m$$

where I, G, H, x, y, z, and m (generally m=0) are input constants.

The JWL equations-of-state and the reaction rates have been fitted to one- and two-dimensional shock initiation and detonation data for four explosives: PBX-9404, RX-03-BB, PETN, and cast TNT. The details of the calculational method are described in Cochran and Chan [12]. The detailed one-dimensional calculations and parameters for the four explosives are given in in Lee and Tarver [11].

Equation-of-State Form 8
(Tabulated-Compaction)

Card 10

Columns	Quantity	Format
1-16	ε_{V0}, (ln V)	e16.0
17-32	ε_{V1}	e16.0
33-48	ε_{V2}	e16.0
49-64	ε_{V3}	e16.0
65-80	ε_{V4}	e16.0

Card 11

Columns	Quantity	Format
1-16	ε_{V5}	e16.0
17-32	ε_{V6}	e16.0
33-48	ε_{V7}	e16.0
49-64	ε_{V8}	e16.0
65-80	ε_{V9}	e16.0

Card 12

Columns	Quantity	Format
1-16	C_0	e16.0
17-32	C_1	e16.0
33-48	C_2	e16.0
49-64	C_3	e16.0
65-80	C_4	e16.0

Card 13

Columns	Quantity	Format
1-16	C_5	e16.0
17-32	C_6	e16.0
33-48	C_7	e16.0
49-64	C_8	e16.0
65-80	C_9	e16.0

(continued next page)

Card 14

Columns	Quantity	Format
1-16	T_0	e16.0
17-32	T_1	e16.0
33-48	T_2	e16.0
49-64	T_3	e16.0
65-80	T_4	e16.0

Card 15

Columns	Quantity	Format
1-16	T_5	e16.0
17-32	T_6	e16.0
33-48	T_7	e16.0
49-64	T_8	e16.0
65-80	T_9	e16.0

Card 16

Columns	Quantity	Format
1-16	K_0	e16.0
17-32	K_1	e16.0
33-48	K_2	e16.0
49-64	K_3	e16.0
65-80	K_4	e16.0

Card 17

Columns	Quantity	Format
1-16	K_5	e16.0
17-32	K_6	e16.0
33-48	K_7	e16.0
49-64	K_8	e16.0
65-80	K_9	e16.0

Card 18

Columns	Quantity	Format
1-16	γ	e16.0
17-32	E(0), initial internal energy per unit reference volume	e16.0
33-48	x(0), initial relative volume	e16.0

The tabulated-compaction model is linear in internal energy. Pressure is defined by

$$P = C(\varepsilon_V) + \gamma T(\varepsilon_V)E$$

in the loading phase. The volumetric strain, ε_V, is given by the natural logarithm of the relative volume. Unloading occurs along the unloading bulk modulus to the pressure cutoff. Reloading always follows the unloading path to the point where unloading began, and continues on the loading path. See Fig. 7. Up to ten points and as few as two may be used to define the tabulated functions. KDYNA will extrapolate to find the pressure if necessary.

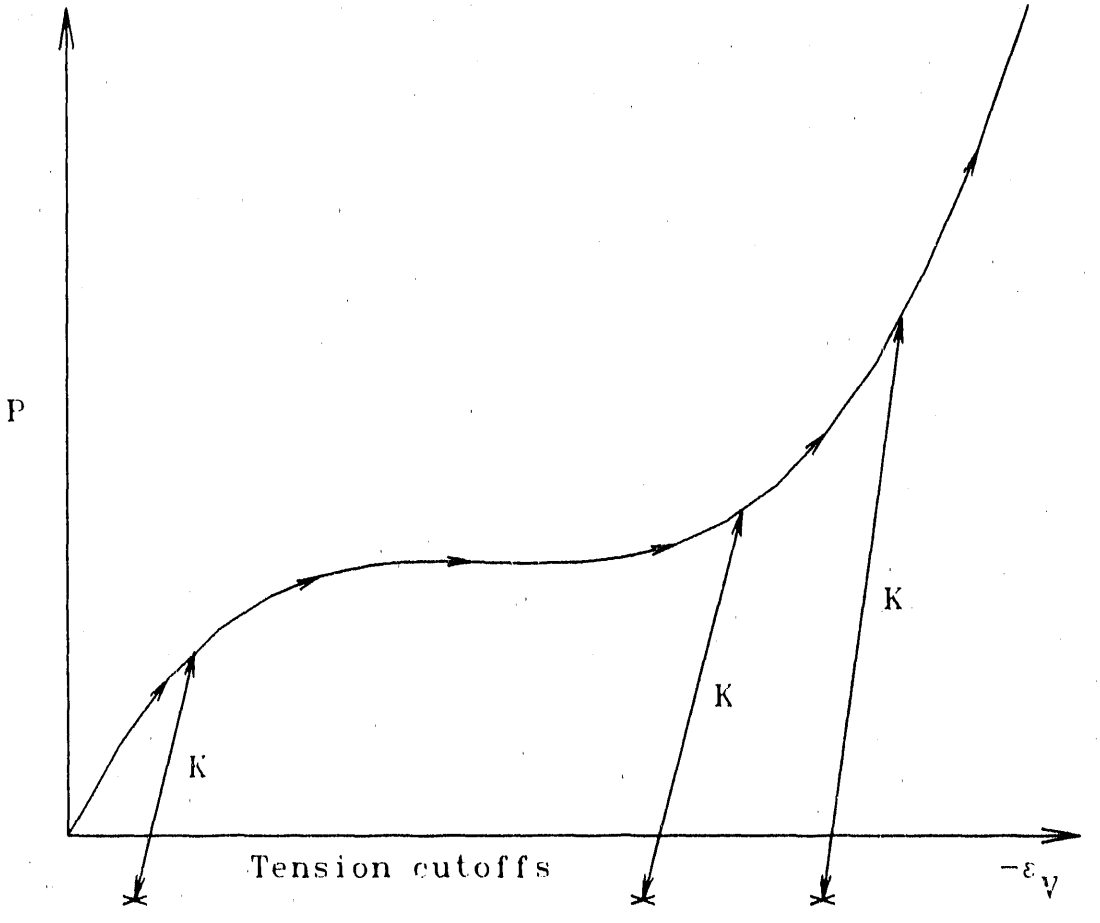

Fig. 7. Pressure versus volumetric strain curve for equation-of-state form 8 with compaction. In the compacted states the bulk unloading modulus depends on the peak volumetric strain.

Equation-of-State Form 9
(Tabulated)

Card 10

Columns	Quantity	Format
1-16	ε_{V0}, (ln V)	e16.0
17-32	ε_{V1}	e16.0
33-48	ε_{V2}	e16.0
49-64	ε_{V3}	e16.0
65-80	ε_{V4}	e16.0

Card 11

Columns	Quantity	Format
1-16	ε_{V5}	e16.0
17-32	ε_{V6}	e16.0
33-48	ε_{V7}	e16.0
49-64	ε_{V8}	e16.0
65-80	ε_{V9}	e16.0

Card 12

Columns	Quantity	Format
1-16	C_0	e16.0
17-32	C_1	e16.0
33-48	C_2	e16.0
49-64	C_3	e16.0
65-80	C_4	e16.0

Card 13

Columns	Quantity	Format
1-16	C_5	e16.0
17-32	C_6	e16.0
33-48	C_7	e16.0
49-64	C_8	e16.0
65-80	C_9	e16.0

(continued next page)

Card 14

Columns	Quantity	Format
1-16	T_0	e16.0
17-32	T_1	e16.0
33-48	T_2	e16.0
49-64	T_3	e16.0
65-80	T_4	e16.0

Card 15

Columns	Quantity	Format
1-16	T_5	e16.0
17-32	T_6	e16.0
33-48	T_7	e16.0
49-64	T_8	e16.0
65-80	T_9	e16.0

Card 16

Columns	Quantity	Format
1-16	γ	e16.0
17-32	E(0), initial internal energy per unit reference volume	e16.0
33-48	x(0), initial relative volume	e16.0

The tabulated compaction model is linear in internal energy. Pressure is defined by

$$P = C(\varepsilon_V) + \gamma T(\varepsilon_V)E$$

in the loading phase. The volumetric strain, ε_V, is given by the natural logarithm of the relative volume. From two to ten points may be used to define the tabulated functions. KDYNA will extrapolate to find the pressure if necessary.

Equation-of-State Form 11 [41]
(TENSOR Pore Collapse)

Card 1

Columns	Quantity	Format
1-5	Number of virgin loading curve points, NLD (<63)	i5
6-10	Number of completely crushed curve points, NCR (<63)	i5
11-20	Excess compression required before any pores can collapse, μ_1	e10.0
21-30	Excess compression point where virgin loading curve and completely crushed curve intersect, μ_2	e10.0
31-40	E(0), initial internal energy per unit reference volume	e10.0
41-50	$\mu(0)$, initial excess compression	e10.0

Cards 2 through NLD+1

Virgin Loading Curve Definition

Columns	Quantity	Format
1-15	Excess compression	e15.0
16-30	Pressure	e15.0

Cards NLD+2 through NLD+NCR+1

Completely Crushed Curve Definition

Columns	Quantity	Format
1-15	Excess compression	e15.0
16-30	Pressure	e15.0

The TENSOR model defines two curves, the virgin loading curve and the completely crushed curve, as shown in Fig. 7.5. It also defines the excess compression point where pore collapse begins, μ_1, and the excess compression point where it ends with the material completely crushed, μ_2. From this data and the maximum excess compression the material has attained, μ_{max}, the pressure for any excess compression can be determined. Unloading occurs along the virgin loading curve until the excess compression surpasses μ_1. After that, the unloading follows a path between the completely crushed curve and the virgin loading curve. Reloading will follow this curve back up to the virgin loading curve. Once the excess compression exceeds μ_2 the unloading follows the completely crushed curve.

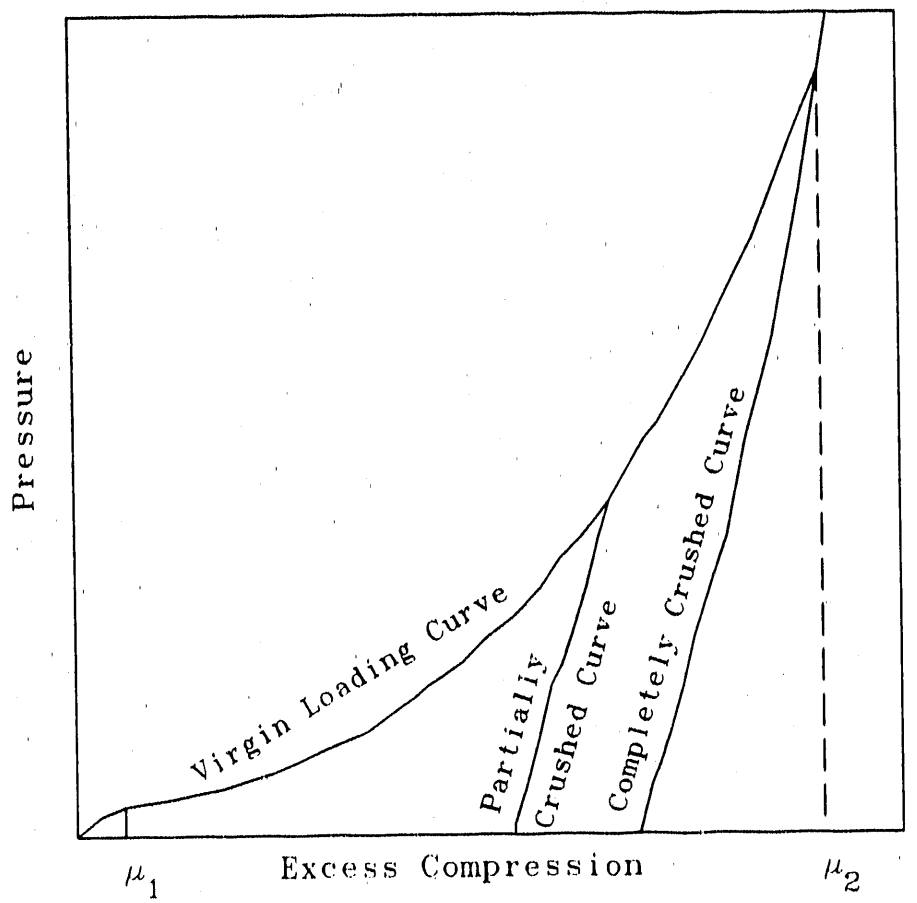

Fig. 7.5 TENSOR Pore Collapse Model

For unloading between μ_1 and μ_2 a partially crushed curve is determined by the relationship:

$$P_{pc}(\mu) = P_{cc}\left(\frac{(1+\mu_B)\ (1+\mu)}{(1+\mu_{max})} - 1\right)$$

where

$$\mu_B = P_{cc}^{-1}(P_{max})$$

and the subscripts pc and cc refer to the partially crushed and completely crushed states, respectively. This is more readily understood in terms of the relative volume, V.

$$V = \frac{1}{1+\mu}$$

$$P_{pc}(V) = P_{cc}\left(\frac{V_B}{V_{min}} V\right)$$

This representation suggests that for a fixed V_{min} $(= \frac{1}{\mu_{max}+1})$ the partially crushed curve will separate linearly from the completely crushed curve as V increases to account for pore recovery in the material.

The bulk modulus K is determined to be the slope of the current curve times one plus the excess compression:

$$K = \frac{\delta P}{\delta \mu} (1+\mu)$$

The slope $(\frac{\delta P}{\delta \mu})$ for the partially crushed curve is obtained by differentiation as:

$$\frac{\delta P}{\delta \mu} = \frac{\delta P_{cc}\left(\frac{(1+\mu_B)(1+\mu)}{(1+\mu_{max})} - 1\right)}{\delta \mu} \frac{(1+\mu_B)}{(1+\mu_{max})}$$

Simplifying,

$$K = \frac{\delta P_{cc}(\mu_c)}{\delta \mu} (1+\mu_c)$$

where

$$\mu_c = \frac{(1+\mu_B)(1+\mu)}{(1+\mu_{max})} - 1$$

The bulk sound speed is determined from the slope of the completely crushed curve at the current pressure to avoid instabilities in the time step.

The virgin loading and completely crushed curves are modeled with monotonic cubic-splines. An optimized vector interpolation scheme is then used to evaluate the cubic-splines. The bulk modulus and sound speed are derived from a linear interpolation on the derivatives of the cubic-splines.

Equation-of-State Form 13 [35]
(TENSOR Pore Collapse with H-Division p(ρ,E) Tabular EOS and Cracking)

Card 1

TENSOR Pore Collapse Parameters

Columns	Quantity	Format
1-5	Number of virgin loading curve points, NLD (<63)	i5
6-10	Number of completely crushed curve points, NCR (<63)	i5
11-20	Excess compression required before any pores can collapse, μ_1	e10.0
21-30	Excess compression point where virgin loading curve and completely crushed curve intersect, μ_2	e10.0
31-40	E(0), initial internal energy per unit reference volume	e10.0
41-50	$\mu(0)$, initial excess compression	e10.0

Cards 2 through NLD+1

Virgin Loading Curve Definition

Columns	Quantity	Format
1-15	Excess compression	e15.0
16-30	Pressure	e15.0

Cards NLD+2 through NLD+NCR+1

Completely Crushed Curve Definition

Columns	Quantity	Format
1-15	Excess compression	e15.0
16-30	Pressure	e15.0

(continued on next page)

(Equation-of-State Form 13 continued)

Cards NLD+NCR+1 through NLD+NCR+8

Rock Gas Parameters

Columns	Quantity	Format
1-12	Reference density excluding air porosity, ρ_{g0}*	e12.5
13-16	Number of density levels, ND	i4
17-21	Number of energy levels, NE	i5
22-27	Number of pressure values, NP	i6
28-37	Minimum value of p_{max}/p_{vap}, i.e., maximum pressure/vaporization pressure, to apply to mixture model, ALPHMIN; set to 1.e-5 for problems without overburden, otherwise 1.e-2	e10.4
38-47	Vaporization pressure, PVAP	e10.4
48-57	Melt energy per unit volume based on reference density excluding air porosity, EMELT	e10.4

Rock Gas Tables **

- Table of monotonically decreasing density levels
- Table of upper energy level indices
- Table of lower energy level indices
- Table of monotonically decreasing energy levels
- Table of pressure values in blocks corresponding to each density level with entries in each block corresponding to each energy level

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* Reference density ρ_0 on Material Card 1 must include φ_0 air porosity so that $\rho_0 = (1-\varphi_0)\rho_{g0}$.

** These tables are supplied by H-Division given a description of the material composition.

Notes:

(1) Materials requiring gas tables must be among the first 10 materials defined in the input deck.

(2) Instead of putting the gas table itself into the input file the user may instead direct the code to read the gas table from public file KKDIV by putting *in place of the table* the symbol >------->xx...x where xx...x is the one- to eight-character ascii identifier, usually a three-digit number, for the equation of state of the material in the KKDIV eos tables. The KKDIV eos tables are ascii and can be viewed with a standard text editor.

Equation-of-State Form 14
(Cavity Pressure)

Card 1

Columns	Quantity	Format
1-10	Number of the load curve defining pressure versus radius or pressure versus time for the cavity	e10.0
11-20	Cavity initiation time; default is initial time specified on Control Card 3a.	e10.0

Notes:

(1) This load curve must be counted in the total number of load curves for the problem, specified on Control Card 1, columns 26-30.

(2) Provide a p(r) table for this load curve, as described in Section 9, with "RADPRES" or "TIMEPRES" for the load table type.

Equation-of-State Form 15 [35]
(H-Division p(ρ,E) Tabular EOS Only)

Card 1

Columns	Quantity	Format
1-20	EOS ascii label	a20

Card 2
Initial data

Columns	Quantity	Format
1-10	E(0), initial internal energy per unit reference volume	e10.0
11-20	x(0), initial relative volume	e10.0

Immediately following Card 2 attach the "Rock Gas Parameters" and "Rock Gas Tables" described for EOS 13.

Equation-of-State Form 16 [37]
(TENSOR Pore Collapse with Cracking)

Card 1
TENSOR Pore Collapse Parameters

Columns	Quantity	Format
1-5	Number of virgin loading curve points, NLD (<63)	i5
6-10	Number of completely crushed curve points, NCR (<63)	i5
11-20	Excess compression required before any pores can collapse, μ_1	e10.0
21-30	Excess compression point where virgin loading curve and completely crushed curve intersect, μ_2	e10.0
31-40	E(0), Initial internal energy per unit reference volume	e10.0
41-50	$\mu(0)$, Initial excess compression	e10.0

Cards 2 through NLD+1
Virgin Loading Curve Definition

Columns	Quantity	Format
1-15	Excess compression	e15.0
16-30	Pressure	e15.0

Cards NLD+2 through NLD+NCR+1
Completely Crushed Curve Definition

Columns	Quantity	Format
1-15	Excess compression	e15.0
16-30	Pressure	e15.0

Equation-of-State Form 17 [38]
(P–α with EOP Tables)

Card 1

Columns	Quantity	Format
1–5	EOP Number	e10.0
11–15	Table/Gruneisen flag EQ.0: Gruneisen EOS or tabular EOS as necessary EQ.1: Gruneisen EOS only	I5
16–25	E(0), initial internal energy per unit reference volume	e10.0
26–35	$\mu(0)$, initial excess compression	e10.0
36–43	P–α parameter file name[1,2]	a8
44–51	EOP table name[1,2]	a8

Notes:

1. Supplied by H-Division upon request with specification of composition.

2. P–α and EOP file need only be given with first material since these files contain data for all materials using EOS 17.

Equation-of-State Form 18 [39]
(Effective Stress Model)

Input consists of three data sets:
1. Dry matrix
2. Solid grain
3. Water

Each data set contains:
a) a header block (see below)
b) a p-μ load curve (as for EOS 11)
c) a p-μ unload curve (as for EOS 11)

Dry Matrix Header Block (1 Card)

Columns	Quantity	Format
1-5	Number of points in load curve	i5
6-10	Number of points in unload curve	i5
11-20	μ_{1m} elastic/crush μ threshold	e10.0
21-30	μ_{2m} compaction μ threshold	e10.0
31-40	$\rho_m(0)$ initial dry matrix density	e10.0
41-50	$\varphi_a(0)$ initial air-filled porosity	e10.0

Solid Grain Header Block (1 Card)

Columns	Quantity	Format
1-5	Number of points in load curve	i5
6-10	Number of points in unload curve	i5
11-20	μ_{1g} elastic/crush μ threshold	e10.0
21-30	μ_{2g} compaction μ threshold	e10.0
31-40	$\rho_g(0)$ initial solid grain density	e10.0

(continued next page)

(continuation of EOS 18)

Water Header Block (1 Card)

Columns	Quantity	Format
1-5	Number of points in load curve	i5
6-10	Number of points in unload curve	i5
11-20	μ_{1w} elastic/crush μ threshold	e10.0
21-30	μ_{2w} compaction μ threshold	e10.0
31-40	$\rho_w(0)$ initial water density	e10.0
41-50	$\varphi_w(0)$ initial water-filled porosity	e10.0

Equation-of-State Form 19 [39]
(Effective Stress Model with Gas Tables)

Input consists of four data sets:

1. Dry matrix
2. Solid grain
3. Water
4. Rock gas tables for homogeneous solid-water mixture

Data sets 1-3 contain:

a) a header block (see below)
b) a p-μ load curve (as for EOS 11)
c) a p-μ unload curve (as for EOS 11)

Data set 4 consists of the Rock Gas parameters and Rock Gas tables.

Dry Matrix Header Block (1 Card)

Columns	Quantity	Format
1-5	Number of points in load curve	i5
6-10	Number of points in unload curve	i5
11-20	μ_{1m} elastic/crush μ threshold	e10.0
21-30	μ_{2m} compaction μ threshold	e10.0
31-40	$\rho_m(0)$ initial dry matrix density	e10.0
41-50	$\varphi_a(0)$ initial air-filled porosity	e10.0

Solid Grain Header Block (1 Card)

Columns	Quantity	Format
1-5	Number of points in load curve	i5
6-10	Number of points in unload curve	i5
11-20	μ_{1g} elastic/crush μ threshold	e10.0
21-30	μ_{2g} compaction μ threshold	e10.0
31-40	$\rho_g(0)$ initial solid grain density	e10.0

(continued next page)

(continuation of EOS 19)

Water Header Block (1 Card)

Columns	Quantity	Format
1-5	Number of points in load curve	i5
6-10	Number of points in unload curve	i5
11-20	μ_{1w} elastic/crush μ threshold	e10.0
21-30	μ_{2w} compaction μ threshold	e10.0
31-40	$\rho_w(0)$ initial water density	e10.0
41-50	$\varphi_w(0)$ initial water-filled porosity	e10.0

(continued on next page)

(Equation-of-State Form 19 continued)

Cards NLD+NCR+1 through NLD+NCR+8

Rock Gas Parameters

Columns	Quantity	Format
1-12	Reference density excluding air porosity, ρ_{g0}*	e12.5
13-16	Number of density levels, ND	i4
17-21	Number of energy levels, NE	i5
22-27	Number of pressure values, NP	i6
28-37	Minimum value of p_{max}/p_{vap}, i.e., maximum pressure/vaporization pressure, to apply to mixture model, ALPHMIN; set to 1.e-5 for problems without overburden, otherwise 1.e-2	e10.4
38-47	Vaporization pressure, PVAP	e10.4
48-57	Melt energy per unit volume based on reference density excluding air porosity, EMELT	e10.4

Rock Gas Tables **

- o Table of monotonically decreasing density levels
- o Table of upper energy level indices
- o Table of lower energy level indices
- o Table of monotonically decreasing energy levels
- o Table of pressure values in blocks corresponding to each density level with entries in each block corresponding to each energy level

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* Reference density ρ_0 on Material Card 1 must include φ_0 air porosity so that $\rho_0 = (1-\varphi_0)\rho_{g0}$.

** These tables are supplied by H-Division given a description of the material composition.

Notes:

(1) Materials requiring gas tables must be among the first 10 materials defined in the input deck.

(2) Instead of putting the gas table itself into the input file the user may instead direct the code to read the gas table from public file KKDIV by putting *in place of the table* the symbol >------->xx...x where xx...x is the one- to eight-character ascii identifier, usually a three-digit number, for the equation of state of the material in the KKDIV eos tables. The KKDIV eos tables are ascii and can be viewed with a standard text editor.

Equation-of-State Form 24
(Gruneisen from Piecewise Linear U_s-U_p Curve)

Card 10

Columns	Quantity	Format
1-5	Number of u_s and u_p values on next two cards, .le.8	i5

Card 11

Columns	Quantity	Format
1-10	$u_p(1)$	e10.0
11-20	$u_p(2)$	e10.0
21-30	$u_p(3)$	e10.0
31-40	$u_p(4)$	e10.0
41-50	$u_p(5)$	e10.0
51-60	$u_p(6)$	e10.0
61-70	$u_p(7)$	e10.0
71-80	$u_p(8)$	e10.0

Card 12

Columns	Quantity	Format
1-10	$u_s(1)$	e10.0
11-20	$u_s(2)$	e10.0
21-30	$u_s(3)$	e10.0
31-40	$u_s(4)$	e10.0
41-50	$u_s(5)$	e10.0
51-60	$u_s(6)$	e10.0
61-70	$u_s(7)$	e10.0
71-80	$u_s(8)$	e10.0

Card 13

Columns	Quantity	Format
1-10	d0	e10.0
11-20	d1	e10.0
21-30	d2	e10.0
31-40	e0	e10.0
41-50	e1	e10.0
51-60	e2	e10.0
61-70	E(0), initial internal energy per unit reference volume	e10.0
71-80	x(0), initial relative volume	e10.0

(continued next page)

(Equation-of-State Form 24 continued)

The Gruneisen equation of state with piecewise linear shock velocity-particle velocity defines pressure for compressed materials ($\rho>\rho_0$) as

$$p = \frac{\rho_0 C_i^2 \mu[1+(1-\gamma_0/2)\mu-(\gamma_0/2)\mu^2]}{[1-(S_i-1)\mu]^2} + (1+\mu)\gamma_0 E$$

and for expanded materials ($\rho<\rho_0$) as

$$p = \rho_0 C_i^2 \mu + (1+\mu)\gamma_0 E.$$

where S_i is the slope and C_i the y-intercept of the ith segment of the u_s-u_p curve and the Gruneisen parameter, γ_0, is defined as

$$\gamma_0 = d_0 + d_1/\rho_0(1+\mu) + d_2/\rho_0^2(1+\mu)^2 \qquad \text{for} \quad \rho>\rho_0,$$

$$\gamma_0 = e_0 + e_1\rho_0(1+\mu) + e_2\rho_0^2(1+\mu)^2 \qquad \text{for} \quad \rho<\rho_0.$$

4. Nodal Point Cards

Columns	Quantity	Format
1-5	Nodal point number, n^i	i5
6-10	Boundary condition code, BCC^i	f5.0
	EQ.0.: no constraint	
	EQ.1.: r-constraint	
	EQ.2.: z-constraint	
	EQ.3.: r- and z-constraints	
	If BCC^i is not any of the above it is assumed to be the angle in degrees between the positive r-axis and the direction of motion along a sliding boundary (see Fig. 8)	
11-20	r^i - global coordinate	e10.0
21-30	z^i - global coordinate	e10.0
31-35	Generation interval KN	i5
	EQ.0: default, set to 1	

Nodal point cards do not have to be in order; however, the highest nodal point number must terminate the nodal data. When nodal data are missing, node numbers are generated according to the sequence:

$$n^i,\ n^i + KN,\ n^i + 2KN,\ \ldots,\ n^j,$$

where n^i and n^j are the nodal numbers defined on two consecutive cards, and KN is taken from the first card. Linear interpolation is used to obtain the coordinates of the generated nodes. The boundary conditions code of generated data is set to zero whenever $BCC^i \neq BCC^i$: otherwise, the code is assumed to be the same.

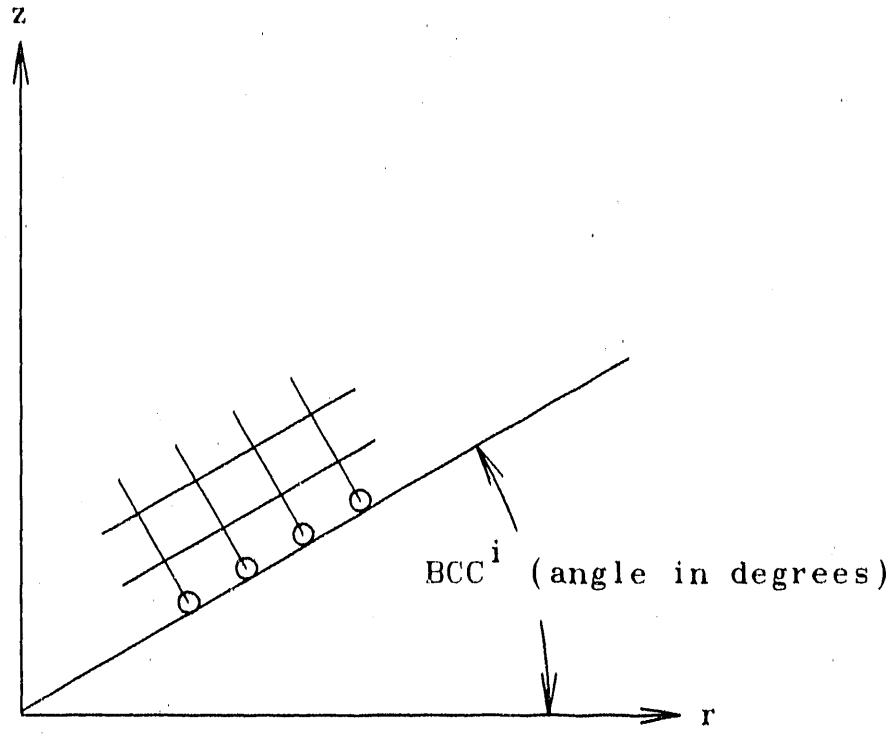


Fig. 8 Roller boundary condition that is obtained if BCC^i is not 0, 1, 2, or 3.

5. Element Cards

Supply one card for each element with the following information:

Columns	Quantity	Format
1-5	Element number	i5
6-10	Node n_1	i5
11-15	Node n_2	i5
16-20	Node n_3	i5
21-25	Node n_4	i5
26-30	Material number	i5
31-35	Generation increment, KN	i5
36-45	Material dependent parameter MT.EQ.2: angle ψ in degrees MT.EQ.8,9: for IBURN.LT.3 value is 1.0 if element is lit at time zero, for IBURN.EQ.3 value is actual burn time of element MT.GE.10: initial internal energy per reference volume V_0.	e10.0
46-55	Initial relative volume for MT.GE.10 only	e10.0

Element cards are assumed to be in element number sequence with the last element terminating the data. Omitted data are automatically generated with respect to the first card prior to the omitted data as follows:

$$n_j^{i+1} = n_j^i + KN.$$

The material properties, the mesh generation parameter, print code, and ψ are taken from the first card. The convention for numbering nodal points is shown in Fig. 9 where n_1, n_2, n_3, and n_4 stand for global node numbers. Triangular zones are defined by setting node $n_4 = n_3$.

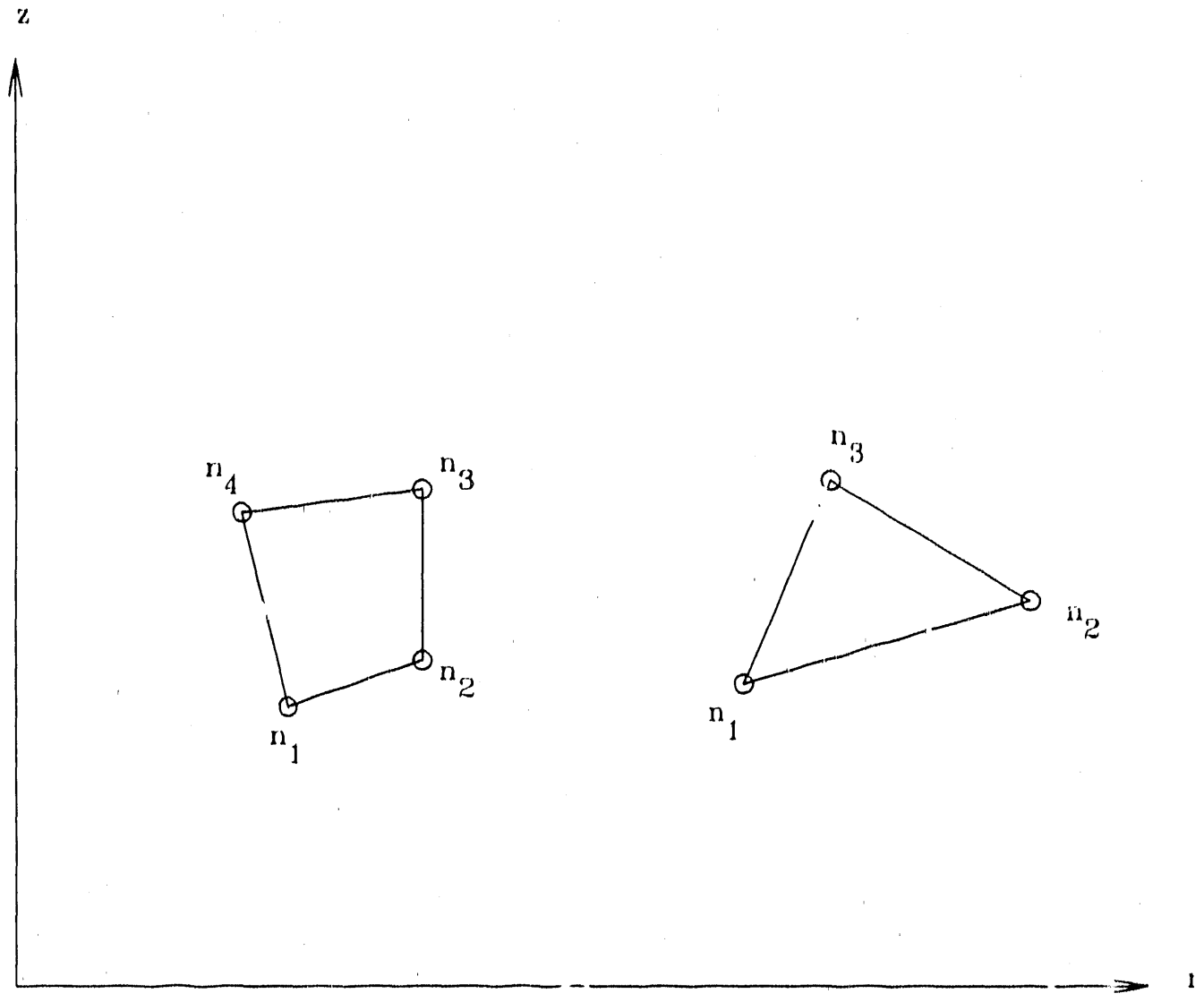


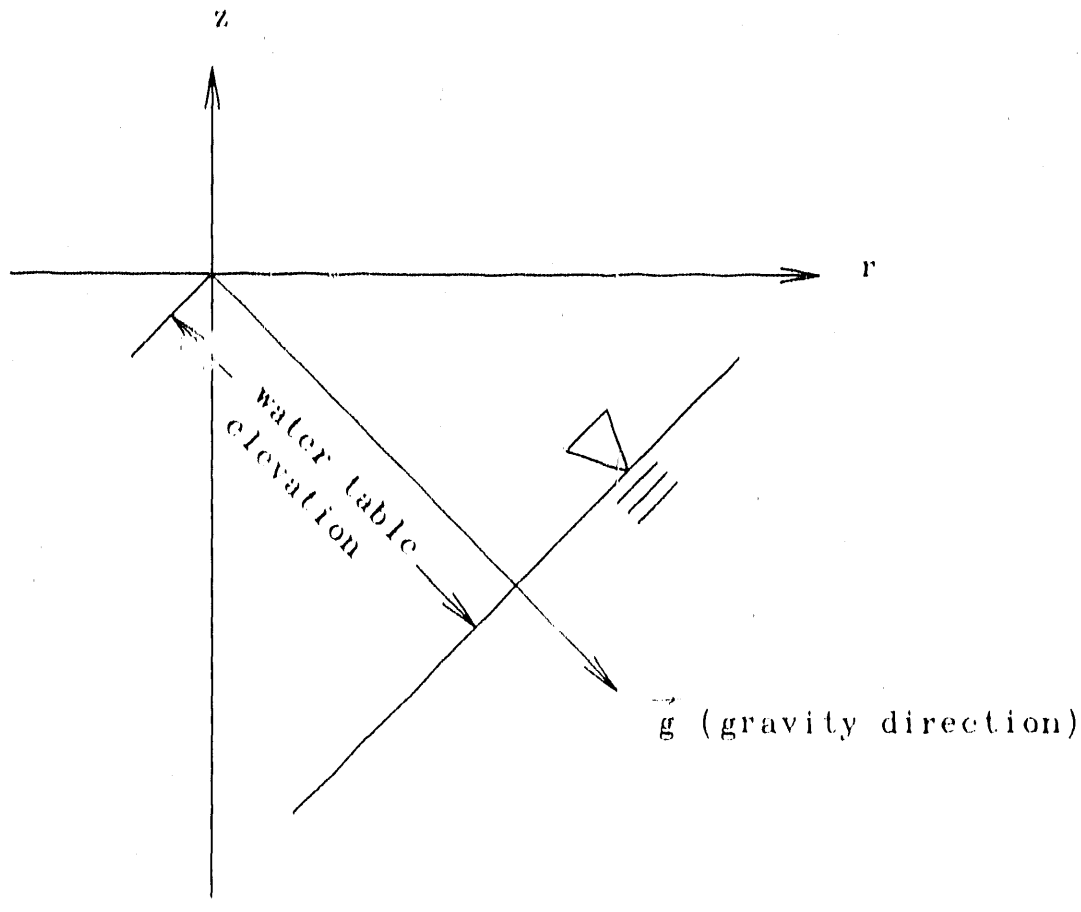
Fig. 9 Three- and four-node elements available in KDYNA.

5A. Gravity Definition Card

Skip this section if the overburden flag (Section 2, Card 2, column 70) is blank; otherwise supply the following card:

Card 1

Columns	Quantity	Format
1-10	Radial component of gravity vector	e10.0
11-20	Axial component of gravity vector	e10.0
21-30	Radial component of seed point in mesh overburden	e10.0
31-40	Axial component of seed point in mesh overburden	e10.0
41-50	Overburden pressure at seed point	e10.0
51-60	Water table elevation, required by effective stress models, EOS 18 and EOS 19	e10.0



6. High Explosive Burn Definition

Skip this section if IBURN (Card 3, Section 2) is less than 2. Three options are available (see Fig. 10): multiple point detonation, line detonation, and Huygens detonation.

Card 1

Columns	Quantity	Format
1-5	Detonation type, IBTYP EQ.0: multiple point detonation EQ.1: line detonation EQ.2: Huygens detonation	i5
6-10	NUMPTS IBTYP.NE.1: NUMPTS is the number of detonation points IBTYP.EQ.1: NUMPTS is the number points in the detonation line	i5

Repeat the following set of cards NUMPTS times:

Card 2

Columns	Quantity	Format
1-5	Nodal point number IBTYP.NE.1: lying at detonation point IBTYP.EQ.1: lying on detonation line	i5
6-15	Lighting time EQ.0. if IBTYP=1	i5
16-20	Material number of HE to be lit (IBTYP=0 only) EQ.0: The possibility of all HE elements being lit by this point is considered	i5
21-30	Detonation velocity outside shadowed HE (optional)	e10.0
31-40	Detonation velocity inside shadowed HE (optional)	e10.0

Card 3

Include the following card only if IBTYP=2.

Columns	Quantity	Format
1-5	NPSS, number of nodal points defining shadow boundary	i5

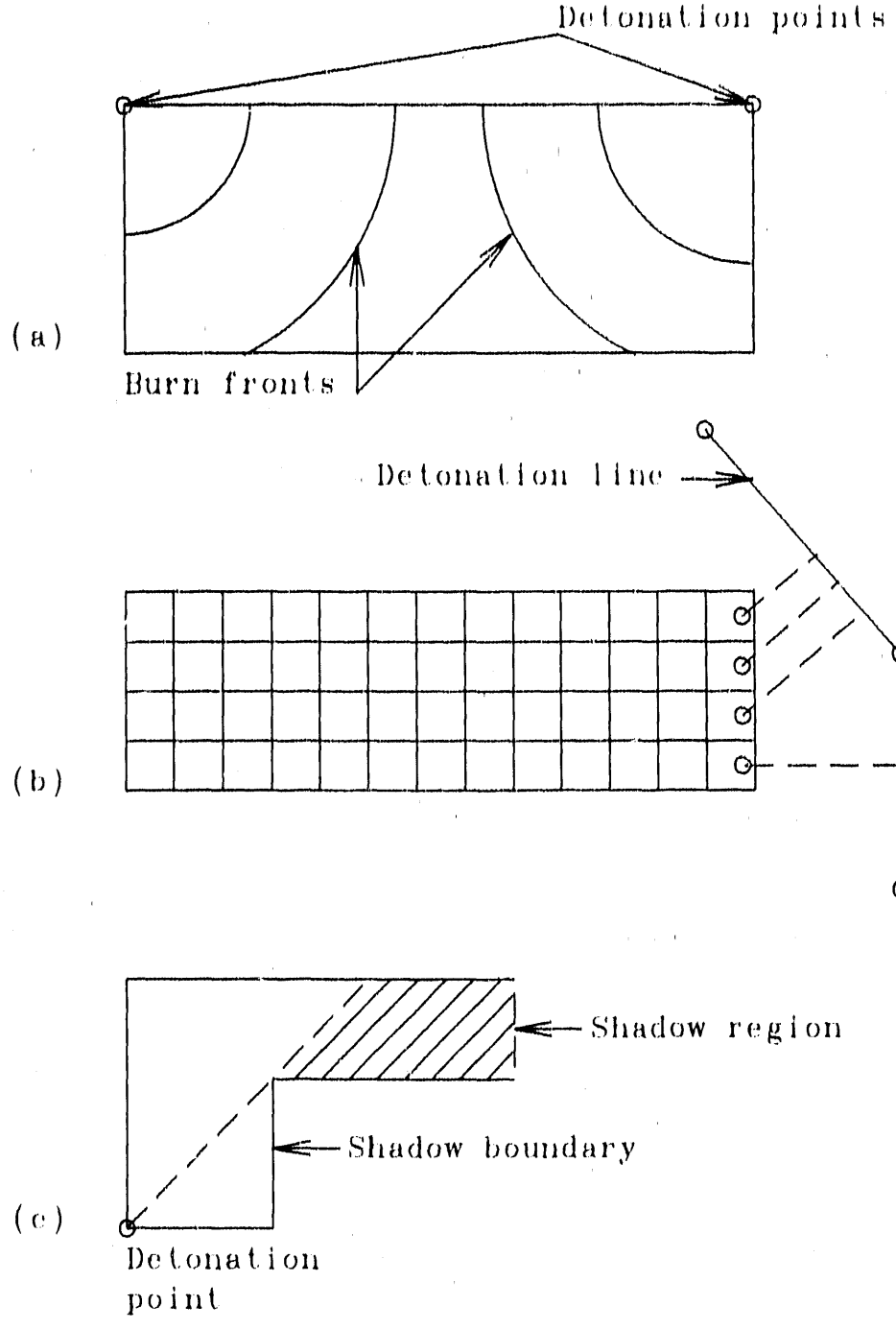


Fig. 10. Burn options: (a) multiple point
(b) line
(c) Huygens

Cards 4, 5, ... , NPSS+3
Include the following cards only if IBTYP=2.

Columns	Quantity	Format
1-5	Shadow point number	I5
6-10	Nodal point number	I5

A line detonation must be defined by at least two points. Nodal points that define a line must be given in the order in which they appear as one moves along the line.

In a Huygens detonation, a shadow boundary must be given for each detonation point. The first point on the shadow boundary must be closest to the detonation point - if it is not the detonation point itself. The shadow points must be defined in the order in which they are encountered as one moves along the boundary. Omitted data are automatically generated by incrementing the nodal point numbers by: $(n_i - n_j)/(sn_i - sn_j)$, where sn_i and sn_j are the shadow point numbers on two successive cards and n_i and n_j are their corresponding code numbers.

7. Nodal Printout Blocks

Skip this section if the number of nodal printout blocks (Card 1, Section 2) is zero. Otherwise insert one or more cards defining the blocks as below.

Columns	Quantity	Format
1-5	First node of printout block #1	i5
6-10	Last node of printout block #1	i5
11-15	First node of printout block #2	i5
16-20	Last node of printout block #2	i5

.
.
.

8. Element Printout Blocks

Skip this section if the number of element printout blocks (Card 1, Section 2) is zero. Otherwise insert one or more cards defining the blocks as below.

Columns	Quantity	Format
1-5	First element of printout block #1	i5
6-10	Last element of printout block #1	i5
11-15	First element of printout block #2	i5
16-20	Last element of printout block #2	i5

.
.
.

9. Load Curve Cards

Define the number of load curve sets specified in columns 26-30 of Card 1 in Section 2. Repeat the following cards for each set:

Card 1

Columns	Quantity	Format
1-5	Load curve number	i5
6-10	Number of points in load curve, NPTS	i5
11-20	Scale factor for time or volume *	e10.0
21-30	Scale factor for pressure values	e10.0
31-35	Initialization flag EQ.0: analysis only EQ.1: initialization only EQ.2: both analysis and initialization	i5
61-68	Load table type "RADPRES" for a function of radius * "TIMEPRES" for a function of time (default)	a8

Cards 2 through NPTS+1

Columns	Quantity	Format
1-10	Time or radius *	e10.0
11-20	Load value	e10.0

* For p(r) option the radius is used to find the volume ($\frac{4}{3}\pi r^3$), which is then multiplied by the scale factor (cols. 11-20 on Card 1).

10. Concentrated Nodal Load and Follower Force Cards

Supply the number of concentrated nodal point loads specified in columns 31-35 of Card 1, Section 2.

Columns	Quantity	Format
1-5	Nodal point number, m, on which this load acts	i5
6-10	Direction in which load acts EQ.1 and IFW.EQ.0: r-direction EQ.2 and IFW.EQ.0: z-direction EQ.n and IFW.EQ.1: perpendicular to the line between nodes m and n pointing towards the right as you move from m to n	i5
11-15	Load curve number	i5
16-25	Scale factor EQ.0.: default, set to 1.	e10.0
26-30	IFW, follower force flag EQ.0: concentrated force acts in either r or z direction EQ.1: follower force considered	i5

11. Pressure and Shear Boundary Condition Cards

Supply the number of cards specified in columns 31-35 of Card 2, Section 2.

Columns	Quantity	Format
1-5	Card number	i5
6-10	Load curve number LT.0: Brode function is used to determine pressure	i5
11-15	Node n_1	i5
16-20	Node n_2	i5
21-30	Multiplier of load curve at n_1, M_1 EQ.0 : default, set to 1.	e10.0
31-40	Multiplier of load curve at n_2, M_2	e10.0
41-50	Arrival time of load on the surface	e10.0
51-55	Generation interval, KN EQ.0: default, set to 1	i5
56-60	Loading type EQ.0: pressure EQ.1: shear	i5

The start times, multipliers, and generation interval are taken from the first card. The interior is kept to the left as one progresses from node n_1 to n_2 (see Fig. 11). Traction loads are always evaluated with respect to the deformed geometry.

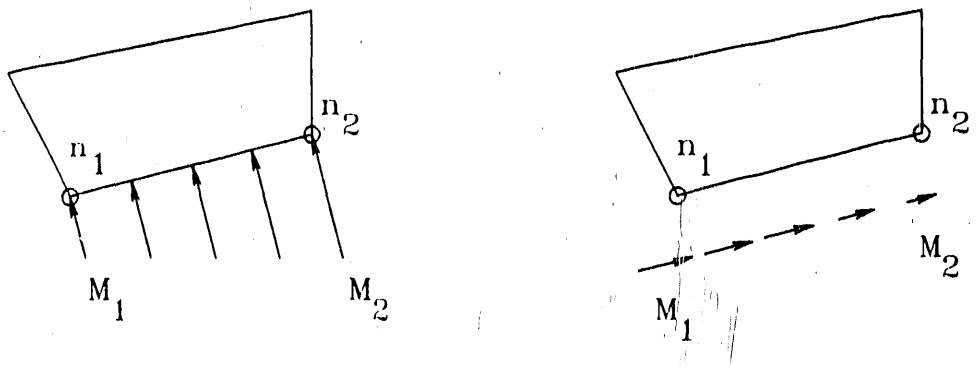


Fig. 11. Traction boundary conditions defined on an element between nodes n_1 and n_2.

12. Velocity Boundary Condition Cards

Supply the number of cards specified in columns 6-10 of Card 2, Section 2.

Columns	Quantity	Format
1-5	Nodal point number to which this velocity is applied	i5
6-10	Load curve number	i5
11-15	Direction in which the node is displaced EQ.1.: r-direction EQ.2.: z-direction NE.1. and NE.2.: the angle in degrees counterclockwise between the r-axis and the direction of the prescribed velocity vector	f5.0
16-25	Scale factor	e10.0

13. Base Acceleration in r-Direction

Skip this card is columns 11-15 of Card 2, Section 2 are blank.

Columns	Quantity	Format
1-5	Load curve number	i5
6-15	Scale factor on r-acceleration EQ.0: default, set to 1.	e10.0

This card applies only to plane strain geometries.

14. Base Acceleration in z-Direction

Skip this card is columns 16-20 of Card 2, Section 2 are blank.

Columns	Quantity	Format
1-5	Load curve number	i5
6-15	Scale factor on z-acceleration EQ.0: default, set to 1.	e10.0

15. Angular Velocity

Skip this card is columns 21-25 of Card 2, Section 2 are blank.

Columns	Quantity	Format
1-5	Load curve number	i5
6-15	Scale factor on angular velocity EQ.0: default, set to 1.	e10.0

Nodal loads due to the angular velocity are always calculated with respect to the deformed configuration. Angular velocity is assumed to have units of radians per unit time.

This card applies only to axisymmetric geometries.

16. Nodal Constraint Cards

Supply the number of nodal constraint card sets specified in Card 2, Section 2.

Card 1

Columns	Quantity	Format
1-5	Number of nodes that share at least one degree-of-freedom	i5
6-10	Degrees-of-freedom in common EQ.1: r is constrained EQ.2: z is constrained EQ.3: r and z are constrained	i5

Card 2

Columns	Quantity	Format
1-5	Nodal point number of first node to be tied	i5
6-10	Nodal point number of second node to be tied	i5
11-15	Nodal point number of third node to be tied	i5
.	.	.
.	.	.
.	.	.

17. Initial Conditions

Skip this section if the initial condition parameter, in columns 26-30 of Card 2, Section 2, is zero.

Columns	Quantity	Format
1-5	Nodal point number	i5
6-15	Initial velocity in r-direction	e10.0
16-25	Initial velocity in z-direction	e10.0
26-35	Nodal point increment EQ.0: default, set to 1	i5

Initial velocity must be defined for each nodal point. These cards do no have to be in order; however, the highest nodal point number must terminate the data. Missing data are generated as described in Section 4.

18. Non-reflecting (Silent) Boundaries

Supply the following cards for each definition.

Card 1

Columns	Quantity	Format
1-5	NBNS, number of boundary nodes	i5

Cards 2, ..., NBNS+1

Columns	Quantity	Format
1-5	Boundary point number EQ.0: increment last value by 1	i5
6-10	Nodal point number	i5

A boundary must be defined by at least two points. Nodal point numbers must be given in the order in which they appear as one moves along the boundary. Omitted data are automatically generated by incrementing the nodal point numbers by:

$$(n_i - n_j) / (bn_i - bn_j)$$

where bn_i and bn_j are the boundary point numbers on two successive cards and n_i and n_j are their corresponding node numbers.

19. Stonewalls

Skip this section if the number of stonewalls specified in columns 31-35 of Card 2, Section 2 is zero. Repeat the following set of cards for each stonewall.

Card 1

Columns	Quantity	Format
1-5	Number of slave nodes	i5
6-15	r-coordinate of tail of any outward drawn normal vector originating on wall (tail) and terminating in space (head)	e10.0
16-25	z-coordinate of tail	e10.0
26-35	r-coordinate of head	e10.0
36-45	z-coordinate of head	e10.0

Cards 2, 3, ...

Columns	Quantity	Format
1-5	Slave number	i5
6-10	Nodal point number	i5

A stonewall extends to infinity and is defined by a normal vector of arbitrary magnitude drawn outward from the wall. Nodes that are designated as slave nodes cannot penetrate a stonewall: other nodes can penetrate.

Omitted slave nodes are automatically generated by incrementing the nodal point numbers by:

$$(n_i - n_j) / (sn_i - sn_j)$$

where sn_i and sn_j are the slave numbers on two successive cards and n_i and n_j are their corresponding node numbers.

Note: Sections 19-21 will be skipped if the number of slidelines is zero.

20. Slideline Control Cards

Supply a control card for each slideline. A discussion of the use of the slideline capability appears in Appendix A.

Columns	Quantity	Format
1-5	Number of slave nodes in slideline, NSN	i5
6-10	Number of master nodes in slidelins, NMN	i5
11-15	Slideline type number, ISLT EQ.1: sliding only EQ.2: tied sliding EQ.3: sliding with voids EQ.4: penalty formulation with friction EQ.5: penalty formulation without friction EQ.6: single surface contact (NMN=0)	i5
16-25	SLFAC, tolerance for determining initial gaps EQ.0.: SLFAC = 0.001	e10.0
26-35	θ_1, angle in degrees of slideline extension at first master node EQ.0.: extension remains tangent to first master segment	e10.0
36-45	θ_2, angle in degrees of slideline extension at last master node EQ.0.: extension remains tangent to last master segment	e10.0
46-55	Scale factor or penalty EQ.0.: default, set to .1	e10.0
56-60	Slideline extension bypass option EQ.1: slideline extensions are not used	i5

Angles θ_1 and θ_2 are measure counterclockwise from the r-axis and remain constant. If θ_1 and θ_2 are zero, the extensions are made tangent to the first and last master segments and remain so throughout the calculation. The force exerted by a slave node lying on an extension of the master node at the origin of the extension diminishes to zero as the slave node moves away a distance equal to the length of one slave segment.

21. Slideline Definitions

Repeat the following card set for each slideline.

Card 1

Columns	Quantity	Format
1-72	Ascii label or blank for ISLT ≠ 4	12a6
1-10	Coefficient of friction for ISLT = 4	e10.0

Cards 2, 3, ..., NSN+1

Columns	Quantity	Format
1-5	Slave number	i5
6-10	Nodal point number	i5

Omitted slave nodes are automatically generated by incrementing the nodal point numbers by:

$$(n_i - n_j) / (sn_i - sn_j)$$

where sn_i and sn_j are the slave numbers on two successive cards and n_i and n_j are their corresponding node numbers.

Cards NSN+2, ..., NSN+NMN+1

Columns	Quantity	Format
1-5	Master number	i5
6-10	Nodal point number	i5

Omitted master nodes are generated automatically as above. The master and slave nodes must be given in the order in which they appear as one moves along the surface. The slave surface must be to the left of the master.

22. Slideline Intersections

If no slidelines intersect, i.e. NUMSI = 0, skip this section. Otherwise supply NUMSI cards.

Cards 1, 2, ... , NUMSI

Columns	Quantity	Format
1-5	Number of slideline that is intersected	i5
6-10	Number of slideline that intersects the above line	i5

There must be one node which is a slave node common to both slidelines, and there must be one node which is a slave node to the first slideline and is a master node to the second slideline.

23. Brode Function Data [40]

Skip this section if columns 41-45 of Card 1, Section 2, are blank; otherwise supply a card set containing Brode function data, as described below.

Card 1

Columns	Quantity	Format
1-10	Yield (Kilotons)	e10.0
11-20	Height of burst	e10.0
21-30	XBO, x-coordinate of Brode origin in DYNA units	e10.0
31-40	YBO, y-coordinate of Brode origin in DYNA units	e10.0
41-50	ZBO, z-coordinate of Brode origin in DYNA units	e10.0
51-60	TBO, time of Brode origin in DYNA units	e10.0

Card 2

Columns	Quantity	Format
1-10	Conversion factor: ft to DYNA length units	e10.0
11-20	Conversion factor: ms to DYNA time units	e10.0
21-30	Conversion factor: psi to DYNA pressure units	e10.0
31-35	Effective yield option, IY EQ.0: default RANGE, COEF, and GFUNC NE.0: read new RANGE, COEF, and GFUNC for effective yield calculation from cards following	i5

Default conversion factors assume DYNA units are meters, seconds, and Pascals. If IY = 0 skip cards 3, 4, and 5 on next page.

Card 3

Columns	Quantity	Format
1-10	RANGE value for Brode effective yield calculation	e10.0
.	.	.
.	.	.
.	.	.
41-50	RANGE value for Brode effective yield calculation	e10.0

Card 4

Columns	Quantity	Format
1-10	COEF value for Brode effective yield calculation	e10.0
.	.	.
.	.	.
.	.	.
71-80	COEF value for Brode effective yield calculation	e10.0

Card 5

Columns	Quantity	Format
1-10	GFUNC value for Brode effective yield calculation	e10.0
.	.	.
.	.	.
.	.	.
61-70	GFUNC value for Brode effective yield calculation	e10.0

Note that the number of fields on each of these cards is different.

24. Discrete Springs, Dampers, and Masses

Skip this section if INPSD is zero.

Card 1

Columns	Quantity	Format
1-5	Number of material definitions, NUMMTDE	i5
6-10	Number of discrete springs and dampers, NUMELD	i5
11-15	Number of discrete masses, NUMMAS	i5

Next, supply NUMMTDE card pairs as described below.

Cards 2, 4, ... , 2*NUMMTDE

Columns	Quantity	Format
1-5	Material number (≤ NUMMTDE)	i5
6-10	Material type, MT: EQ.1: linear elastic EQ.2: linear viscous EQ.3: isotropic elastoplastic EQ.4: nonlinear elastic EQ.5: nonlinear viscous	i5

Cards 3, 5, ... , 2*NUMMTDE+1

Columns	Quantity	Format
1-10	Meaning and format depend upon material type, MT:	
	MT.EQ.1: elastic stiffness (force/displacement)	e10.0
	MT.EQ.2: damping constant (force/displacement rate)	e10.0
	MT.EQ.3: elastic stiffness (force/displacement)	e10.0
	MT.EQ.4: number of load curve describing force versus displacement	i10
	MT.EQ.5: number of load curve describing force versus displacement rate	i10
11-20	Tangent stiffness (force/displacement) for MT.EQ.3, otherwise not used	e10.0
21-30	Yield (force) for MT.EQ.3, otherwise not used	e10.0

(continued next page)

Next, supply NUMELD spring-and-damper cards as described below.

Cards 2*NUMMTDE+2 through 2*NUMMTDE+NUMELD+1

Columns	Quantity	Format
1-5	Element number	i5
6-10	Node, n_1	i5
11-15	Node, n_2	i5
16-20	Material number	i5
21-30	Scale factor on force, defaulted to 1.	e10.0

Finally, supply NUMMAS lumped mass cards as described below.

Cards 2*NUMMTDE+NUMELD+2 through 2*NUMMTDE+NUMELD+NUMMAS+1

Columns	Quantity	Format
1-5	Node number	i5
6-15	Mass	e10.0

25. Benson-Christensen-Margolin Viscosity

Columns	Quantity	Format
1-10	OPTJ (suggest 1.)	e10.0
11-20	OPTB (suggest 0.)	e10.0
21-25	IOPTF (suggest 0) EQ.0: Benson's viscosity EQ.1: Margolin's viscosity	i5
26-30	IOPTCE (suggest 0) EQ.0: turn on viscosity only in compression EQ.1: keep viscosity on all the time	i5
31-35	IOPTPT (suggest 0) only applies when IOPTF = 0 EQ.0: use full tensor formulation EQ.1: Set $Q_{11} = Q_{22}$ in tensor formulation	i5
36-40	IOPTS (suggest 0) EQ.0: do not symmetrize the viscosity tensor EQ.1: average shear terms to symmetrize	i5

OPTJ: range [0.,2.] sets the compressiveness of the flux limiting procedure. When set to 2. it produces the sharpest shocks. When set to 0. there is no flux limiting and the standard differencing of velocities is done, but the extra gathers and slope calculations are eliminated.

OPTB: range [0.,1.] scales the shear viscosity terms in Benson's tensor formulation. Benson typically uses values of .2 or .3 but computation is saved if it is set to 0. and this is safe for materials that have significant strength.

IOPTCE: value of 0 is cheaper

IOPTPT: For true scalar viscosity set both OPTB and IOPTPT to 0

IOPTS: should always be 0 for Benson's viscosity, while for Margolin's it should be 0 for elements of large aspect ratio, 1 otherwise

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Note: This card is only used for start runs.

RESTART INPUT DECK

An input deck is not needed to restart DYNA2D unless material properties or equation-of-state data are being read from tables. In that case, all material properties and eos data must be redefined in the restart file as in the original input file. The restart deck is used to redefine the following parameters:

- o termination time
- o output printing interval
- o output plotting interval
- o time history curves
- o material and equation-of-state constants

In addition, slidelines and blocks of elements may be eliminated from the calculations. All changes made when restarting will be reflected in subsequent restart dumps.

1. Title Card

Columns	Quantity	Format
1-66	Heading to appear on output	11a6

2. Control Card (Restart)

Columns	Quantity	Format
1-10	Termination time EQ.0.: termination time remains unchanged	e10.0
11-20	Output printing interval EQ.0.: interval remains unchanged	e10.0
21-30	Output plotting interval EQ.0.: interval remains unchanged	e10.0
31-35	Number of time histories to be redefined, NTHRD	i5
36-40	Number of slidelines to be eliminated from the calculation	i5
41-45	Number of element blocks to be eliminated from the calculation	i5
46-50	Number of material blocks to be eliminated from the calculation	i5
51-55	Number of slidelines to be defined	i5
56-60	Number of slideline intersections, NUMSLI	i5
61-65	Number of materials to be redefined, NMRD	i5
66-70	Flag for resetting default viscosities, IRQ EQ.1: new defaults are read in*	i5
71-80	Scale factor for computed time step size, SFCT EQ.0.: SFCT remains unchanged	e10.0

If the number of slidelines to be defined is nonzero, each slideline used in the subsequent calculation must be defined, even if it already exists in the restart file. The total number of slidelines to be defined must not exceed the number used in the original input deck.

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* If default viscosity option was not used during the START run, then the same option must be read back in upon RESTART.

3. Time-History Cards

Skip these cards if NTHRD equals zero; otherwise supply NTHRD card sets.

Card 1

Columns	Quantity	Format
1-5	Number associated with time history curve to be redefined.	i5

Cards 2, 3, . . . , NPTS+1

Columns	Quantity	Format
1-10	Time	e10.0
11-20	Function value	e10.0

The number of points in the load curve, NPTS, may not change from the original input.

4. Deleted Slidelines

Skip this section if the number of slidelines to be deleted is zero.

Columns	Quantity	Format
1-5	Number of first slideline to be deleted	i5
6-10	Number of second slideline to be deleted	i5
.	.	
.	.	
.	.	

5. Deleted Element Blocks

Skip this section if the number of element blocks to be deleted is zero.

Columns	Quantity	Format
1-5	First element of first block to be eliminated	i5
6-10	Last element of first block to be eliminated	i5
11-15	First element of second block to be eliminated	i5
16-20	Last element of second block to be eliminated	i5
.	.	
.	.	
.	.	

6. Deleted Material Blocks

Skip this section if the number of material blocks to be deleted is zero.

Columns	Quantity	Format
1-5	Material number of first material to be deleted	i5
6-10	Material number of second material to be deleted	i5
.	.	
.	.	
.	.	

7. Default Viscosities

Define if IRQ = 1.

Columns	Quantity	Format
1-5	Hourglass control, IHQ EQ.0: default set to 1 EQ.1: standard DYNA2D EQ.2: rotational EQ.3: Flanagan-Belytschko EQ.4: Hancock	i5
6-15	Hourglass viscosity coefficient, QH (default .1) IHQ.EQ.1: QH ≤ .15 IHQ.EQ.2: QH ≤ .20 IHQ.EQ.3: QH ≤ .40 IHQ.EQ.4: QH ≤ .40	e10.0
16-20	Bulk viscosity type, IBQ EQ.0: default set to 1 EQ.1: standard DYNA2D EQ.2: Richards-Wilkins EQ.5: Benson-Christensen-Margolin	i5
21-30	Quadratic viscosity coefficients, Q1 default value is 1.3 for IBQ = 5 default value is 1.5 otherwise	e10.0
31-40	Linear viscosity coefficient, Q2 default value is 1.0 for IBQ = 5 default value is .06 otherwise	e10.0

These are defaults that can be overridden for each material defined below, unless IBQ = 5 (BCM bulk viscosity).

8. Material Cards

Define NMRD sets of material cards following the procedure described in Section 3 of the chapter on the starting input deck.

INTERACTIVE REZONING

ENTERING THE REZONER

The user can cause KDYNA to enter the rezoner in one of four ways: by typing the rezoner sense switch during execution, by specifying periodic rezone times in the input file and supplying a rezone command file, by setting a future rezone time during a rezoning session with a time-to-rezone command, or by requesting a rezone on the execute line when restarting KDYNA. Each method is dicussed in more detail below.

The user can cause KDYNA to enter the rezoner in interactive mode by typing sense switch "SW5," from the terminal during execution. The viewer may then view the mesh and, if desired, make changes to it by typing rezoner commands from the terminal. The commands "F" and "FR" cause KDYNA to exit the rezoner and resume execution.

KDYNA may be caused to enter the rezoner at regular intervals and to take rezoning commands from a file, at least initially, by specifying initial and final rezone times and a rezone interval on Control Card 1 of the initial input deck. A rezone command file must be named on the execute line as shown here: KDYNA I=*inp* C=*cmd*
where *inp* is the name of the input file and *cmd* is the name of the rezone command file. If the command file does not contain an "F" or "FR" command, the rezoner will go into interactive mode.

While KDYNA is in a rezone session the user may set the time for it to reenter the rezoner after it has returned to execution for a while by using the "TR" command. The TR command may come from the terminal or from a command file. The TR rezone time takes precedence over periodic rezoning. TR cancels periodic rezoning.

When restarting from a dump file KDYNA may be caused to enter the rezoner in interactive mode immediately by an execute line of the form:
KDYNA Z=REZONE R=*rtf*
where *rtf* is the name of the restart dump to be read in.

REZONING COMMANDS

The commands of the KDYNA interactive mesh rezoner perform one of the following fourteen functions:

* Doing nothing
* Providing help with other rezoner commands

* Selecting devices and picture styles
* Entering and exiting rezoner
* Resetting output intervals
* Setting graphics windows for mesh plots
* Setting graphics windows for x versus y plots
* Setting other x versus y plot controls
* Displaying mesh
* Modifying mesh
* Modifying part boundaries
* Displaying computed quantities on a mesh
* Defining MAZE part boundaries
* Displaying or modifying mesh with a cursor

The rezoner is easy to use. Commands for viewing and rezoning material number n can be invoked after the material number is specified by the "M n" command. To view the material, use "V". To smooth the interior mesh, use "S". Boundary nodes can be adjusted after the "B" command has been used to display material boundary node and side numbers. The commands available for moving boundary nodes are ER, EZ, ES, VS, BC, ERS, EZS, ESS, VSS, BDS, SLN, and SLNS. Rezoning is performed material by material.

Do not include the TMDS monitor number when setting up a command file for periodic noninteractive rezoning. No plotting is done when the rezoner is used in this mode unless the "PLOTS" command is specified. In this latter case, one graphics file is created per rezone.

When stacking several sessions of periodic noninteractive rezoning, end each session with the sequence:

NORE
F

NORE prevents rewinding of the rezoner command file. F tells the code to resume execution after a rezone session rather than terminating.

Complete definitions of the available rezoning commands and an example of rezoning follow in this chapter.

REZONER OUTPUT

Upon entering the rezoner KDYNA prints the mass and energy of each material type into the output HSP file. For axisymmetric problems this is for a one-radian segment. If any mesh adjustment is done then upon exiting KDYNA prints the resulting new mass and energy of each material type.

REZONING COMMANDS BY FUNCTION

DOING NOTHING

C	Comment. Proceed to next command.

PROVIDING HELP WITH OTHER REZONER COMMANDS

HELP	Enter help package giving the list and definitions of all rezoning commands. Typing RETURN terminates the help mode.
HELP/command	Do not enter HELP package but only print the description of command to the terminal.
PHP ans	Print help package to ascii output file if ans is 'y'.

SELECTING DEVICES AND PICTURE STYLES

CLASS level	Set classification level of DLI output files. Choices are PROGLEV, PARD, ADP CONFIDNT, SRD, and SYSTEM. Default is PARD. Command must precede PLOTS.
FONT	Plot text in a stroked font (futura). Necessary if picture is to be rotated with DLTV afterwards.
FRAME	Frame plots with a reference grid (default).
FF	Encircle picture with a reference grid. Default is grid is plotted along bottom and left side of picture only.
FR80 filmtype	Select FR80 camera for DLI files. The default filmtype is FICHE48. The other choices are FICH48D, FICHE24, FICH24D, 35MM, COLOR35, DICO35, P16MM, COLOR16, DICO16, CSLIDE35 (color slides), HARDCOPY, REPORT, VUGRAPH, and VUGRAF11. If this command is used it must precede the PLOTS command.

GIVE	Give the DLI output files to the system for plotting upon termination. If this command is used it must precede the PLOTS command.
LOGO	Put LLNL logo on all plots (default.) Retyping removes the logo.
NOFRAME	Do not plot the reference grid.
PLOTS	Create a DLI file to save the pictures displayed on the TMDS. This command should only be called once, before generating the images to be saved.
RESO n_x n_y	Set the x and y resolutions for FRINGE plots to n_x and n_y, respectively. The defaults for both are 1024.
RJET n i	Upon termination send a copy of the DLI output file to rjet n with plot format i where: i=1 gives a 5" plot i=2 gives an 8" plot i=3 gives a 10.5" plot i=4 gives the larges possible plot If i is negative, the plot is turned sideways, rotated 90 degrees clockwise on the paper. Plots may be sent to either the 11" or 22" plotters.
TV n	Connect to TMDS with monitor number n. If n is the red channel for a color TMDS monitor the corresponding green and blue channels may be connected automatically if the authors are aware of the user's channel assignments.
TV $-n_1$ n_2 n_3	Connect to color TMDS with monitor numbers n_1, n_2, and n_3 for the red, green, and blue channels respectively.

ENTERING AND EXITING THE REZONER

TR t	Begin next interactive rezoning session at problem time t.
F	Terminate interactive phase, remap, and continue in execution phase.
FR	Terminate interactive phase, remap, write restart dump, and terminate.
T or END	Terminate.

RESETTING OUTPUT INTERVALS

PRTI Δt	Reset the time history dump or printout interval to Δt.
PLTI Δt	Reset the global plot dump interval to Δt.
TERM t	Reset the termination time to t.

SETTING GRAPHICS WINDOWS FOR MESH PLOTS

ESET n Δr Δz	Center TMDS pictures at element n with a rectangular Δr x Δz window. This window is set until it is reset with the FSET, GSET, ESET, or SETF commands or released with UNFIX.
FIX	Set TMDS picture to its current window. This window is set until it is reset by the GSET, FSET, or SETF commands or released by the UNFIX command.
UNFIX	Release current TMDS window set by the FIX, GSET, or SETF commands.
FSET n Δr Δz	Center TMDS pictures at node n with a rectangular Δr x Δz window. This window is set until it is reset with the FSET, GSET, ESET, or SETF commands or released with UNFIX.

GSET r z $\Delta\ell$	Center TMDS pictures at point (r,z) with square window of width $\Delta\ell$. This window is set until it is reset with the FSET, GSET, ESET, or SETF commands or released with UNFIX.
GRID	Overlay TMDS displays with a grid of orthogonal lines to aid in zooming.
NOGRID	Do not overlay TMDS displays with a grid of orthogonal lines (default).
SETF r z Δr Δz	Center TMDS pictures at point (r,z) with rectangular Δr x Δz window. This window is set until it is reset with the FSET, GSET, ESET, or SETF commands or released with UNFIX.
UZ a b $\Delta\ell$	Zoom in at point (a,b) with window $\Delta\ell$ where a, b, and $\Delta\ell$ are numbers between 0 and 1. The picture is assumed to lie in a unit square.
UZG	Overlay currently displayed picture with a 10 x 10 square grid to aid in zooming with the UZ command.
Z r z $\Delta\ell$	Zoom in at point (r,z) with window $\Delta\ell$.

SETTING GRAPHICS WINDOWS FOR X VERSUS Y PLOTS

The following commands apply to LINE plots, IFP plots, etc.

ASCL f_a	Scale all abcissa (horizontal) data by f_a. The default is 1.
ASET amin amax	Set minimum and maximum abcissa limits to amin and amax respectively. For amin=0 and amax=0 KDYNA chooses limits according to the data.
OSCL f_o	Scale all ordinate (vertical) data by f_o. The default is 1.
OSET omin omax	Set minimum and maximum ordinate limits to omin and omax respectively. For omin=0 and omax=0 KDYNA chooses limits according to the data.

SETTING X VERSUS Y PLOT CONTROLS

SMOOTH n	Smooth a data curve by replacing each data point by its average with the 2n adjacent points. Default is n=0.

DISPLAYING THE MESH

ELPLT	Plot element numbers on mesh of material n.
FSON	Plot only free surfaces and slideline interfaces with the O command. This command must precede the O command.
FSOFF	Turn off the FSON feature.
G	Show the mesh.
GO	Show the mesh to the right of the centerline and the outline to the left of the centerline.
GS	Show the mesh and solid fill the elements to identify materials by color.
M n	Select material n for rezoning or viewing.
MNOFF	Do not plot material number with the O, G and GO commands (default).
MNON	Plot material numbers with the O, G, and GO commands.
NDPLT	Plot node numbers on mesh of material n.
O	Plot outlines of all materials.
RPHA	Reflect the mesh, contour, or fringe plot about the horizontal axis. Retyping this command turns off the feature.
RPVA	Reflect the mesh, contour, or fringe plot about the vertical axis. Retyping this command turns off the feature.

TN r z Δl	Type node numbers and coordinates of all nodes within window (r ± $\Delta l/2$, z ± $\Delta l/2$)
UG	Display the undeformed mesh.
V	Display material n on TMDS.
VSF	Display material n on TMDS and solid fill the elements.

MODIFYING THE MESH

BACKUP	Restore mesh to its previous state. This command undoes the result of a previous rezoning command.
BLEN s	Set smooth option parameter s, where s=0 and s=1 correspond to equipotential and isoparametric smoothing, respectively. By setting s between 0 and 1 combined blending is achieved.
CN m r z	Change coordinates of node m to (r,z).
DE e_1 e_2	Delete elements e_1 to e_2.
DEB n f_1 l_1 ... f_n l_n	Delete n element blocks consisting of elements f_1 to l_1, f_2 to l_2, ... f_n to l_n inclusive. These elements will be inactive in future calculations.
DELK n k_1 ... k_n	Delete n k-lines, k_1, k_2, ... k_n. Must have done KLMX and LLMX beforehand.
DELL n l_1 ... l_n	Delete n l-lines, l_1, l_2, ... l_n. Must have done KLMX and LLMX beforehand.
DM n m_1 m_2 ... m_n	Delete n materials, m_1, m_2, ... m_n.
DMB n f_1 l_1 ... f_n l_n	Delete n material blocks consisting of materials f_1 to l_1, f_2 to l_2, ... f_n to l_n inclusive. These materials will be inactive in future calculations.

KLMX n	Set number of nodes in k-direction to n (n < 1013) for regular part of mesh.
LLMX n	Set number of nodes in l-direction to n (n < 313) for regular part of mesh.
R	Restore original mesh.
S	Smooth mesh of meterial n. To smmooth a subset of elements a window can be set with the GSET, FSET, or SETF command. Only elements lying within the window are smoothed.

MODIFYING MESH BOUNDARIES

A	Display all slidelines. Slave sides are plotted dashed.
B	Display on TMDS boundary nodes and sides of material n with numbers.
BD m n	Dekink boundary between boundary nodes m and n in a counterclockwise direction.
BDS s	Dekink side s.
DSL n l_1 l_2 ... l_n	Delete n slidelines including slideline numbers l_1, l_2, ... , l_n.
ER m n	Equal space in r-direction boundary nodes m to n in counterclockwise direction.
ERS s	Equal space in r-direction boundary nodes on side s.
ES m n	Equal space by distance along boundary boundary nodes m to n in a counterclockwise direction.
ESS s	Equal space by distance along boundary boundary nodes on side s.

EZ m n	Equal space in z-direction boundary nodes m to n in counterclockwise direction.
EZS s	Equal space in z-direction boundary nodes on side s.
MC n	Check master nodes of slideline n and put any nodes that have penetrated the slave surface back on the slave surface.
MD n	Dekink master side of slideline n. After this command it is advisable to use the SC or MC command.
MN n	Display slideline n with master node numbers.
SC n	Check slave nodes of slideline n and put any nodes that have penetrated the master surface back on the master surface.
SD n	Dekink slave side of slideline n. After this command it is advisable to use the SC or MC command.
SLN m n	Equal space boundary nodes between nodes m and n on a straight line connecting the two.
SLNS s	Equal space boundary nodes along side s on a straight line between its two endpoints.
SN n	Display slideline n with slave node numbers.
VS m n r	Vary the spacing of boundary nodes m through n so that r is the ratio of the length of the first segment to that of the last segment.
VSS s r	Vary the spacing of boundary nodes on side s so that r is the ratio of the lengths of the first segment to that of the last segment.

CONTOUR c n m_1 m_2 ... m_n	Contour component number c on n materials, numbers m_1, m_2, ... ,m_n. If n is zero, only the outline of material m_1 with contours is plotted. Component numbers are given in Table 1.
FRINGE c n m_1 m_2 ... m_n	Shade contours of component number c on n materials, numbers m_1, m_2, ... ,m_n. Component numbers are given in Table 1.
FRN l m	Include boundary nodes l to m in a counterclockwise direction in the interface. This command must follow B command.
IFD n	Begin definition of interface n. If interface n was previously defined that definition will be lost.
IFP c m	Plot component c along interface m. Component numbers are found in Table 2.
IFS m	Include side m in the interface. The B command determines the side numbers for a material.
IFVA r_c z_c	Plot the angular location of the interface based on the center point (r_c,z_c) along the abcissa. Positive angles are measured counterclockwise from the y-axis.
IFVS	Plot the distance along the interface from the first interface node along the abcissa (default).
LINE c n m_1 m_2 ... m_n	Plot value of component c versus distance along line defined with the NLDF, PLDF, NSDF, or NSSDF command described below as it passes through materials m_1, m_2, ... , m_n.

MOLP	Overlay CONTOUR, FRINGE, and PRIN plots with the mesh. Retyping MOLP cancels the option.
NCOL n	Set number of colors in fringe plots to n. The default value of n is 6 which includes magenta, blue, cyan, green, yellow, and red. If n is 5 the magenta used for the minimum level is dropped.
NLDF n i_1 i_2 ... i_n	Define a line for the LINE command using n nodes, i_1, i_2, ... i_n. This line moves with the nodes.
NLOC	Do not plot letters on contour lines.
NSDF m	Define a line for the LINE command that is side m of some part. Use the B command to determine side numbers for a part.
NSSDF l m	Define a line for the LINE command to be the section of a part boundary between nodes l and m moving counterclockwise. A B command for the part must precede this command.
NUMCON n	Use n contour levels in CONTOUR plots. The default is 9.
PLDF n r_1 z_1 ... r_n z_n	Define a line for the LINE command using n points, (r_1,z_1), (r_2,z_2), ... (r_n,z_n). This line is fixed in space.
PLOC	Plot letters on contour lines to identify their levels (default).

PRIN c n m_1 m_2 ... m_n

Plot lines of principal stress and strain in the yz-plane on n materials, numbers m_1, m_2, ... ,m_n. If n is zero, only the outline of material m_1 with lines is plotted. The lines are plotted in the principal stress and strain directions. The permissable component numbers from Table 1 are 0, 5, 6, 100, 105, 106, etc. Orthogonal lines of both maximum and minimum stress are plotted if components 0, 100, 200, etc. are requested.

PROFILE c n m_1 m_2 ... m_n

Plot component c versus element number for n materials including materials m_1, m_2, ... m_n. If n is 0 then component c is plotted for all elements. Component numbers are listed in Table 1.

RANGE r_1 r_2

Set the range for CONTOUR levels to be from r_1 to r_2 instead of the default range chosen by the code. To deactivate the feature type RANGE 0. 0.

VECTOR c n m_1 m_2 ... m_n

Make a vector plot of component c on n materials including m_1, m_2, ... m_n. If n is 0 only the outline of material m with vectors is plotted. Component c is one of "D" and "V" for displacement or velocity, respectively.

DEFINING MAZE PART BOUNDARIES

The command sequence "M m B" for a material m supplies the boundary information required by the following two commands.

LD n k l

Define line n for MAZE to include boundary nodes k to l. Line definition with nodal coordinates written to MAZEIN file.

LDS n s

Define line n for MAZE to include side s. Line definition with nodal coordinates written to MAZEIN file.

ELEMENT COMPONENTS

#	component	#	component
1	r stress	21*	$\ln(V/V_0)$
2	z stress	22*	r displacement
3	hoop stress	23*	z displacement
4	yz stress	24*	maximum displacement
5	maximum principal stress	25*	r velocity
6	minimum principal stress	26*	z velocity
7	effective stress	27*	maximum velocity
8	pressure	28	ij normal stress
9	max.-min. prin. stress	29	jk normal stress
10	r hoop stress	30	kl normal stress
11	maximum shear stress	31	li normal stress
12	ij&kl normal stress	32	ij shear stress
13	jk&li normal stress	33	jk shear stress
14	ij&kl shear stress	34	kl shear stress
15	jk&li shear stress	35	li shear stress
16	r deviatoric stress	36*	relative volume V/V_0
17	z deviatoric stress	37*	$V_0/V - 1$
18	hoop deviatoric stress	38*	bulk viscosity
19*	effective plastic strain	39*	pressure+bulk q ++
20*	internal energy per unit reference volume, V_0	40*	density

41* - 70* element history variables

TENSOR peak values of:

71*	r acceleration	76*	min. in-plane prin. stress
72*	z acceleration	77*	max. hoop stress
73*	r velocity	78*	min. hoop stress
74*	z velocity	79*	pressure

++ For case of BCM viscosity component 39 is just pressure. Bulk Q's are stored as element history variables.

Table 1. Component numbers for element variables. By adding 100, 200, 300, 400, 500, or 600 to component numbers not followed by an asterisk, numbers for infinitesimal strains, Lagrange strains, Almansi strains, strain rates, extensions, and residual strain may be obtained. Maximum and minimum principal stresses and strains are in the rz plane. The corresponding hoop quantities must be examined to determine overall extrema.

INTERFACE COMPONENTS

#	component
1	pressure
2	shear stress
3	normal force
4	tangential force
5	r force
6	z force

Table 2. Component numbers for interface variables. In axisymmetric geometries the force is per unit radian.

DISPLAYING OR MODIFYING MESH WITH A CURSOR

DBD a b	Use cursor to define points a and b on boundary. Dekink boundary starting at a, moving counterclockwise, and ending at b.
DCN a b	Use cursor to define points a and b. The node closest to point a will be moved to point b.
DCNM a b	Use cursor to define points a and b. The node at point a is given coordinates of point b.
DCSN n a	Move nodal point n to a point a defined by the cursor.
DER a b	Use cursor to define points a and b on the boundary. Equal space nodes in r-direction along boundary starting at a, moving counterclockwise, and ending at b.
DES a b	Use cursor to define points a and b on the boundary. Equal space nodes along boundary starting at a, moving counterclockwise, and ending at b.
DEZ a b	Use cursor to define points a and b on the boundary. Equal space nodes in z-direction along boundary starting at a, moving counterclockwise, and ending at b.
DTE a b	Use cursor to define points a and b on the diagonal of a window. The element numbers and coordinates of centers of elements lying within the window are typed to the terminal.
DTN a b	Use cursor to define points a and b on the diagonal of a window. The node numbers and coordinates of nodes lying withing the window are typed on the terminal.

DTNC a	Use cursor to defina point a. The node number and coordinates of the node lying closest to a will be typed to the terminal.
DVS a b r	Use cursor to define points a and b on the boundary. Variable space nodes along the boundary starting at a, moving counterclockwise, and ending at b.
DZ a b	Use cursor to define points a and b on the diagonal of a window for zooming.
DZZ a	Use cursor to define point a and zoom in at this point. The new window is .15 of the size of the previous window. The zoom factor can be reset with the CRZF command.

REZONING EXAMPLE

Use of the rezoner is demonstrated in the example which follows. Below the commands typed at the terminal are correlated with resulting pictures on the TMDS. In interactive mode KDYNA first prompts for the TMDS monitor number. It then prompts for other commands with a period (.).

Terminal Commands	Resulting Images
TMDS: 556	
.PLOTS W41 G	=> Fig. 12
.NOFR G	=> Fig. 13a (top)
.M 1 NDPL M 2 NDPL	=> Fig. 13a (bottom)
.KLMX 3 LLMX 11 DELK 1 1 G	=> Fig. 13b (top)
.M 1 NDPL M 2 NDPL	=> Fig. 13b (bottom)
.DELL 2 3 8 G	=> Fig. 13c (top)
.M 1 NDPL M 2 NDPL	=> Fig. 13c (bottom)
.F	

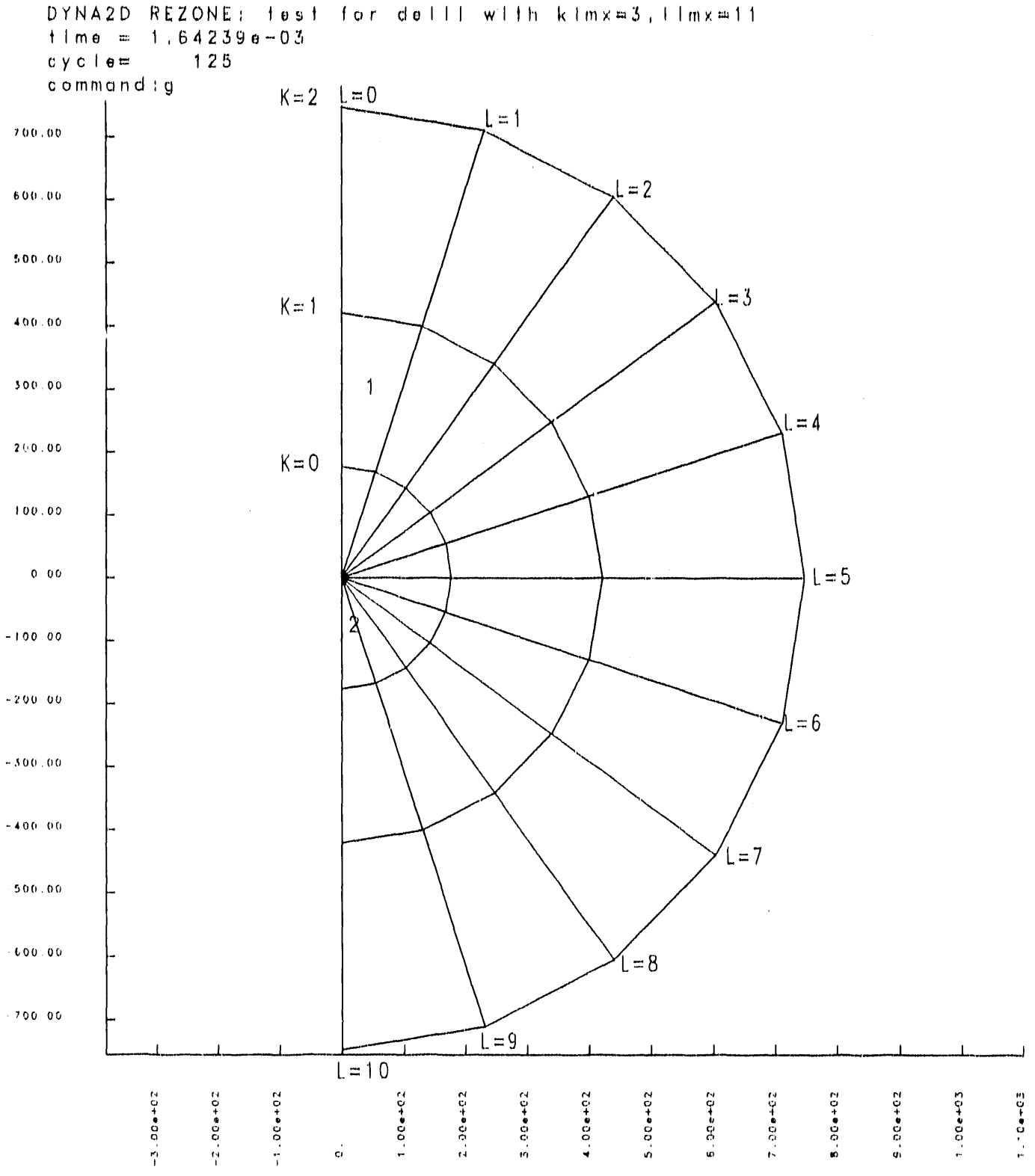
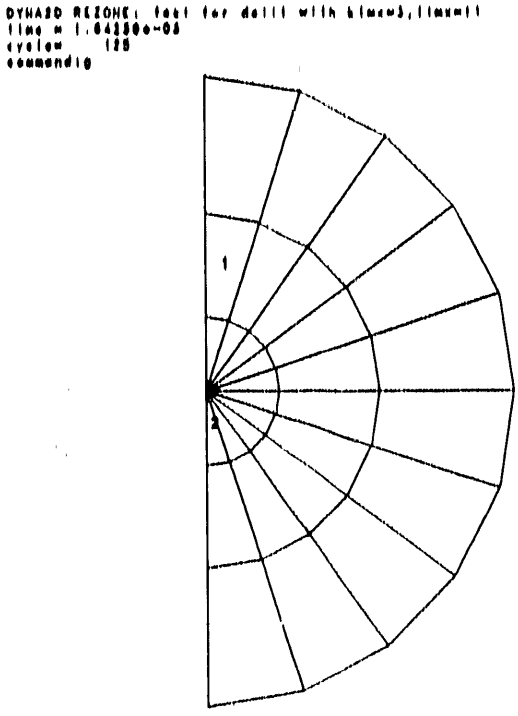
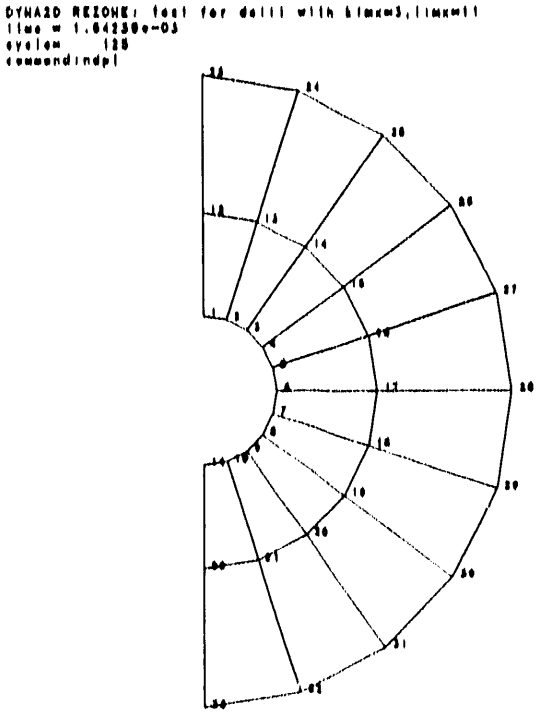


Fig. 12. Plot of initial mesh on reference grid showing k-lines and l-lines.





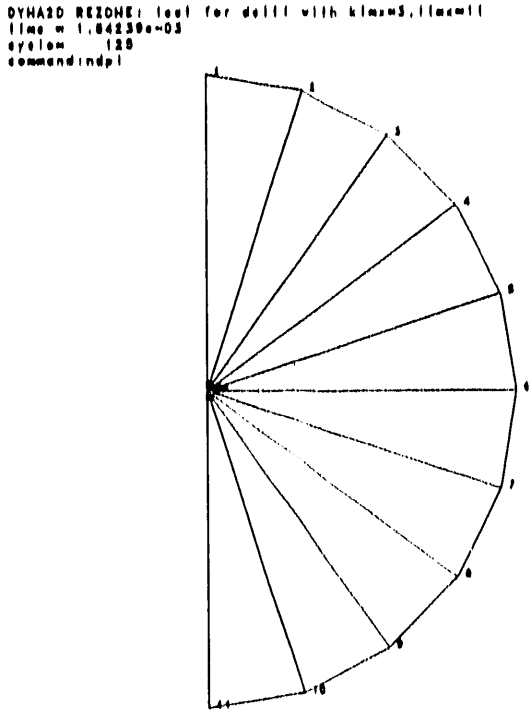
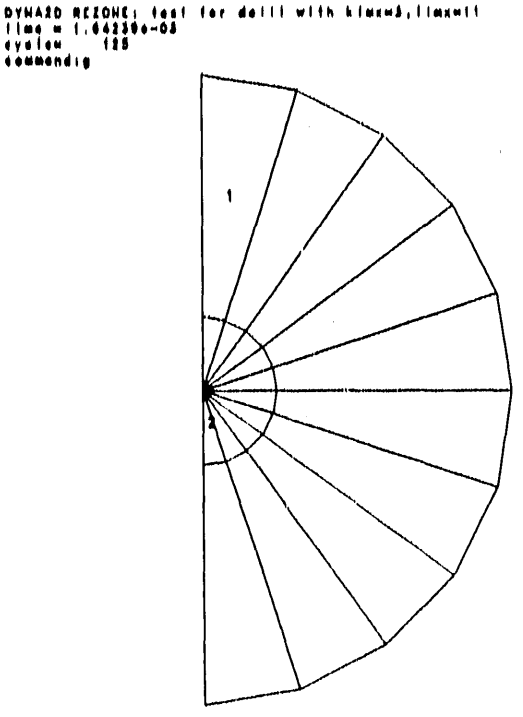
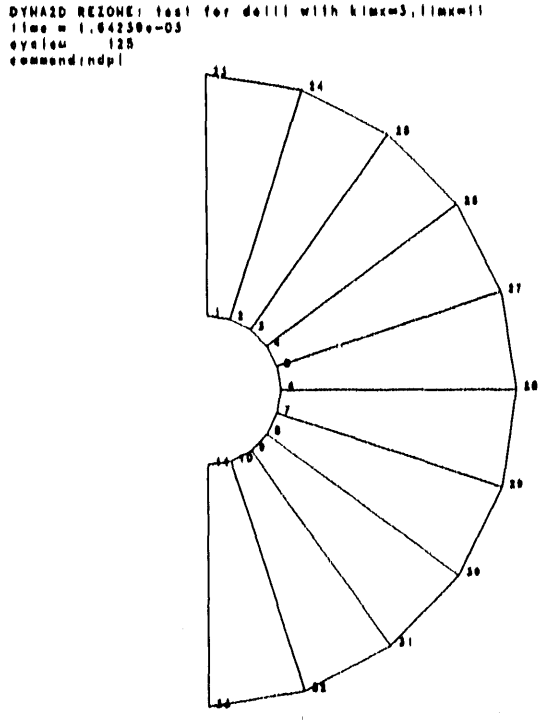


Fig. 13a. Initial mesh: grid plot, node number plot for material 1, and node number plot for material 2 (cavity).





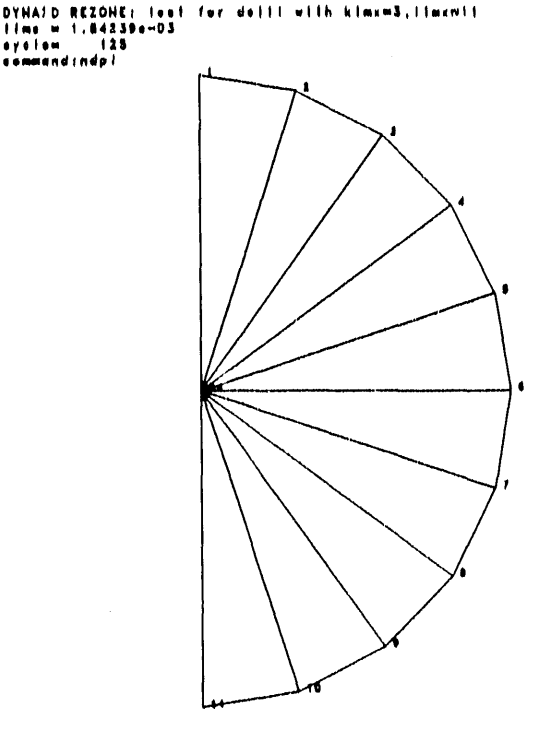


Fig. 13b. Mesh after k-line deletion: grid plot, node number plot for material 1, and node number plot for material 2 (cavity).

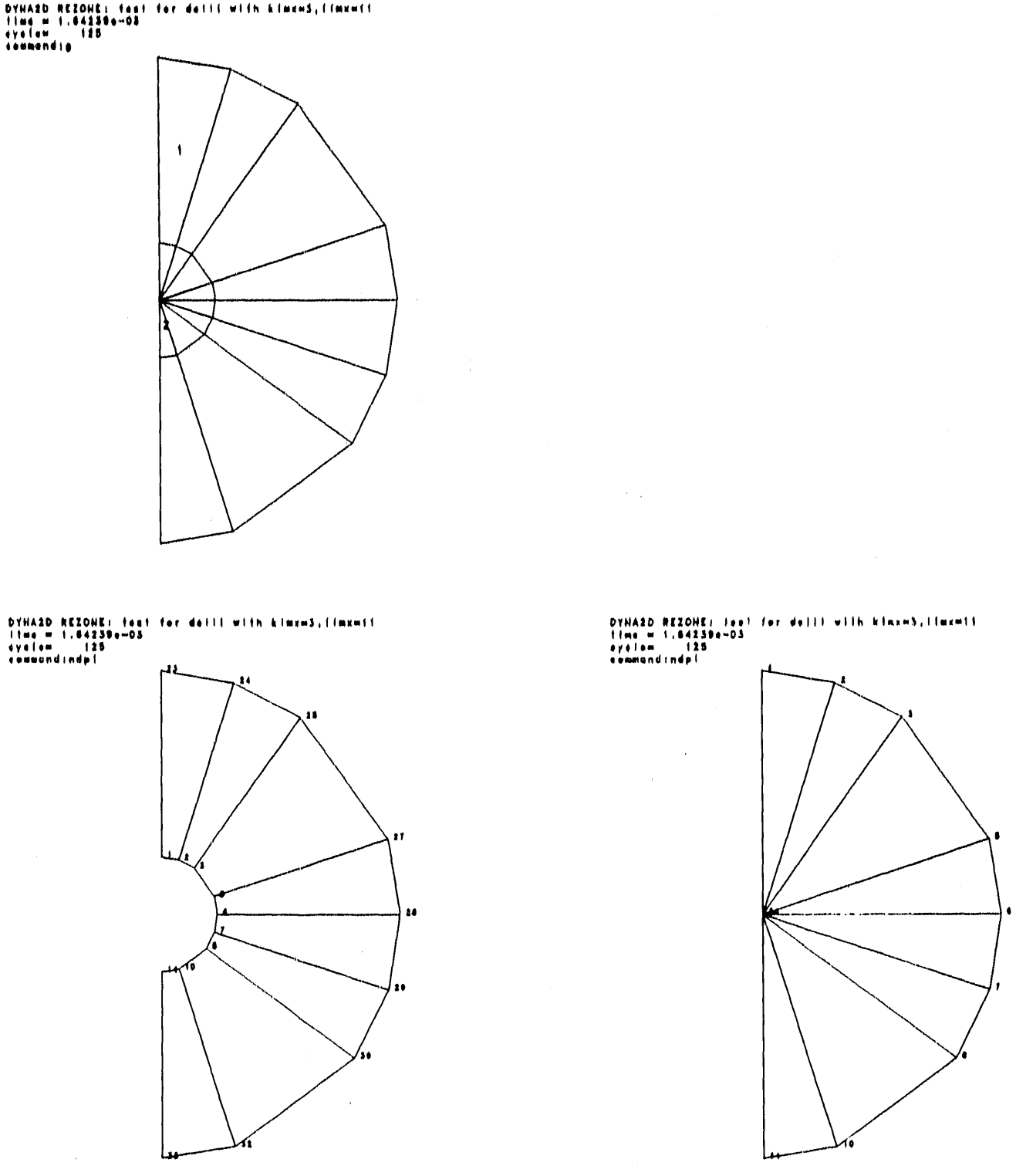


Fig. 13c. Mesh after 1-line deletion: grid plot, node number plot for material 1, and node number plot for material 2 (cavity).

REMAPPING

PURPOSE OF REMAPPING

The purpose of the remapping is to redefine the mesh inside the boundary of a given material. Usually this is done because the mesh has become distorted or unnecessarily compressed during calculation. To remap a material the KDYNA rezoner must first be used to determine the boundary of the material. The rezoner's "LD" and "LDS" commands are then used to write coordinate data for each side of the boundary to a MAZE input file as MAZE line definitions. After this data has been read into MAZE a new part can be defined inside the old boundary. The mesh on this part should be considerably less distorted or compressed than the original one. Finally, the MAZE output is read into the KDYNA remapper to redefine the mesh for the specified material.

REMAPPER EXECUTION INSTRUCTIONS

STEP 1: Extract old material boundaries form original mesh. Type
---

KDYNA Z=REZONE R=*dmpo* M=*mfr*

where

dmpo = dump of original mesh

mfr = material boundary definitions for building new mesh

User specifies REZONER line definition commands such as B, M, LD, and LDS.

STEP 2: Create input to define the new mesh. Type

MAZE C=*mfr* O=*dyn*

where

mfr = boundary definitions & other commands for building new mesh

dyn = KDYNA input deck for new mesh

STEP 3: Remap from old mesh to new mesh and continue calculations on
--- new mesh. Type

KDYNA Z=REMAP I=*dyn* R=*dmpo* D=*dmpn* G=*ptf* F=*thf* O=*otf*

REMAPPER DATA FLOW

STEP 1

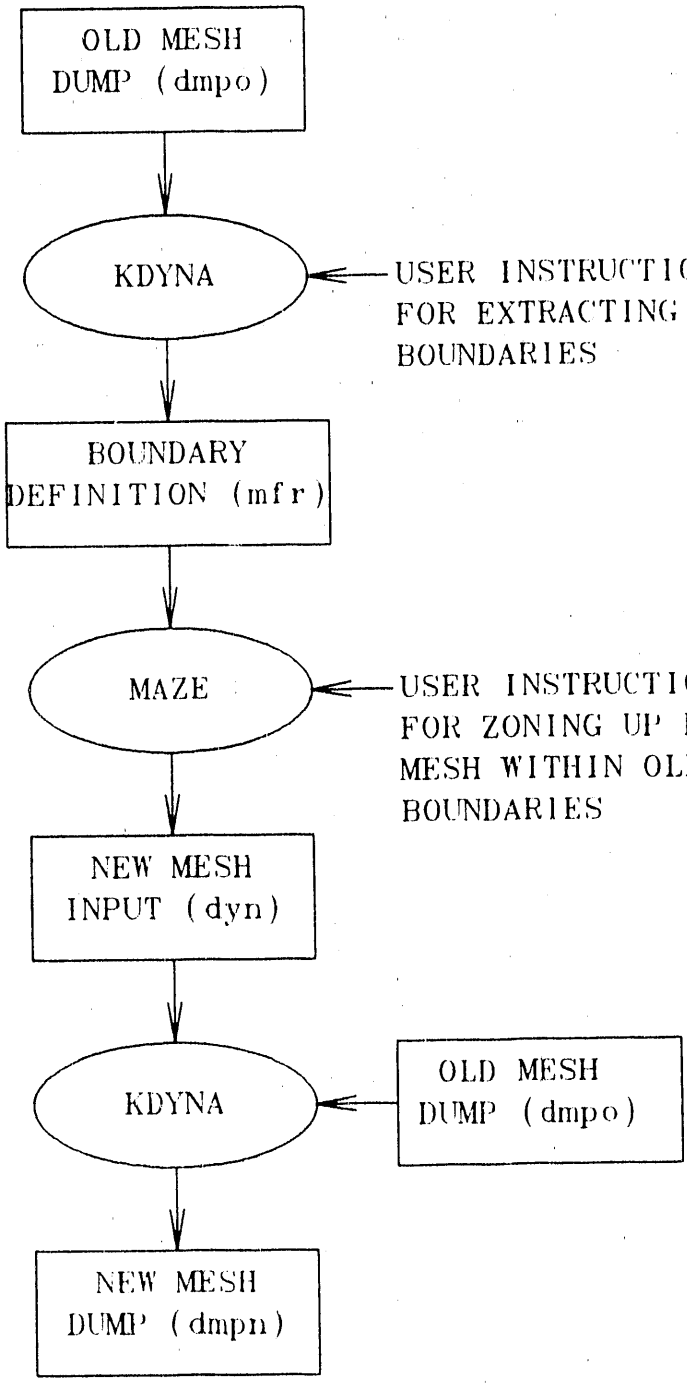
EXTRACT MATERIAL BOUNDARIES FROM OLD MESH

STEP 2

BUILD NEW MESH

STEP 3

REMAP FROM OLD MESH TO NEW MESH AND CONTINUE CALCULATION



ACKNOWLEDGEMENTS

The authors would like to thank Denise M. Maddix for installing many of the KDYNA features described in this manual. Teresa M. Quinn, William E. Warren, and Ellen M. Corey also made software contributions.

We would also like to thank William C. Moss, Carl E. Rosenkilde, and John T. Rambo for constructive comments on the manual.

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APPENDIX A
USE OF SLIDELINES

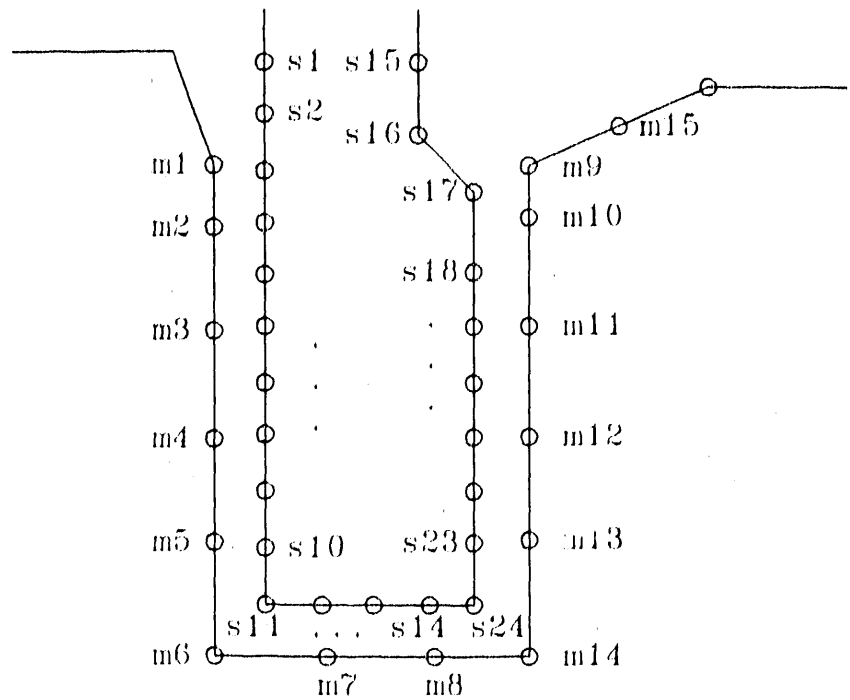
This appendix briefly describes the proper use of slidelines.

Consider two surfaces in contact. In KDYNA it is necessary to designate one as a slave surface and the other as a master surface. Nodal points defining the slave surface are called slave nodes. Similarly, nodes defining the master surface are called master nodes. Each slave-master surface combination is referred to as a slideline.

Many potential problems with the algorithm can be avoided by observing the following precautions:

- o For explosive-metal interfaces the master surface should be on the metal side.
- o For explosive-metal interfaces a "sliding only" type slideline should be used. The penalty formulation is not recommended for this case.
- o If one surface is more finely zoned than another, the more finely zoned surface should be the slave. If penalty slidelines, type 4, are used, the slave-master distinction is irrelevant.
- o A slave node may have more than one master segment, and may be included as a member of a master segment if a slideline intersection is defined.
- o Penalty, type 4, slidelines handle intersections automatically and should not be used for intersecting slidelines.
- o Angles in the master side of a slideline that approach 90^{o} must be avoided. Whenever such angles exist in a master surface, two or more slidelines should be defined there. This procedure is illustrated in Fig. A1. An exception to this rule arises if the surfaces are tied. Then only one slideline is needed.
- o Rigid walls are defined by a series of fixed master nodes (boundary condition code 3.0) which outline the desired profile. For best results, the spacing of these nodes should be approximately the same as that of the slave nodes. If very large spacing is used, errors may occur during the KDYNA initialization phase.
- o Whenever two surfaces are in contact, the smaller of the two should be used as the slave surface. For example, in modeling a missile impacting a wall, the contact surface on the missile should be designated as the slave surface.
- o Care should be taken in defining a master surface to prevent the extension from interfering with the solution. In Figs. A2 and A3 slideline extensions are shown.

o Wherever slidelines intersect, as shown in Fig. A4, a slideline intersection should be declared.



1		2		3	
Slaves	Masters	Slaves	Masters	Slaves	Masters
s1	m1	s11	m6	s24	m14
s2	m2	s12	m7	s23	m13
.	.	.	m8	.	.
.	.	.	m14	.	.
.	.	.		.	.
.	.	s14		.	m9
s11	m6	s24		s15	m15

Fig. A1. Proper definition of illustrated slave-master surface requires three slidelines. Note that slave surface is to left of master surface as one moves along master nodes in order of definition.

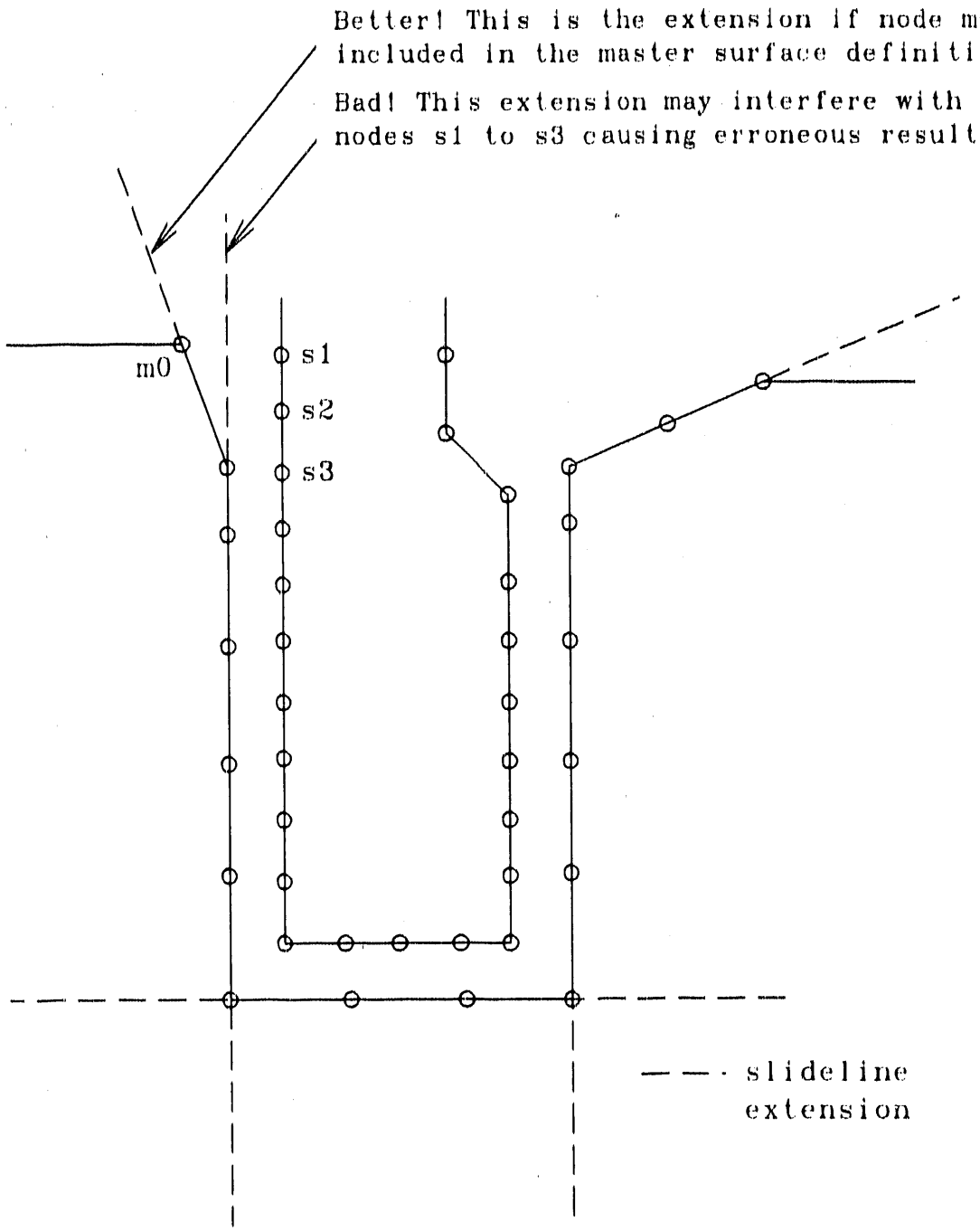


Fig. A2. Master surface extensions defined automatically by KDYNA. Extensions are updated every time step to remain tangent to ends of master sides of slidelines unless angle of extension is defined in input.

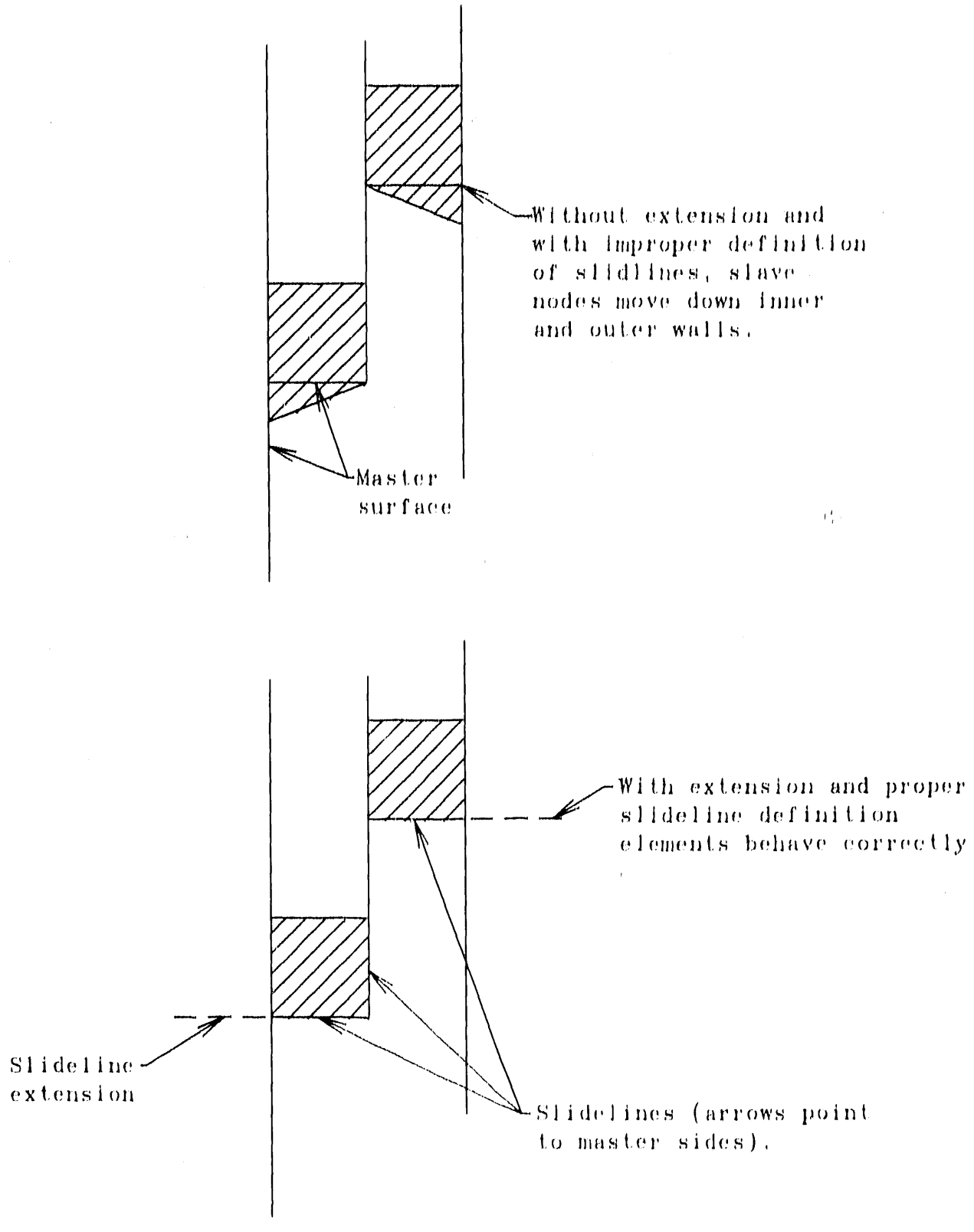


Fig. A3. Example of slideline extensions helping to provide realistic response. A compressive loading is assumed.

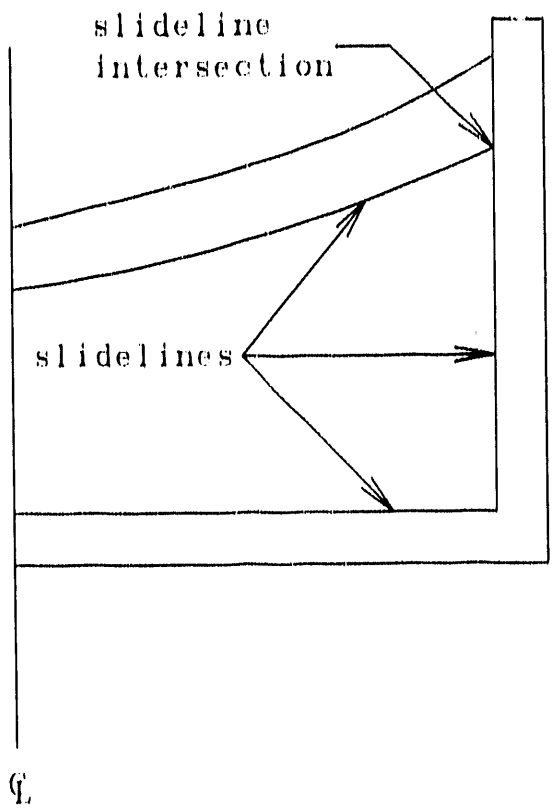


Fig. A4. Example of slideline intersection.

APPENDIX B
MATERIAL TYPE - EOS COMPATIBILITIES

MATERIAL TYPE \ EOS FORM	1	2	3	4	5	6	7	8	9	10	11	13	14	15	16	17	18	19	24
8	X	X	X	X	X	X	X	X	X										X
9	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	N		X
10	X	X	X	X	X	X	X	X	X										X
11	X	X	X	X	X	X	X	X	X										X
12	X	X	X	X	X	X	X	X	X										X
16								X	X		X	X				X			
19											X	X				X			
22												X			X		X	X	
23											X				N				

x implemented
(blank) not implemented
N not allowed

APPENDIX C
MATERIAL MODEL DRIVER

DRIVER is a mode of operation that allows the user to evaluate constitutive and volumetric response models for a given strain path. In this mode the equations of motion are not invoked, so that the dynamic effects of nodal motion are eliminated. DRIVER can only be used with a single-zone mesh. Strain paths can be redefined interactively, permitting new responses to be calculated without restarting the code. Ascii labels can be assigned to the state variables, and an output file readable by the PAMPERS plotting package is produced.

The format of a complete DRIVER input deck is described here:

Title Card

Columns	Quantity	Format
1-80	Any problem title	a80

Control Card 1

Columns	Quantity (Value)	Format
1-2	Idv flag (87)	i2
3-5	Number of materials (1)	i2
6-25	(Blank)	
26-30	Number of strain paths, NPATH .EQ.3: to input μ, $\delta u/\delta z$, $\delta v/\delta r$ .EQ.5: to input e_r, e_z, e_θ, $\delta u/\delta z$, $\delta v/\delta r$	i5

Control Card 2

Blank

Control Card 3

Columns	Quantity (Value)	Format
1-10	Termination time	e10.0
11-20	(Blank)	
21-30	Driver time step size	e10.0

(continued next page)

Control Card 3a

Columns	Quantity (Value)	Format
1-5	IHDMP, flag to dump history variables (1)	I5
6-10	IPDMP, flag to dump peak variables (1)	I5

Material Input Data
(see manual)

EOS Input Data
(see manual)

Element Card

Columns	Quantity	Format
36-45	Initial internal energy per reference volume (All other fields left blank.)	e10.0

Load Curve Cards

NPATH sets of these define the strain paths. See Control Card 1 description on previous page.

Card 1

Columns	Quantity	Format
1-5	Table number	i5
6-10	Number of points, NPTS (NPTS < 101)	i5

Cards 2 through NPTS

Columns	Quantity	Format
1-10	Time t	e10.0
11-20	Strain function value at time t	e10.0

APPENDIX D
SOFTWARE INSIGHTS

To understand KDYNA a programmer should begin by looking at the subroutine FE2DA where the cycles of the finite element calculation occur. Practically every other routine feeds into it or takes data from it. For this reason it may be considered the central routine of the code. Fig. 14 on the next page is a flow diagram of FE2DA. Fig. 15 contains a data flow diagram for the call to FE2DA from SOLTO.

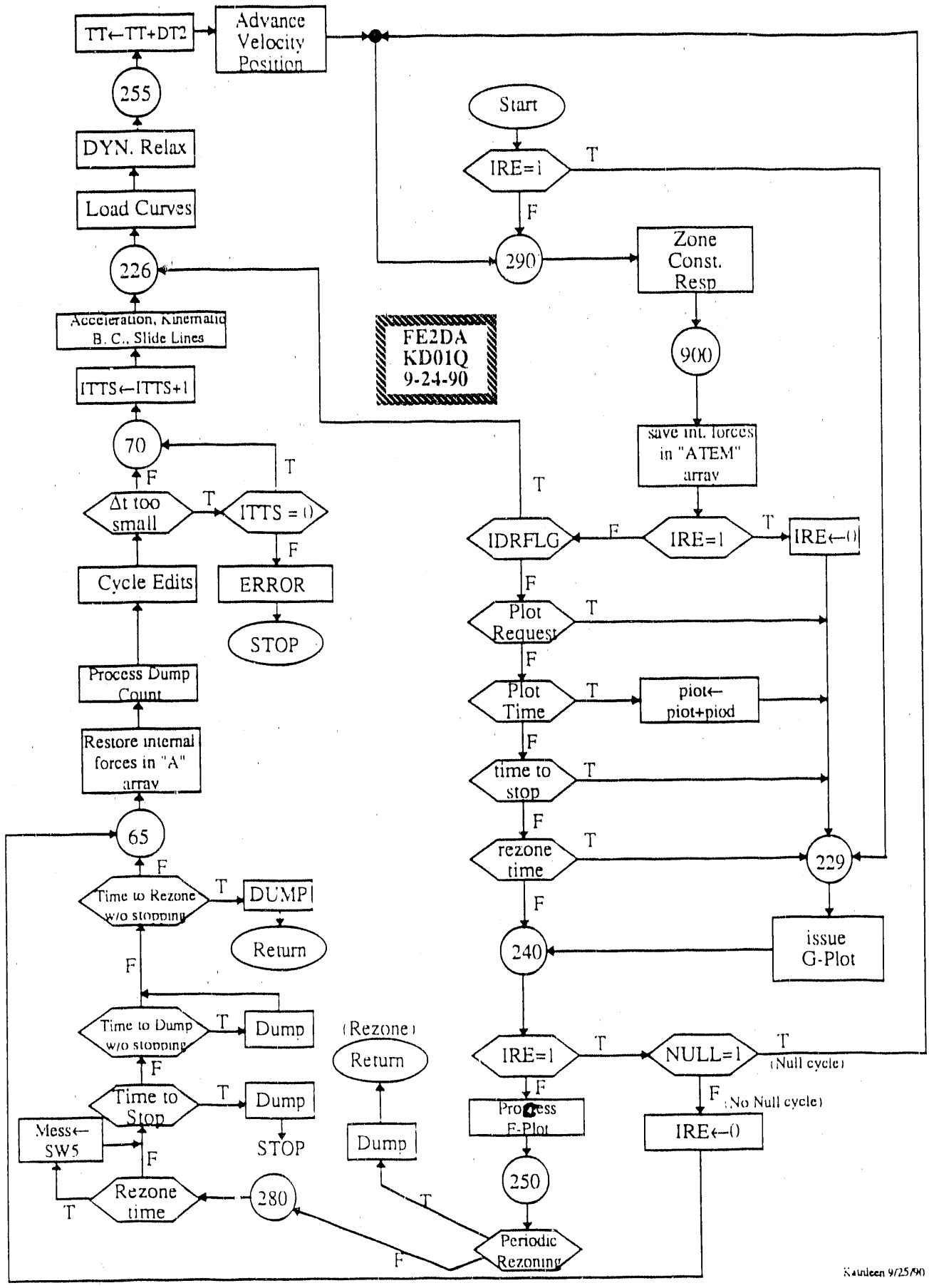
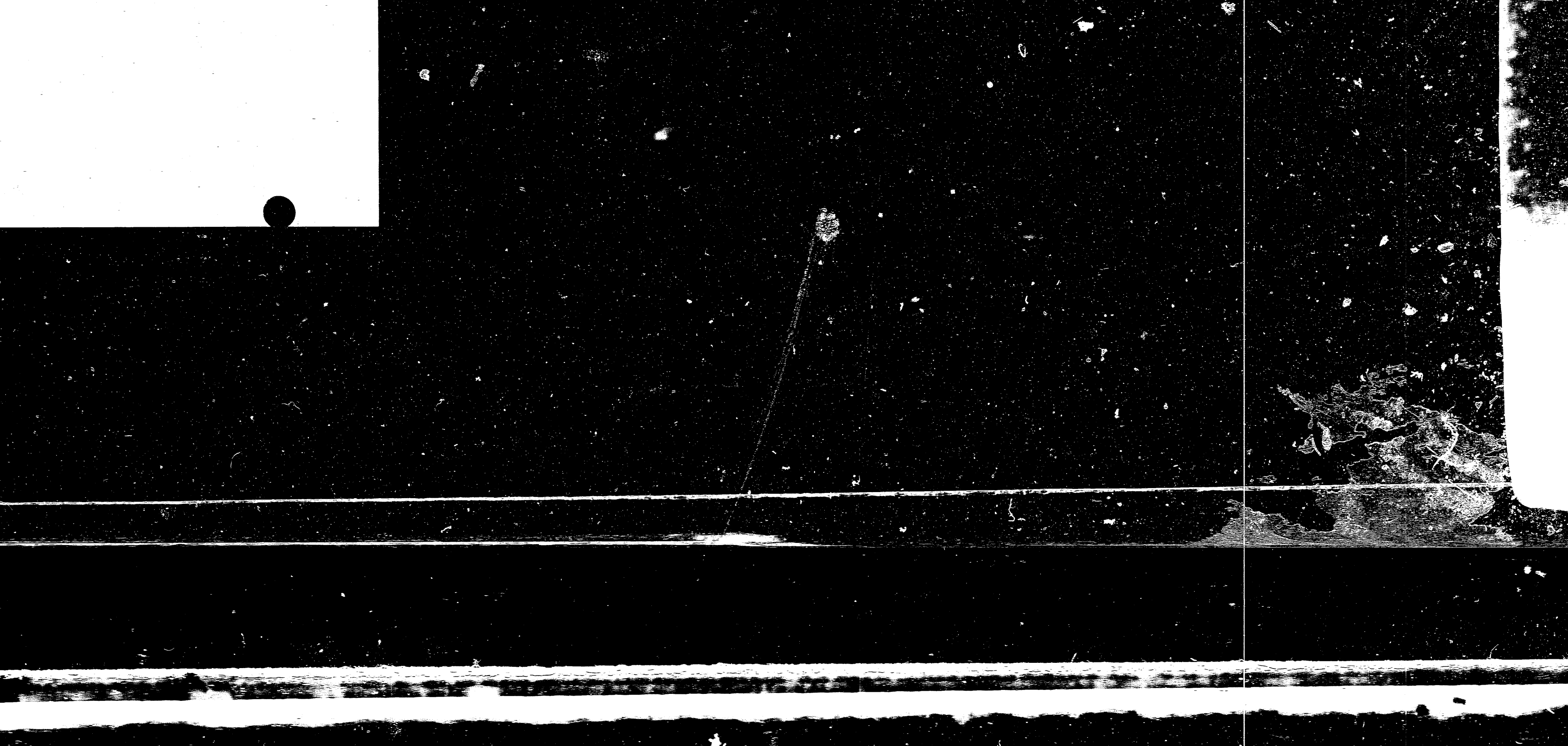


Fig. 14. Flow diagram of FE2DA.

SOLTO -->	FE2DA	SOLTO -->	FE2DA
a(1)	r	a(lg1)	u
a(n2)	z	a(lg2)	v
a(n3)	code	a(lg3)	a
a(n4)	amm	a(lg4)	ms
a(n5)	mtype	a(lg4+numnp)	bqs
a(n6)	ro	a(lg5)	ams
a(n7)	cm	a(1)	b
a(n8)	nodes	a(n21)	slang
a(n9)	pmult	a(n27a)	iloce
a(n10)	t	a(n27b)	mzfac
a(n11)	lcp	a(lc2)	sig
a(n12)	npc	a(lg3a)	tta
a(n13)	p	a(n26b)	ilcw
a(n14)	lcv	a(lg6)	xms
a(n15)	nvel	a(n7a)	nsubgv
a(n16)	vr	a(n7b)	mtnum
a(n17)	vz	a(n7c)	nfegp
a(n18)	told	a(n4a)	ieost
a(n19)	tnew	a(n4b)	eosp
a(n23)	nsln	a(n4c)	ihgq
a(n24)	nmln	a(n4c+nummat)	hgq
a(n25)	idsl	a(n4d)	iqtype
a(n26)	msr	a(n4e)	bkqs
a(n27)	nsv	a(lg4+numnp+numel)	atem
a(n28)	msm	a(n22)	icn
a(n29)	iloc	irestr	irestr
a(n30)	ipt1	a(n25+nsl)	fric
a(n31)	ipt2	a(n26d)	slbuff
a(n32)	izone	maxmsl	maxmsl
a(n33)	ift	a(n26e)	iextop
a(n34)	fcnts	a(n23c)	nnnrb
a(n35)	tim	a(lc1)	ixc
a(n36)	ener	a(ld09)	peaks
a(n37)	nsli	a(lg7)	bf
a(n38)	nsnic	ipdmpm	ipdp
a(n39)	msric	a(n3a)	ndsout
a(n40)	nic	a(n3b)	nstout

Fig. 15 Data flow between subroutine SOLTO and subroutine FE2DA.

END

DATE FILMED

11 / 21 / 90