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Argonne National Laboratory

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Ax-1, A COMPUTING PROGRAM FOR COUPLED NEUTRONICS-HYDRODYNAMICS CALCULATIONS ON THE IBM-704

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Ax - 1, A COMPUTING PROGRAM FOR COUPLED NEUTRONICS-HYDRODYNAMICS CALCULATIONS ON THE IBM-704

I. INTRODUCTION

In connection with studies in the safety of fast reactors, it is necessary to calculate the energy yield and explosive force of a variety of hypothetical nuclear accidents. (1, 2) A valuable analytical technique for calculating such incidents was developed by Bethe and Tait, (3) and since modified by Jankus. (1, 2) To achieve an analytic solution, however, various simplifications and approximations were required, with consequent reduction of accuracy and applicability. A numerical solution, employing high speed digital computers, was needed to improve upon the accuracy available from the analytic solution and to provide a more flexible computational method. To gain this end most efficiently, the Argonne National Laboratory asked for and was granted the full cooperation of the Los Alamos Scientific Laboratory. R. B. Lazarus, assisted by M. B. Wells, drew upon Los Alamos experience in the field of coupled neutronicshydrodynamics calculations to devise a program reasonably well suited to Argonne's needs. They collaborated closely with J. M. Cook, D. Okrent, and D. Satkus of ANL in the debugging of the original program. As operating experience was gained at ANL, some refinements in the sensitive control apparatus of the program were introduced at ANL, to provide improved accuracy and more efficient use of the computing machine. The program has not been fully optimized in every sense, however, and a reworking should make possible further increases in efficiency. The utilization and a very rough outline of a similar computing program have been given by Stratton, Colvin, and Lazarus, (4) but no details of the code were presented.

Modification of Ax-1 to permit the use of other equations of state is under study. A special version designed to permit a study of the errors introduced by certain assumptions in the analytic technique is described in Appendix E, as Ax-1'.

The presentation to follow includes a very general outline of the program, a semi-detailed flow diagram which emphasizes the physics and control aspects of the calculation, and then a detailed flow diagram and listing of the program (which is written in Fortran). Explanatory notes accompany the diagrams.

Following the notes on the program, master lists detailing the roles of the sense switches, sense lights, pauses, and stops are presented. The operating instructions are then given, followed by a sample problem., including detailed information on input data.

The theoretical discussion has been kept primarily in the appendices, and is generally in outline form with references, rather than in full exposition.

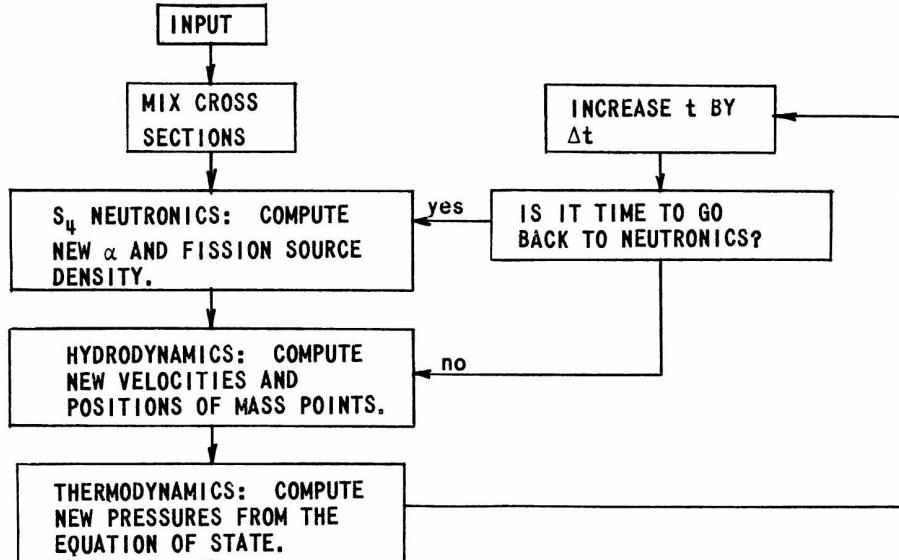
II. GENERAL DESCRIPTION OF THE PROGRAM

Given a spherically symmetric, super-prompt critical system, the program computes the variation in time and space of the specific energy, temperature, pressure, density, and velocity. As a function of time it computes the reactivity (in the form of alpha, the inverse period), the power, the total energy, and the position of the boundaries of the various shells into which the system has been subdivided. All delayed neutron effects are ignored, and no allowance is made for transfer of heat by conduction or radiation. The input information includes the initial reactivity or geometry, the initial velocities and temperatures of the mass points, the composition and disposition of materials, the appropriate equation of state constants, and the microscopic neutron cross sections.

For calculational purposes the spherical assembly is divided into a number of hypothetical spherical shells or mass points. The neutronics of this system is calculated in conventional fashion, using the S_n method, (5,6,7) thereby providing a power distribution across the radial network, as well as the alpha of the system.

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From the neutronics calculation one goes to the thermodynamics and hydrodynamics portion to calculate the variation of power, temperature, pressure, density, and velocity with time. One may characterize the overall arrangement by means of the following block diagram.



The calculation proceeds initially like the usual S_n calculation. After computing average cross sections for each of the spherical shells, in the mixture code, the program proceeds either to a calculation of alpha ($= \frac{k_{ex}}{\ell}$) for the specified configuration, or to a scaling of the reactor radii to provide the alpha originally specified. Before proceeding to the hydrodynamics the code also computes k_{eff} for the initially converged configuration, if so requested.

The neutronics portion of the program is always done in the S_4 approximation. It supplies to the succeeding portions of the program the alpha corresponding to that specific configuration. It also supplies a relative power distribution, to be used in assigning the increase in energy within each spherical shell or mass point, while this configuration remains a reasonable approximation.

The program proceeds into the hydrodynamic and thermodynamic portions. For one or more short time intervals, Δt , alpha is considered to remain constant while the power varies as $e^{\alpha\Delta t}$. From the pressure gradients in the system the average accelerations of the mass points are computed and, hence, the new velocities at the end of a time interval. These, in turn, lead to the new radial positions of each shell boundary at the end of a time interval. The solution is performed in a Lagrangian coordinate system, i.e., the mesh is embedded in the material, and follows it along throughout its motion.

During the time interval energy is added to the system (the average power times Δt) and this is distributed among the shells in accord with the previously calculated fission distribution. By allowing for the work done by or on a shell in expansion or compression, the net change in internal energy is computed, and from the internal

energy a new pressure and temperature are obtained. In the *Ax - 1* program, the relation between pressure and temperature has been taken to be linear, namely

$$P_H = \alpha\rho + \beta\theta + \tau$$

while the specific heat at constant volume is given by

$$\left(\frac{\partial E}{\partial \theta}\right)_V = A_{cv} + B_{cv}\theta$$

where

$$\begin{aligned} P_H &= \text{pressure} \\ \rho &= \text{density} \\ \theta &= \text{temperature} \\ E &= \text{internal energy} \end{aligned}$$

The various coefficients are allowed to vary from shell to shell, but no provision is made for mixing several substances within a shell to generate average values of these coefficients, as with cross sections.

The thermodynamic equations are solved using an iterative procedure, guessing the new pressure at each mass point to be the old pressure for the first iteration. The so-called viscous pressure, a mathematical procedure devised by von Neumann and Richtmyer (see Reference 8 and Appendix C) is included to permit thermodynamic and hydrodynamic calculations in the presence of a steep shock front. Hence, the total pressure is the sum of the hydrodynamic pressure, P_H , and the synthetic viscous pressure, P_V .

When calculation of the thermo- and hydro-dynamic changes during the time interval Δt is complete (a hydrocycle), a series of tests are run, and the program either proceeds with another hydrocycle or goes back to the neutronics calculation.

To control the pace of a problem, the code continually examines the magnitude or rate of change of certain crucial parameters, and varies

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the Δt of a hydrocycle or the number of hydrocycles per neutron cycle accordingly. This latter number begins at unity and is allowed to build up gradually if the forces present are not changing alpha too rapidly or modifying the density of a mass point radically. When the power variation in a hydrocycle, or the change in alpha between neutron cycles, gets so large as to damage the accuracy of the solution,

the pace of the calculation is slowed automatically - or stopped in extreme cases.

III. LIST OF SYMBOLS AND DEFINITION OF TERMS

The program is written in Fortran, forcing a symbolic notation consistent with the requirements of the Fortran system and not always identical to customary physical usage. Hence, a dual list of symbols follows, that on the left comprising the Fortran symbols in alphabetical order. There is generally an associated physical symbol next to it, together with a translation or definition of the pair. In the explanation which follows, the physical symbol will generally be used.

The system of units used in the calculation is somewhat different from that conventionally used by the reactor physicist, so a brief discussion is given.

The basic choice for mass, length, time, and temperature is as follows:

unit of mass = grams
unit of length = cm
unit of time = μ sec
unit of temperature = kev

Then, it follows that

the unit of velocity = $\text{cm}/\mu\text{sec}$
the unit of acceleration = $\text{cm}/\mu\text{sec}^2$
the unit of force = $\text{gm cm}/\mu\text{sec}^2 (= 10^{12} \text{dynes})$
the unit of energy = $\text{gm cm}^2/\mu\text{sec}^2 (= 10^{12} \text{ergs})$
the unit of power = $\text{gm cm}^2/\mu\text{sec}^3 (= 10^{12} \text{ergs}/\mu\text{sec})$
the unit of pressure = $\frac{\text{g}}{\mu\text{sec}^2 \cdot \text{cm}^{12}} \left(= 10^{12} \frac{\text{cm}^2}{\text{gm cm}^2} \right)$
the unit of specific heat = $\frac{\text{gm}^2}{\mu\text{sec}^2 \cdot \text{kev}}$

ACV(M)	A _{cv} (M)	$\frac{\text{cm}^2}{\mu\text{sec}^2 \text{kev}}$	Constant in equation $C_V = A_{CV} + B_{CV}\theta$
AITCT			Total number of S _n iterations completed
AK(I)	K _{eff,i}		K _{eff} from previous iteration
AKEFF	K _{eff}		Multiplication factor
ALPH(M)	$\alpha(M)$	$\frac{\text{cm}^2}{\mu\text{sec}^2}$	Constant in equation of state
ALPHA	α	μsec^{-1}	Inverse of reactor period = $\frac{K_{ex}}{\ell}$
ALPHAO	α_0	μsec^{-1}	Absolute value of alpha at Order No. 6820, the maximum absolute value of alpha
ALPHA P	α'	μsec^{-1}	The alpha resulting from the previous converged S _n calculation
AM(1)	M(1)		
...	...		S _n constants
AM(5)	M(5)		
AMBAR (1)	$\bar{M}(1)$		
...	...		S _n constants
AMBAR (5)	$\bar{M}(5)$		

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Fortran Symbol	Physical or Mathematical Symbol	Units	Definition
AMBART	\bar{M}_T		S _n constant
AMT	M _T		S _n constant
ANU (IG)	$\nu(g)$		Fraction of fission neutrons born in a fission
ANUSIG (IG, N)	$(\nu\sigma_f)g, N$	Barns	Microscopic fission cross section
B(1)	B(1)		
...	...		S _n constants
B(5)	B(5)		
BCV(M)	B _{cv} (M)	$\frac{\text{cm}^2}{\mu\text{sec}^2 \text{kev}^2}$	Constant in equation $C_V = A_{CV} + B_{CV}\theta$
BETA(M)	$\beta(M)$	$\frac{\text{g}}{\text{cm}\mu\text{sec}^2 \text{kev}}$	Constant in equation of state
BS	B _S		Intermediate term in S _n
BT	B _T		S _n constant
CHECK			Fractional difference in total energy
CSC	C _{sc}		Courant stability constant. Is defined as
			$\gamma(\gamma - 1) \approx \left(\frac{\partial p}{\partial \rho}\right)_s / E_{int} = \frac{C^2}{E_{int}}$
CVP	C _{vp}		Viscous pressure coefficient for the fluid

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Fortran Symbol	Physical or Mathematical Symbol	Units	Definition
DELE	ΔE	10^{12}ergs g	Increment in specific internal energy
DELQ	ΔQ	$\frac{10^{12} \text{ergs}}{\text{g}}$	Energy per gram added to mass
DELR	ΔR	cm	$= R(I) - R(I-1)$, outer radius
DELT	ΔT	$\mu \text{ sec}$	Time increment between hydrodynamic steps
DELTA(I)	$\Delta(I)$	cm	$\bar{R}(I) - R(I-I)$
DELTP	$\Delta t'$	μsec	The time interval appropriate to the problem
DELV	ΔV	cm^3/g	$= \frac{1}{\rho_{\text{Hyd}}^T} - \frac{1}{\rho_{\text{Hyd}}(I)}$, the change in specific volume
DTMAX	Δt_{\max}	μsec	Largest Δt allowed
E(I)	$E(I)$		$= \rho_{\text{neut}}(I) \sum_g \sigma_{gg} K(I) \cdot N_g(I)$, total energy
EN(IG, I)	$N_g(I)$		Total flux in group g at $\bar{R}(I)$
ENN(I, J)	$N(I, \mu_j)$		Flux in direction J at $R(I)$ for group g

Fortran Symbol	Mathematical Symbol	Units	Definition
ENNN(I)	$N(I)$		$= \sum_g \frac{N_g(I)}{V_g}$, average inverse neutron velocity at mass point I
EPS	ϵ		Internal parameter set equal to EPSA, EPSI
EPSI	ϵ_1	megabars	Largest negligible pressure, needed in temperature iteration
EPSA	ϵ_A	μsec^{-1}	Convergence criterion on calculation of $\alpha \Delta T$
EPSK	ϵ_K		Convergence criterion on K_{eff} calculation
EPSR	ϵ_R	cm	Convergence criterion on outer radius R
ERRLCL	Error Local	10^{12}ergs g	The maximum difference between the successive values of ΔE
ETAI	η_1		Convergence criterion for iteration on hydrodynamic steps
ETA 2	η_2		1/4 the maximum value for $\alpha \Delta T$ which is 0.001

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Fortran Symbol	Physical or Mathematical Symbol	Units	Definition
ETA 3	η_3		Tolerance on fractional change in α
F (I)	$F(I)$		Relative fission density of zone I
F BAR	\bar{F}		$= \sum_I T(I) F(I)$, total fissions in system
FE BAR	\bar{FE}		$= \sum_I WN(I) \cdot E(I)$, the elastic collisions
FE BAR P	\bar{FE}'		The elastic collisions for the previous iteration
FEN BAR	\bar{FN}		$= \sum_I WN(I) \cdot \sum_{g=1}^G \frac{n_g(I)}{V_g}$, average in zone I
F FAKE			Internal parameter in convergence test
FF BAR	\bar{FF}		$= \sum_I WN(I) \cdot F(I)$, the fissions for next iteration
FF BAR P	\bar{FF}'		The fissions for the previous S_n calculation

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Fortran Symbol	Physical or Mathematical Symbol	Units	Definition
FLAG 1			If α becomes negative having once been positive
H(I)			$= \Delta(I) \left(\sigma_{g,n} \rho(I) + \frac{\alpha}{V_g} \right)$ for alpha calculation
HE(I)	$E_{int}(I)$	$\frac{10^{12} \text{ ergs}}{\text{gram}}$	Specific internal energy of mass point I
HEO(I)	$E_0(I)$		Constant of integration in equation for internal energy
HMASS(I)	$H_{mass}(I)$	grams	Mass in region between $R(I)$ and $R(I-1)$ ($R(0)$)
HP(I)	$P_H(I)$	megabars	Pressure, including viscous pressure, where applicable
HPBAR	\bar{P}_H	megabars	Maximum pressure in system
HPT	$pT H$	megabars	Temporary value of $P_H(I)$ used to begin iteration
I			Mass point number
ICNTRL	α -control		Input controlling α to be used (=01 if random)

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*These quantities lack a factor of 4π .

Fortran Symbol	Mathematical Symbol	Units	Definition
IG	g		Energy group index
IGMAX	G		Number of energy groups
IH	h		Energy group index
II			Dummy variable
IMAX	I_{\max}		The total number of zones (or real mass points)
IRCNBR			Number of last memory dump
J			Dummy label used for storage of thermodynamic variables
JMAX	J_{\max}		Largest J to have appeared in the calculation
K(I)	$K(I)$		Material label of I'th mass point
KCALC			Internal parameter used to initiate calculation
KCNTRL			Input parameter for requesting calculation of
KP(J)	$K'(J)$		Temporary storage used for keeping track of
L			Dummy variable

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Fortran Symbol	Physical or Mathematical Symbol	Units	Definition
LDONT			A temporary storage which denotes
M			Mixture number
MA	M_a		The number of the particular substance
MMAX	M_{\max}		Number of mixtures the code is to handle
MN(M, IS)	$N_{M,i}$		The i'th substance to appear in the mixture
N			Dummy variable
NDMAX	ND_{\max}		Number of hydrodynamic cycles before
NDUMP			NDMAX minus number of hydrodynamic cycles
NH			$NH\Delta T$ = total time elapsed. When
NIT	N_{it}		Number of iterations in pressure correction
NITMAX	$N_{it \max}$		Maximum number of iterations allowed

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Fortran Symbol	Physical or Mathematical Symbol	Units	Definition
NL			NL_{\max} - NL is the number of hydrocycles
NLMAX	NL_{\max}		Minimum number of hydrocycles
NMAX	N_{\max}		Number of substances for which calculations are made
NP	N_p		Number of hydrodynamic cycles before
NPOFF	$N_p, \text{ off}$		Number of hydrodynamic cycles before
NPOFFP	$N'_p, \text{ off}$		Number of hydrodynamic cycles before
NS 4	N_{S4}		Number of hydrodynamics cycles before
NS4R	N_{S4R}		Number of hydrodynamics cycles before
OKI			Test parameter used in VJ-OK test.
OK 2			Test parameter used in VJ-OK test.
P(M, IS)			The atom fraction of I'th substance

Fortran Symbol	Physical or Mathematical Symbol	Units	Definition
PBAR	\bar{P}	megabar cm^3	$= \sum_I P_{H(I)}(I) \cdot T(I)$ is $\frac{1}{4\pi} x v$
POWER		$\frac{10^{12}\text{ergs}}{\mu\text{sec}}$	Total energy generated in
POWNGL		$\frac{10^{12}\text{ergs}}{\mu\text{sec}}$	Power following burst after
PSTAR	P^*	megabars	Temporary value of $P_H(I)$ when
PTEST		megabars	Maximum local pressure at
Q	Q	10^{12}ergs	Total energy (except for final)
QBAR	\bar{Q}		Internal parameter in calculation
QP	Q_p	10^{12}ergs	Total energy at end of pre-explosion
QPRIME	Q'	10^{12}ergs	Total energy (except for final)
R(I)	$R(I)$	cm	Outer radius of mass point
RBAR(I)	$\bar{R}(I)$	cm	$\frac{1}{2}[R(I) + R(I - 1)] = \text{average radius}$

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Physical			
Fortran Symbol	or Mathematical Symbol	Units	Definition
RHO(I)	$\rho_{\text{neut}}(I)$	$\frac{10^{24} \text{ atoms}}{\text{cm}^3}$	Atom density of the region between I
RHOT	$T_{\rho_{\text{Hyd}}}$	g/cm^3	Density of mass point I at end of new
RIE	Running E _{Internal}	$\frac{10^{12} \text{ ergs}}{\text{gram}}$	Specific internal energy of mass point
RKE	Running E _{Kinetic}	$\frac{10^{12} \text{ ergs}}{\text{gram}}$	Kinetic energy per gram for mass poi
RL(I)	$R_L(I)$		Lagrangian coordinate of mass point
RO(I)	$\rho_{\text{Hyd}}(I)$	$\frac{\text{g}}{\text{cm}^3}$	Density of mass point I at beginning o
ROLAB(M)	$\rho_{\text{Lab}}(M)$	$\frac{10^{-24} \text{ g}}{\text{atom}}$	Conversion factor between atomic de
ROSN(I)	$RO_{\text{sn}}(I)$	g/cm^3	Density of mass point I during S _n calc
S(I)		$\frac{\Delta R(I)}{R(I)}$	
SIG(IG,N)	$\sigma_{g,N}$	barns	Microscopic transport cross section fo
SIGMA (IG, IH, N)	σ_{gh}, N	barns	Microscopic scattering cross section f
SO(I)	$S_o(I)$		$= 4\Delta(I) (\nu_g F(I) + \rho_{\text{neut}}(I))$ $\sum_h N h(I) \sigma_g \leftarrow h \right),$ the term in S _n calculation proportion

Fortran Symbol	Mathematical Symbol	Units	Definition
S4R	S_{4R}		Floating point notation for N _{S4}
SUM(IH)	$\sum h$		SUM has no unique definition.
SUM 1	Σ_1		SUM is used to provide storage space for
T(I)		cm^3	$1/3 [R(I)^3 - R(I-1)^3] = \frac{1}{4\pi} x$
TAU(M)	$\tau(M)$	megabars	Constant in equation of state $p = \alpha\rho + \beta\theta$
THET	θ	kev	Temporary value of θ (I) used during iter
THETA(I)	$\theta(I)$	kev	Temperature of zone between $R(I)$ and $R(I+1)$
TOTIEN	E _{internal}	10^{12} ergs	Total internal energy
TOTKE	E _{Kinetic}	10^{12} ergs	Total kinetic energy
U (I)	$U(I)$	$\frac{\text{cm}}{\mu\text{sec}}$	Velocity of i'th boundary
V(IG)	V_g	$\frac{\text{cm}}{\mu\text{sec}}$	Velocity of neutrons in g 'th energy group
VJ		$\frac{1}{\text{gcm}^2}$	Input parameter for VJ - OK test on relativ

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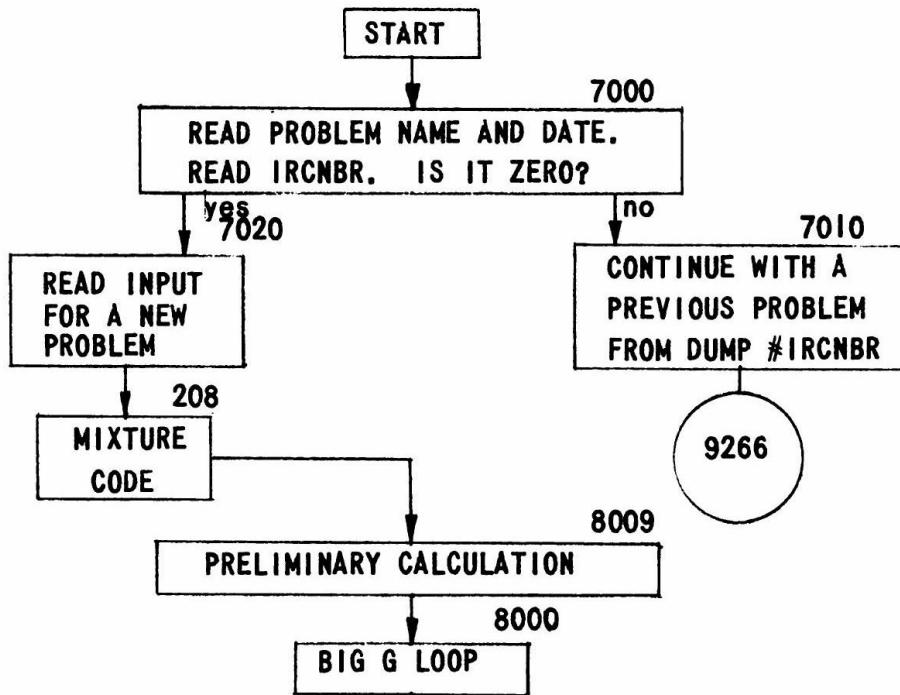
Fortran Symbol	Physical or Mathematical Symbol	Units	Definition
VP	P_v	megabars	Viscous pressure (See Appendix)
W			Criterion for stability of hydrostatic equilibrium: $\sum_{g=1}^G N_g(I) \cdot T(I)$, is volume element
WR			Criterion for stability of hydrodynamic equilibrium
Z			Dummy internal parameter

IV. DISCUSSION OF CONTROLS OF THE PROGRAM

The course of the solution and many of the controls thereon are explained in this section with the aid of a flow diagram. Details of the S_n calculation, the mixture code, and various other aspects not directly pertinent to this area of understanding are left for a later section covering the entire program step by step. Order numbers corresponding to various sequences of events are usually indicated in the upper right hand corner of the boxes in the flow diagram. It is cautioned that at times steps have been omitted to simplify an explanation.

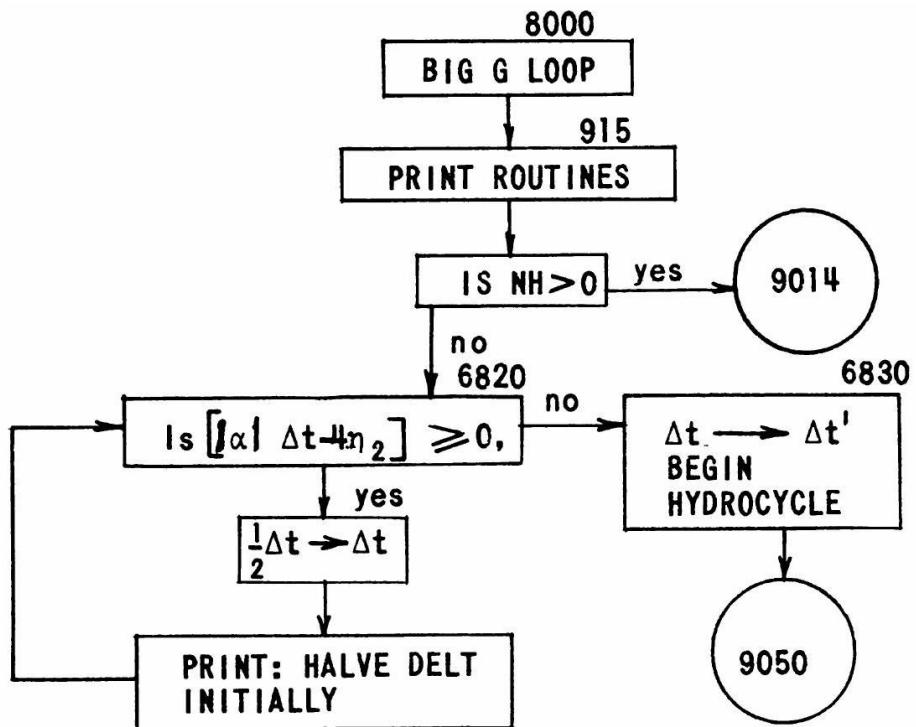
The first illustration outlines the steps followed at the start of a problem.

*These quantities lack a factor of 4π .



The S_n calculation (or Big G Loop) is treated like a black box in this section. It is noted that the problem originator can request the computing machine to scale the radii to provide some initial alpha. Also, the machine will calculate and print the k_{eff} of the initially converged configuration if so requested, enabling a determination of the neutron lifetime, $\ell = K_{ex}/\alpha$.

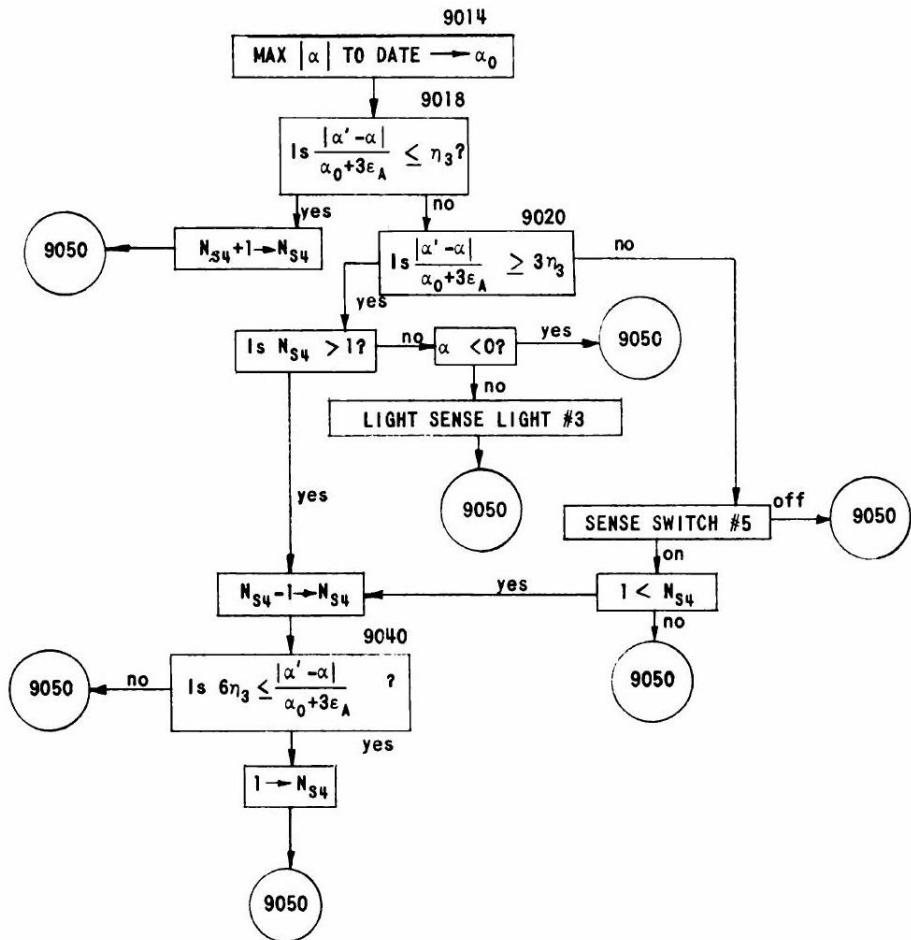
When the S_n calculation has converged, the program begins to exercise control on Δt , the time interval, as follows.



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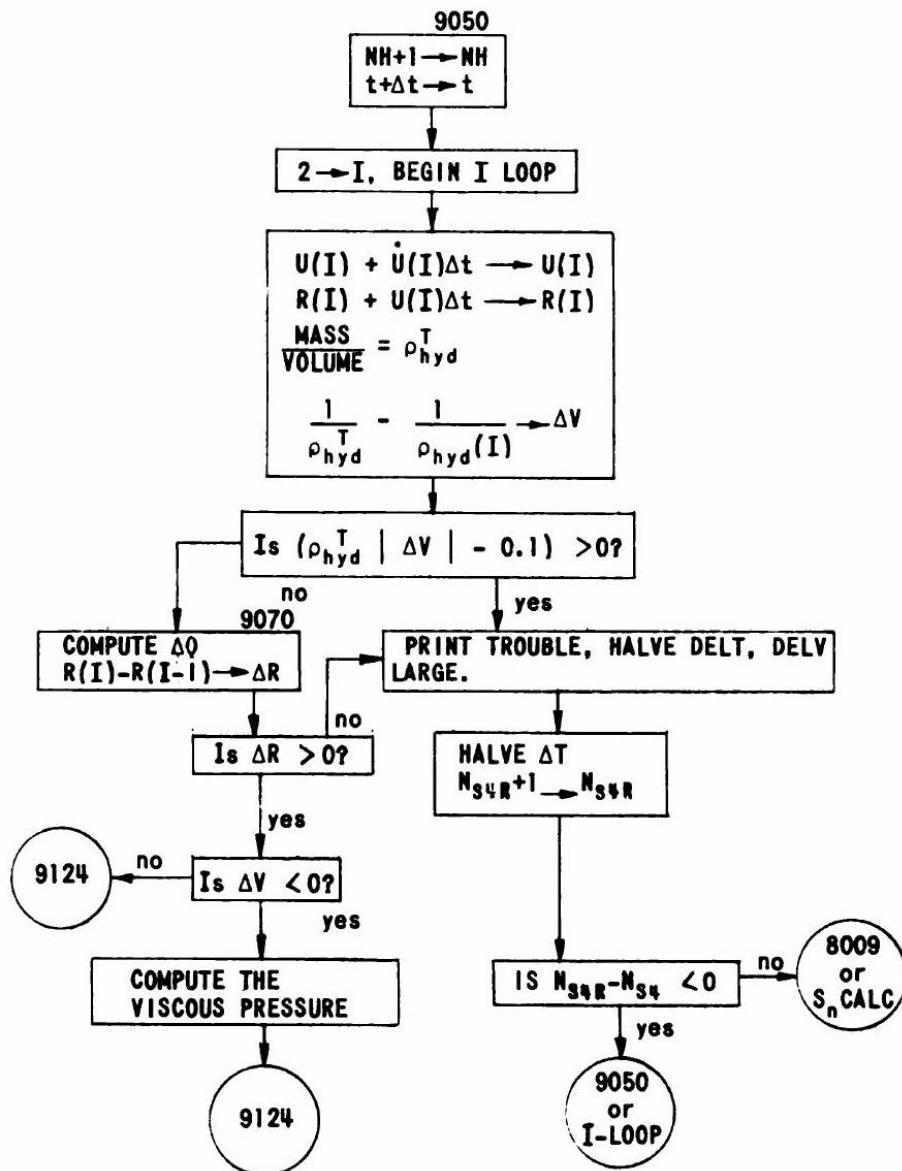
Thus, if $\alpha\Delta t$, the fractional change in power per hydrocycle, is too great in the original specification, Δt is reduced. At Order 9014, further controls are exercised following all neutronics calculations except the first.



In this sequence the last two alphas are compared to see if alpha is changing too slowly or too rapidly between successive S_n calculations. If the difference is very small, N_{S4} , the number of hydrocycles per neutron cycle, is increased by one. This number starts at unity and slowly builds up during a typical burst where a step function of reactivity is inserted at very low power. The program then sends the computation to Order 9050 to begin a hydrocycle. If the difference in alphas, compared to the maximum alpha encountered, exceeds η_3 but not $3\eta_3$, the hydrocycle begins unless the operator had decided, based on observation of the output, that N_{S4} should be reduced. In this case he turns on (or depresses) Sense Switch No. 5, which reduces N_{S4} by one before performing the hydrocycle. If $3\eta_3$ is exceeded, N_{S4} is reduced by one and the comparison is again made, this time with the upper limit, $6\eta_3$. If this is not exceeded, the hydrocycle proceeds. If it is, N_{S4} is set all the way back to unity before the hydrocycle begins. However, if N_{S4} was already unity when $3\eta_3$ was exceeded, sense light

No. 3 is turned on before beginning the hydrocycle. Following the cycle, the time interval Δt will be halved, since there is no further recourse to N_{S4} to control the variation in alpha between successive S_n calculations.

We continue from 9050.



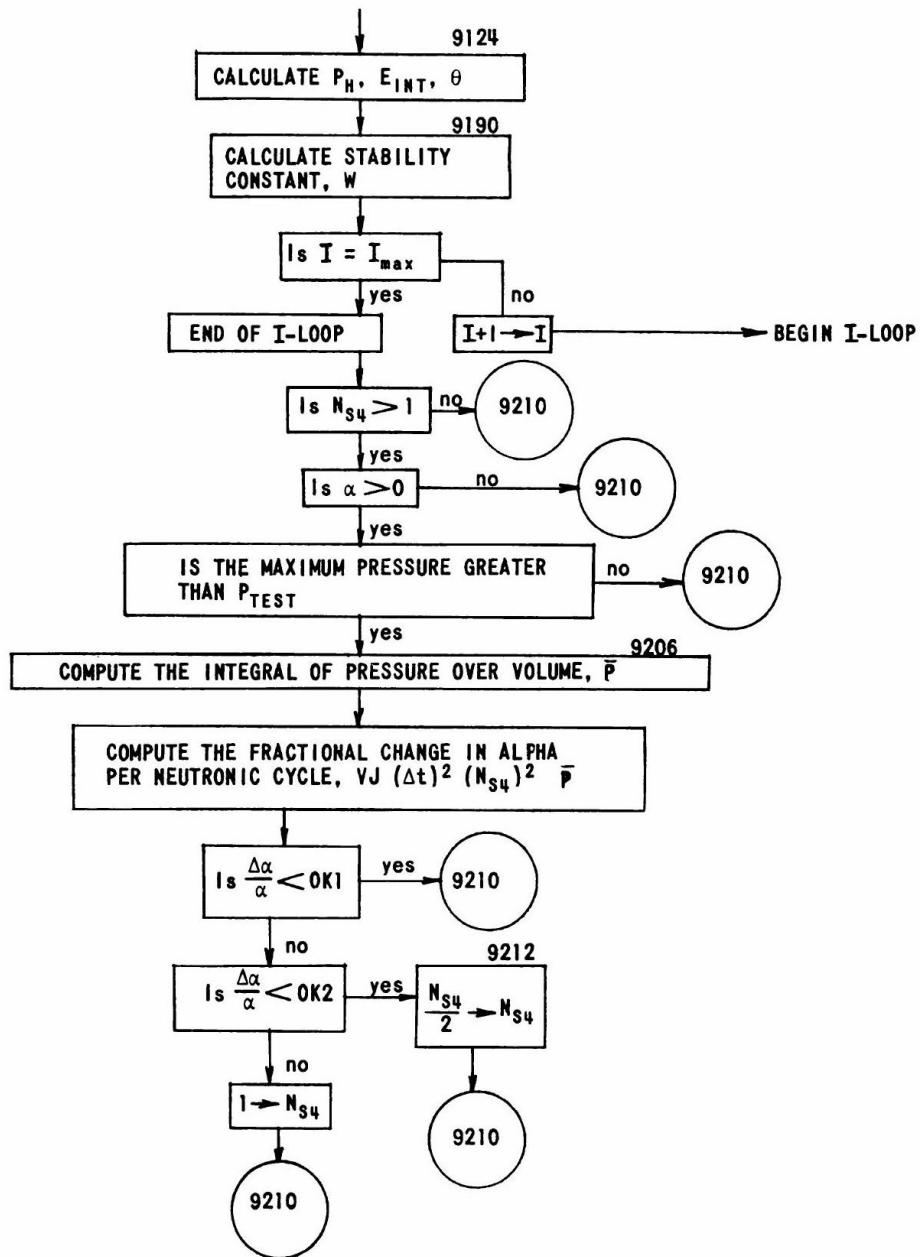
In this last set of steps control is exercised on the density change occurring in any volume element in a single hydrocycle. If it is too great, Δt is halved. Or, if the motion of one radial boundary should

be so great as to cross the next boundary, the time interval is also halved. The presence of these serious difficulties in the course of the solution is printed on the output for the benefit of the operator.

The viscous pressure is a mechanism devised to permit calculation without the ordinary difficulties which would accompany the passage of strong shock waves. (See Appendix C).

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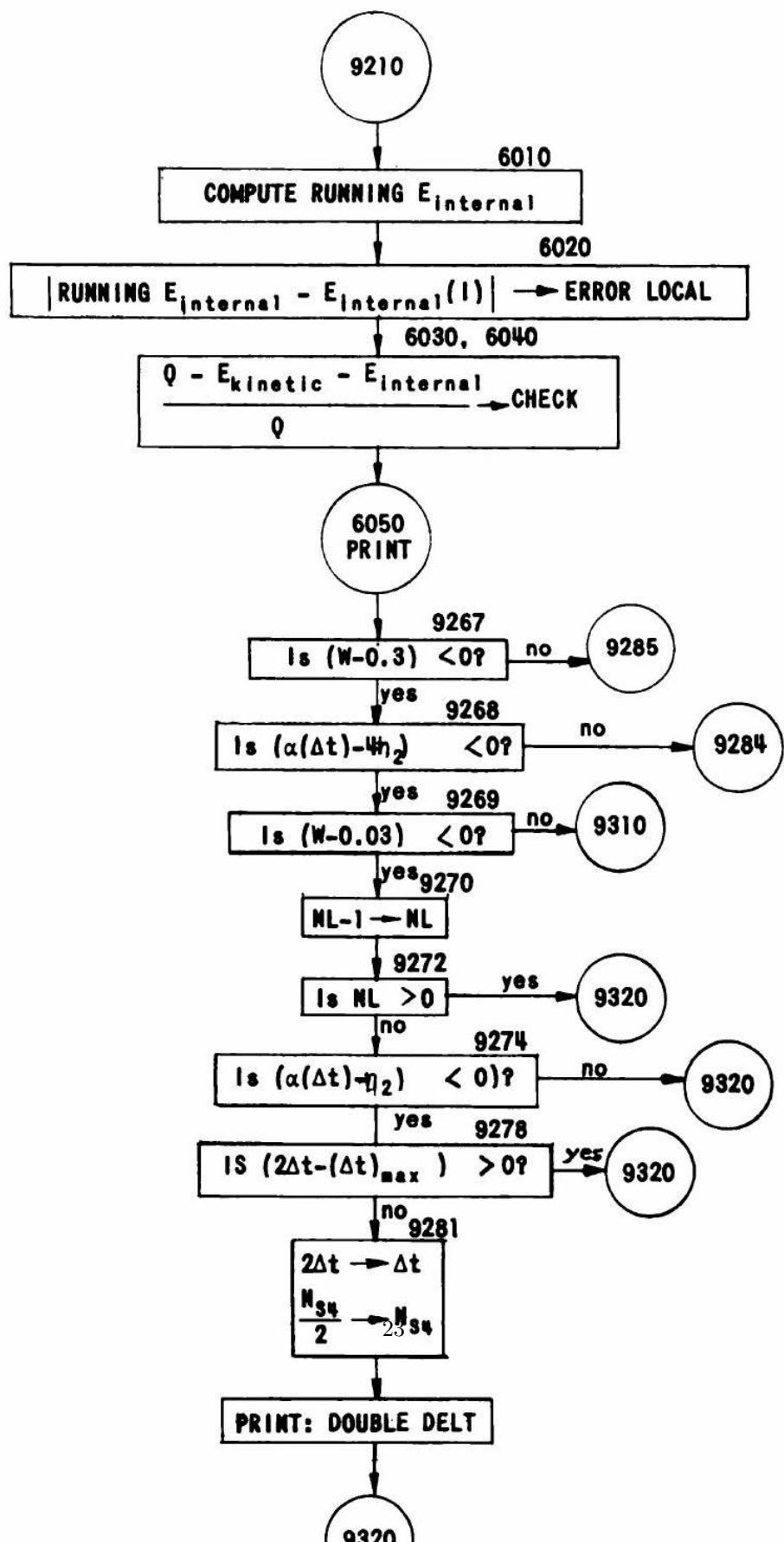


In this sequence a criterion for stability of the calculation is computed which is designed to prevent the generation of excessively high changes in density per hydrocycle. The criterion, W , will be examined later in the program. The controls then ask a series of questions designed to exercise a control on the rate of change of alpha per neutronics cycle during the peak of the burst. Not wishing to keep N_{S4}

small during the low power portion, a test is installed to reduce N_{S4} when the rate of change of alpha becomes significant. (See Appendix A).

From Order 9210, the program goes on to a pair of checks on the numerical accuracy of the computation. First the internal energy at each mass point is computed in an alternate fashion and compared with the previous calculation. Second, the sum of kinetic and internal energies is computed and compared with Q .

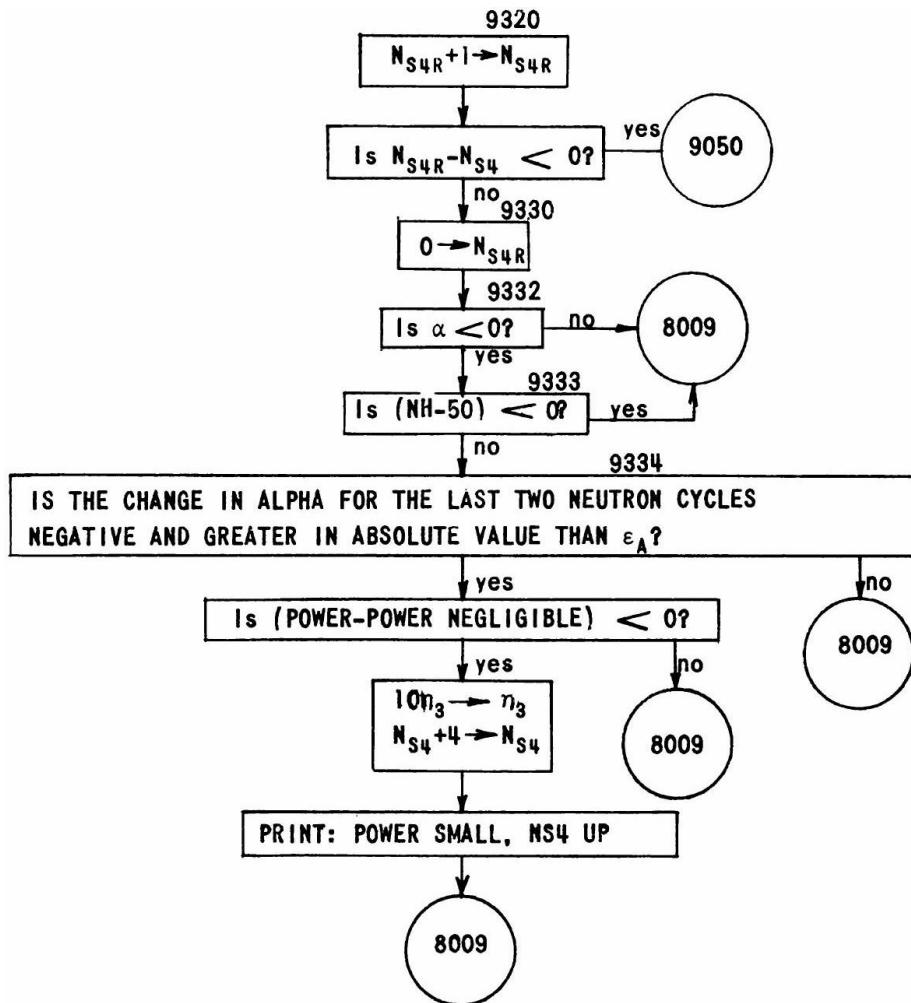
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Following the check on numerical accuracy, which is merely printed out for the information of the problem originator, a series of questions are asked to determine whether the time interval Δt is appropriate. If W , the stability function, is larger than 0.3, Δt is halved (9285 , 9290). If the fractional change of power per cycle, $\alpha\Delta t$, exceeds $4\eta_2$, Δt is halved, assuming the stability test has not already done so (9284,9290). If the problem has gone through $N_{L_{Max}}$ hydrocycles since the last doubling of Δt , and if W and $\alpha\Delta t$ are sufficiently small, Δt is doubled.

When the above tests are completed $N_{S4R} + 1 \rightarrow N_{S4R+1}$ and if $N_{S4R} < N_{S4}$, a new hydrocycle is begun at Order 9050. Otherwise, a final series of controls is exercised before sending the problem back to the neutronics cycle (8009).

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This last series of tests is devised to reduce the number of time-consuming neutronics calculations after the burst when α has turned negative and the power has fallen to a low value. This can also be taken as a signal to the operator to terminate the problem if there is no desire to study post-burst phenomena.

V. DETAILED FLOW DIAGRAM AND EXPLANATORY NOTES

Notes on Sheet No. 1

Since there are many possible reasons for wishing to rerun a portion of a previous problem, or extending a solution timewise, a provision has been made for starting up a problem anew from a previous dump. Automatic dumping on tape at regular intervals is provided (Order No. 9263) to facilitate such procedures. Sense switch No. 1 provides the operator the opportunity to alter the memory when rerunning a problem from the middle. It also enables one to use the proper precautions when working from a consolidated tape. (The term "on" is used in the flow diagrams to indicate a switch is "depressed.")

Notes on Sheet No. 2

As mentioned previously, the problem originator can specify a configuration and take the starting alpha which accompanies it, or can specify an alpha, guess a configuration, and let the program vary all radii linearly to achieve this alpha before beginning the hydrodynamics solution. If

Generated at New York University through HathiTrust on 2025-11-22 04:22 GMT <https://hdl.handle.net/2027/mdp>. 39015078509448 / Public Domain, Google-digitized ICNTRL (or α -control) is zero, the program proceeds to the usual calculation of alpha, first setting α_3 slightly different from α_4 to prevent premature convergence on the first S_n calculation. If ICNTRL is unity, the guessed outer radius goes to α_4 ; as the calculation progresses, the successively adjusted values of R (IMAX) are compared for the test of convergence, and a special convergence criterion, ϵ_R is used.

A complete on-line print-out of input data is normally obtained at the beginning of a new problem. This can be prevented to save machine time by turning on Sense Switch No. 6. There is no provision for off-line print-out of input data at the present time.

Notes on Sheet No. 3

The following is an elaboration of the procedure for calculating mixtures.

Each of the N_{\max} substances is assigned a number $N = 1, 2, \dots, N_{\max}$. For each such N a set of cross section tables is read in.

If $M_{\max} = 0$, there is no mixing to be performed and the mixture code is by-passed.

Otherwise, for the integers $M = 1, 2, \dots, M_{\max}$, in that order, the computer mixes substances numbered $N_{M,1}, N_{M,2}, \dots, N_{M,i_M}$ in the proportions $P_{M,1}, P_{M,2}, \dots, P_{M,i_M}$ (atom fraction) and assigns this new mixture the number N_{M,i_M+1} where i_M is the smallest integer such that $N_{M,i_M+2} = 0$.

Each region is assigned its material label K , that of the material of which it is composed.

Input functions of mixture numbers (ROLAB (N), ALPHA (N), ..., BCV (N); see (7110),) must be (see (7080) to (7120)) read in that order of mixture numbers obtained by starting from the mesh point $I = 2$ and recording each $N = K$ (I) as it appears (if it has not appeared before).

Notes on Sheet No. 4

To expedite the preparation of this over-all program an existing S_4 program in Fortran was borrowed and tied into the over-all calculation. This calculation employs cross sections in barns and uses a material density in atoms/cc. Since the hydrodynamics calculation requires a density in grams/cc, it was necessary to employ more than one definition of density. The method used is as follows:

RO (I) is the hydrodynamic density, $\rho_{\text{Hyd}}(I)$, g/cc.

RHO (I) is the neutronic density, $\rho_{\text{neut}}(I)$, atoms /ccx 10^{-24}

ROLAB M is a conversion factor between the two previous quantities ($\rho_{\text{Hyd}} = \rho_{\text{lab}} \cdot \rho_{\text{neut}}$), and equals the average grams/atom $\times 10^{24}$ for mixture M .

If the problem originator sets KCNTRL equal to unity, he is requesting the value of k_{eff} corresponding to the original configuration, or alpha. The program is arranged to converge first on alpha, then to set KCALC equal to unity and send the computation back to Order No. 8000 to rebegin the Big G loop. The test for KCALC then routes the solution away from the alpha solution to the convergence test on k_{eff} .

The S_4 calculation itself is conventional (5, 6, 7) except for a slight variation in the manner of iterating or achieving convergence. This is similar to the approach adopted in reference 6 (pgs. 11, 21) in that the various sums are performed with a semi-empirical weight function, $WN(I) = T(I) \cdot \left(\sum_{g=1}^6 N_g(I) \right)$ (Order No. 8301) rather than merely a volume term $T(I)$. (See Order No. 301, for example, defining $\overline{FE'}$.) The procedure used for calculating the next α is identical to that in reference 6. For the convergence on radius or k_{eff} , however, the sums of weighted fissions and elastic collisions are employed in a somewhat different manner.

Notes on Sheet No. 8

Under Order No. 6801 the initial values of k_{eff} 1, 2, 3, 4 are arranged to insure a minimum of four iterations before convergence of the k_{eff}

calculation.

Under Order No. 6810, when $\text{NH} = 0$ the Lagrangian coordinates R_L (I) are computed. These are time independent and serve throughout the problem when the mass of a mass point is needed to calculate the total value of a quantity at a mass point from the value per gram. They are also used in the calculation of acceleration, at the beginning of the I loop (below Order No. 9066).

Notes on Sheet No. 9

Since the simple linear equation of state is generally not adequate over the entire temperature range, and since one frequently wishes to provide a threshold temperature above which the steep rise in pressure begins, the equation of state may yield negative pressures for low temperatures. In this event Order No. 6833 substitutes zero for the hydrodynamic pressure, P_H .

The constants ϵ_0 (I) are discussed in Appendix D. They are utilized in an accuracy check involving an energy balance. Running E_{kinetic} , E_{kinetic} and E_{internal} are normally lacking in the factor $\frac{4\pi}{3}$ which is supplied directly before printout.

The outer boundary of the system is a free surface with zero pressure. This is accomplished mathematically by defining the pressure at the center of the next (fictitious) mass point as the negative of the pressure at the center of the outermost true mass point.

Notes on Sheet No. 10

The three quantities Q , Q' and Q_p are defined as follows.

At the beginning of a new hydrocycle the energy Q (less a factor $\frac{4\pi}{3}$) is stored as Q' , the energy after the previous increment in time. The new Q is then calculated by adding in the energy rise during the present time increment. Thus the primed quantity is always the one previous in time. Q_p is " Q to be printed," i.e., Q multiplied by the $\frac{4\pi}{3}$ factor.

Notes on Sheet No. 11

The new hydrocycle begins with a calculation of the new velocity and requires a new acceleration. From Appendix B we see that the velocity at time $(n + 1/2)\Delta t$ is computed using the acceleration at time $(n)\Delta t$. We may write 9 (Chapt. 10)

$$U^{n+\frac{1}{2}}(I) = U^{n-\frac{1}{2}}(I) - \Delta t \frac{1}{\rho_{Hyd}} \frac{\partial P_H}{\partial R}$$

The Lagrangian coordinates, R_L , are defined by the relation $\rho R^2 dR = R_L^2 dR_L$, so that

$$\frac{1}{\rho} = \frac{R^2}{R_L^2} \frac{\partial R}{\partial R_L}$$

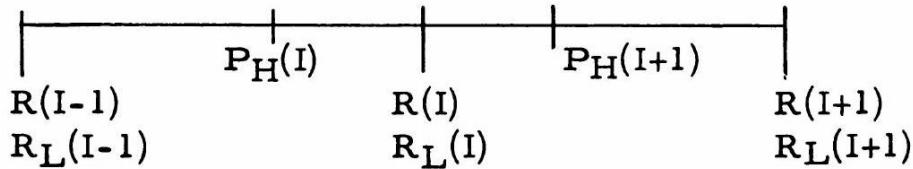
Thus,

$$U^{n+\frac{1}{2}}(I) = U^{n-\frac{1}{2}}(I) - \Delta t \frac{R^2}{R_L^2} \frac{\partial P_H}{\partial R_L}$$

or

$$U^{n+\frac{1}{2}}(I) = U^{n-\frac{1}{2}}(I) - \frac{\Delta t R^2(I)}{R_L^2(I)} \cdot \frac{P_H(I+1) - P_H(I)}{\frac{1}{2}[R_L(I+1) - R_L(I-1)]}$$

On a diagram in space, these variables are located as follows:



The calculation of the new density, ρ_{Hyd}^T , follows directly from the definition of the Lagrangian coordinates.

Below Order No. 9082, the question "Is $\Delta V < 0$?" is asked to determine whether a compression or rarefaction wave is traversing that mass point. For a compression, the viscous pressure is computed and added to the true hydro-pressure, as explained in Appendix C.

An iterative procedure called the modified Euler method is used in the pressure calculation. At Order No. 9124 the previous pressure is guessed to be the answer at the next time interval. The temperature is calculated from energy considerations, and then a new pressure is calculated using the equation of state. This pressure is compared with the first guess, and if sufficiently different is used as the next guess. This subcycle is then repeated. In the convergence test (Order No. 9150) ϵ_1 is a small pressure to provide some denominator if $P_H = 0$. It should be negligible compared to P_H at the values of interest.

The thermodynamic considerations are presented in Appendix D. A different equation of state could be used with appropriate changes in the program.

Notes on Sheet No. 12

The VJ-OK test, included to provide more frequent calculation of alpha when alpha starts to change rapidly under pressure buildup, is discussed in Appendix A. With Order No. 9213 the number of hydrocycles between off-line prints can be reduced at this point in the computations, thereby providing more frequent detailed results.

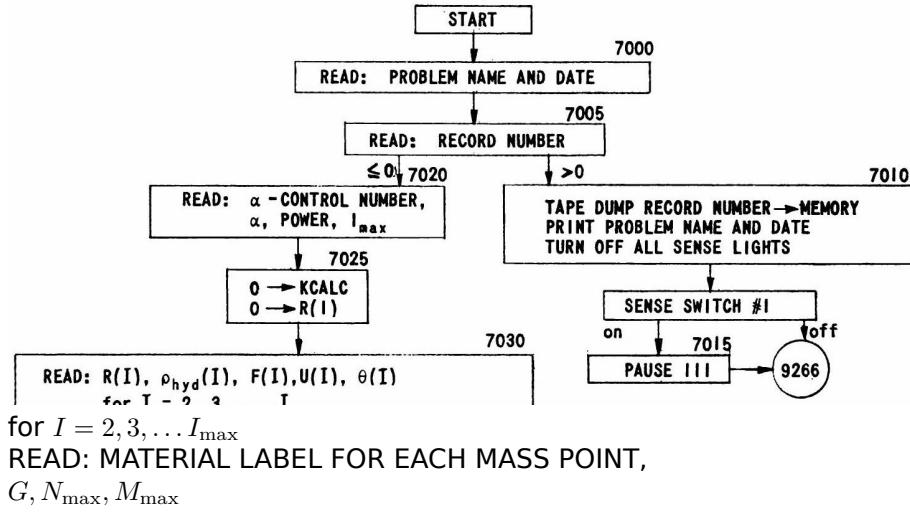
Notes on Sheet No. 13

The error checks are discussed in Appendix D. Briefly, the internal energy of each mass point is computed in an alternate manner and compared to that resulting from the normal procedure. Similarly, the total energy is computed in an alternate fashion and a comparison made.

Notes on Sheet No. 15

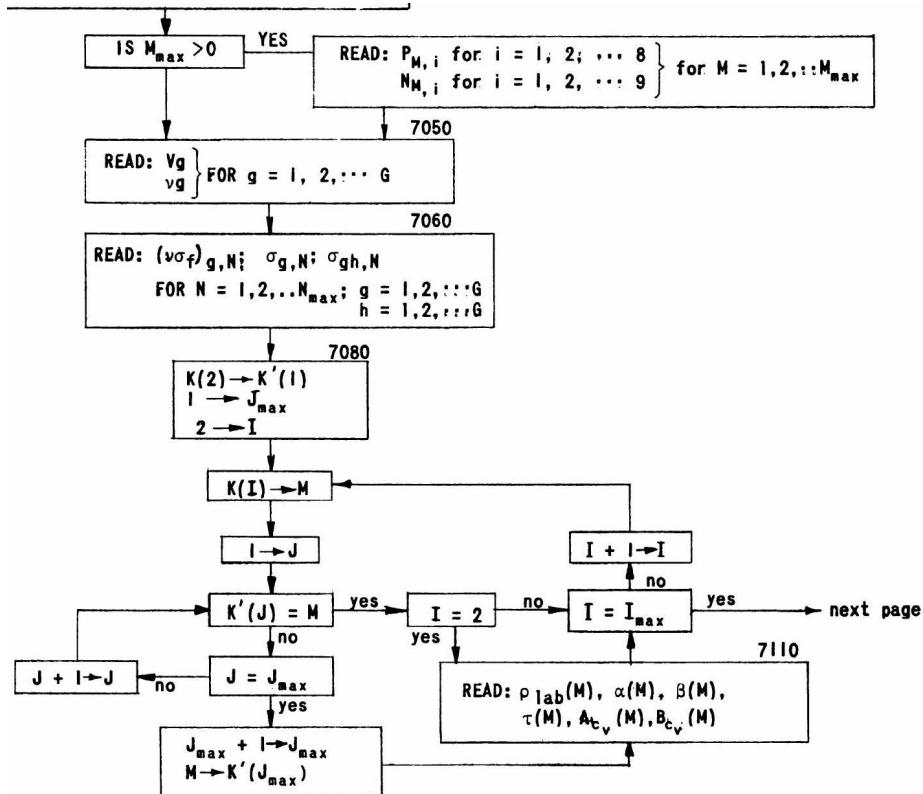
The reasons for the different shifts in Δt and $\Delta t'$ when the time interval is halved or doubled are discussed in Appendix B.

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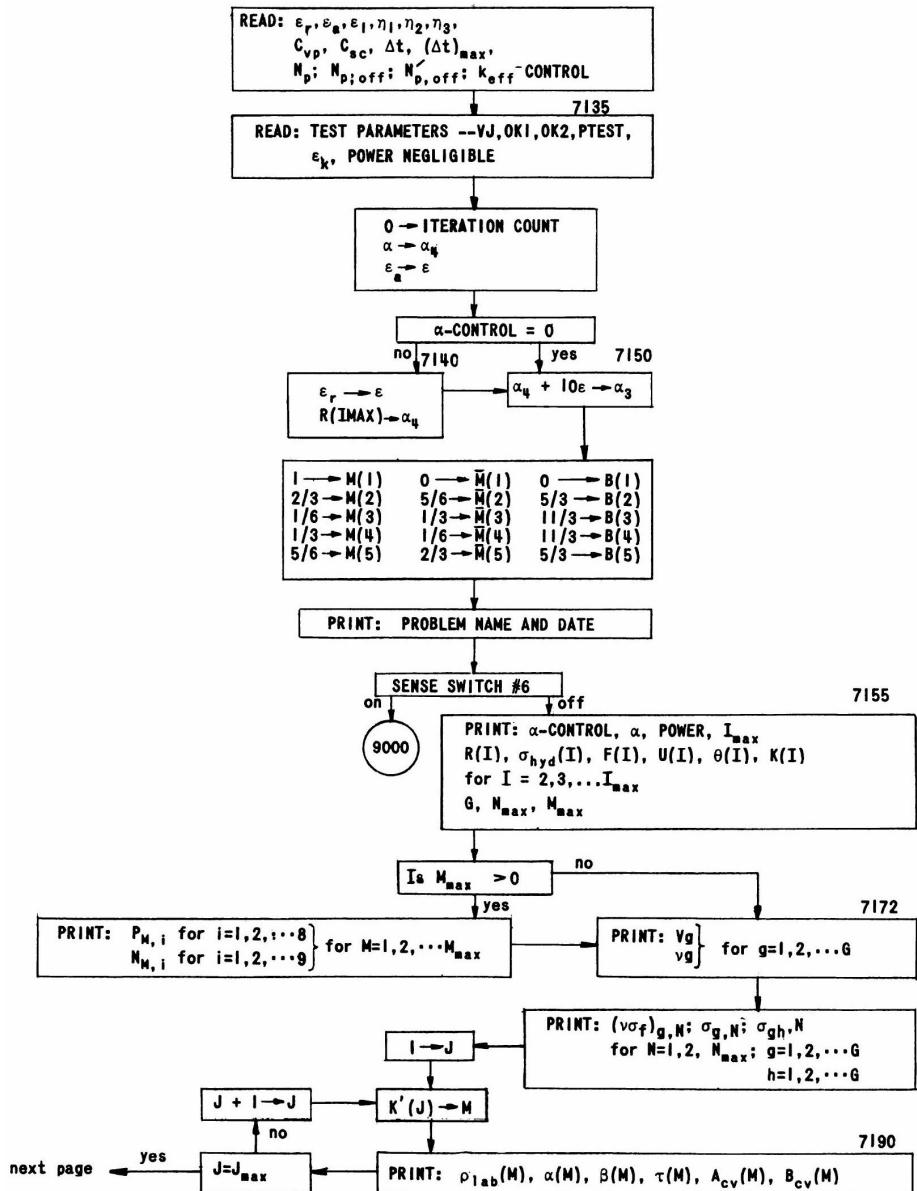


for $I = 2, 3, \dots, I_{\max}$

READ: MATERIAL LABEL FOR EACH MASS POINT,
 G, N_{\max}, M_{\max}

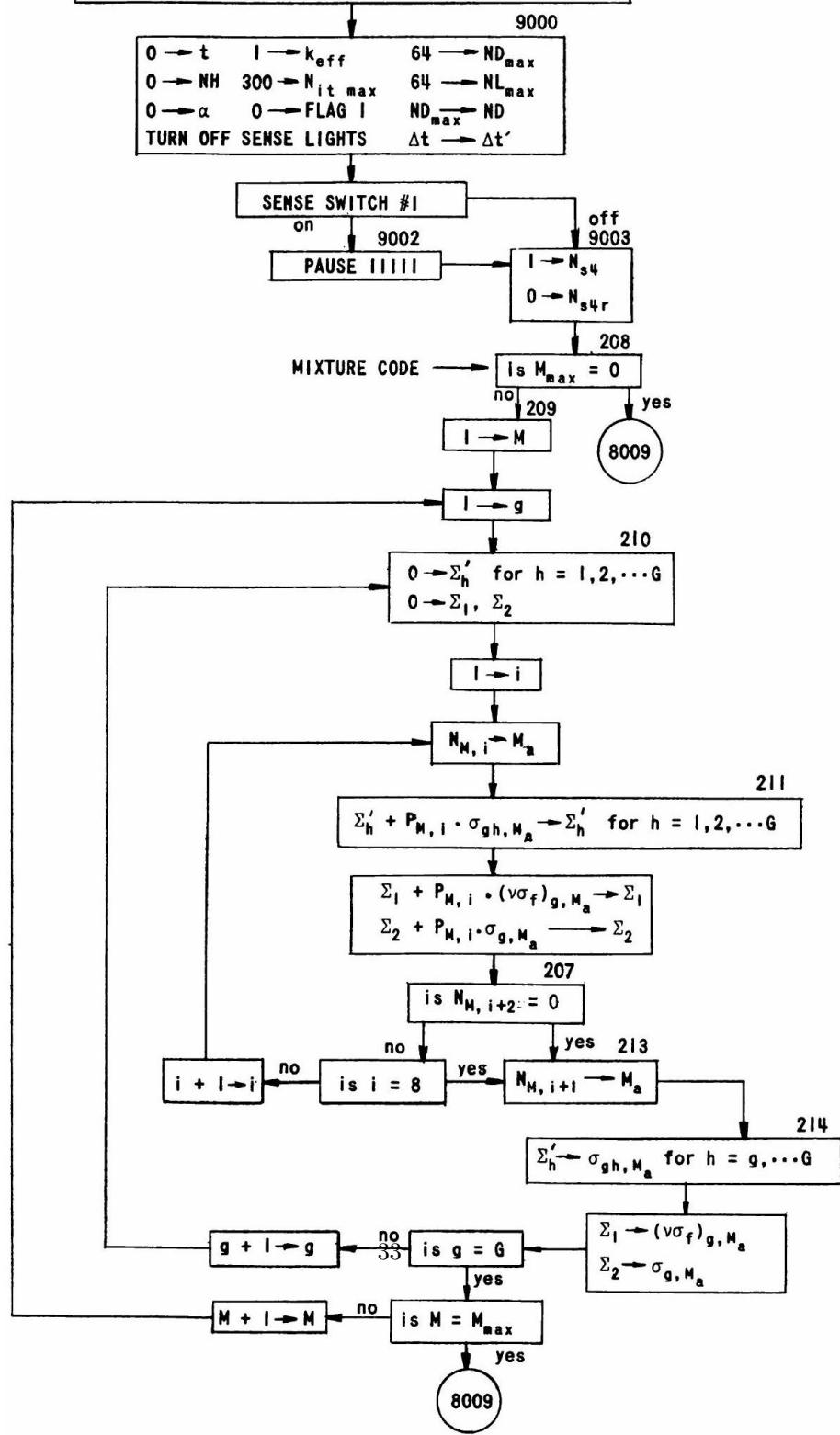


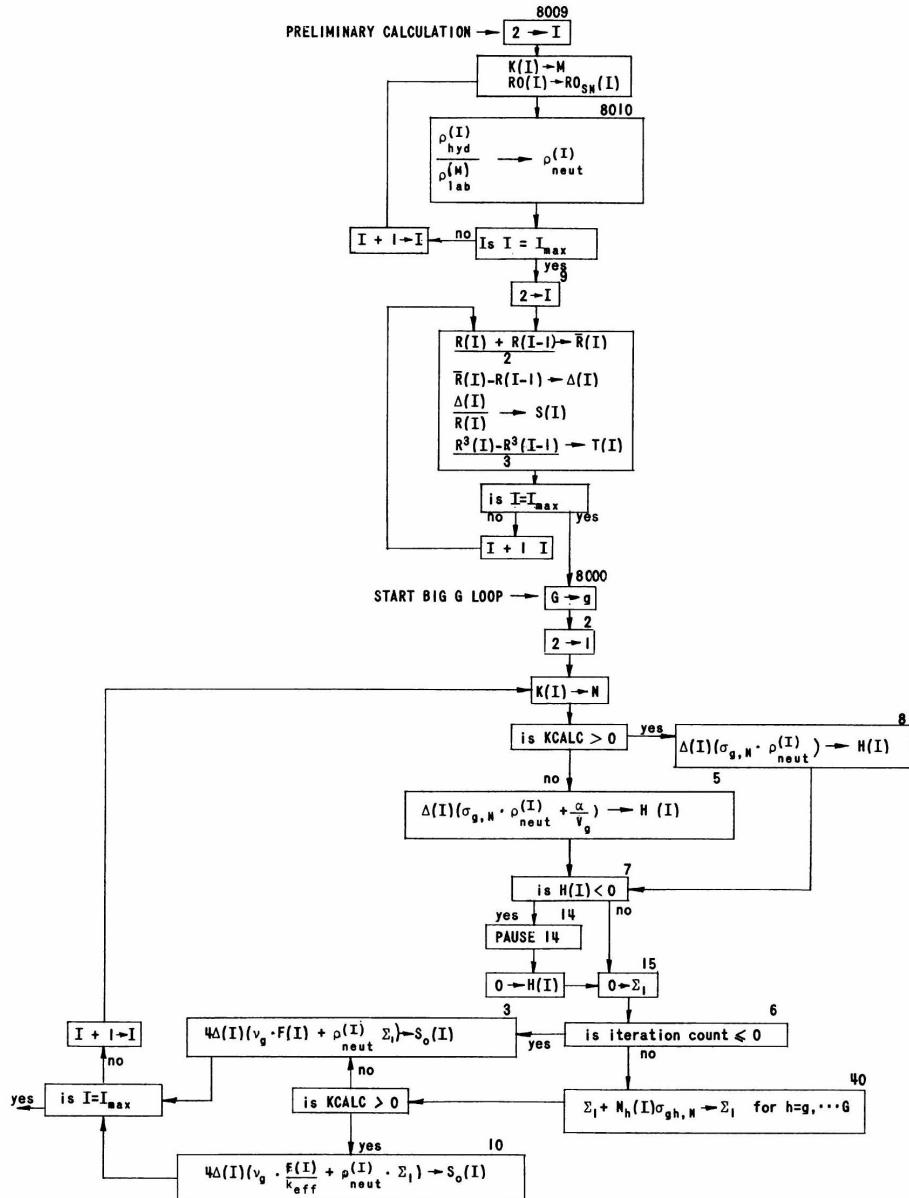
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PRINT: ϵ_r , ϵ_a , ϵ_1 , η_1 , η_2 , η_3 ,
 C_{vp} , C_{sc} , Δt , $(\Delta t)_{max}$,
 N_p ; $N_{p,off}$; $N_{p,off}$; k_{eff} CONTROL,
 TEST PARAMETERS -VJ,OK1,OK2 PTEST,
 ϵ_k , POWER NEGIGIBLE



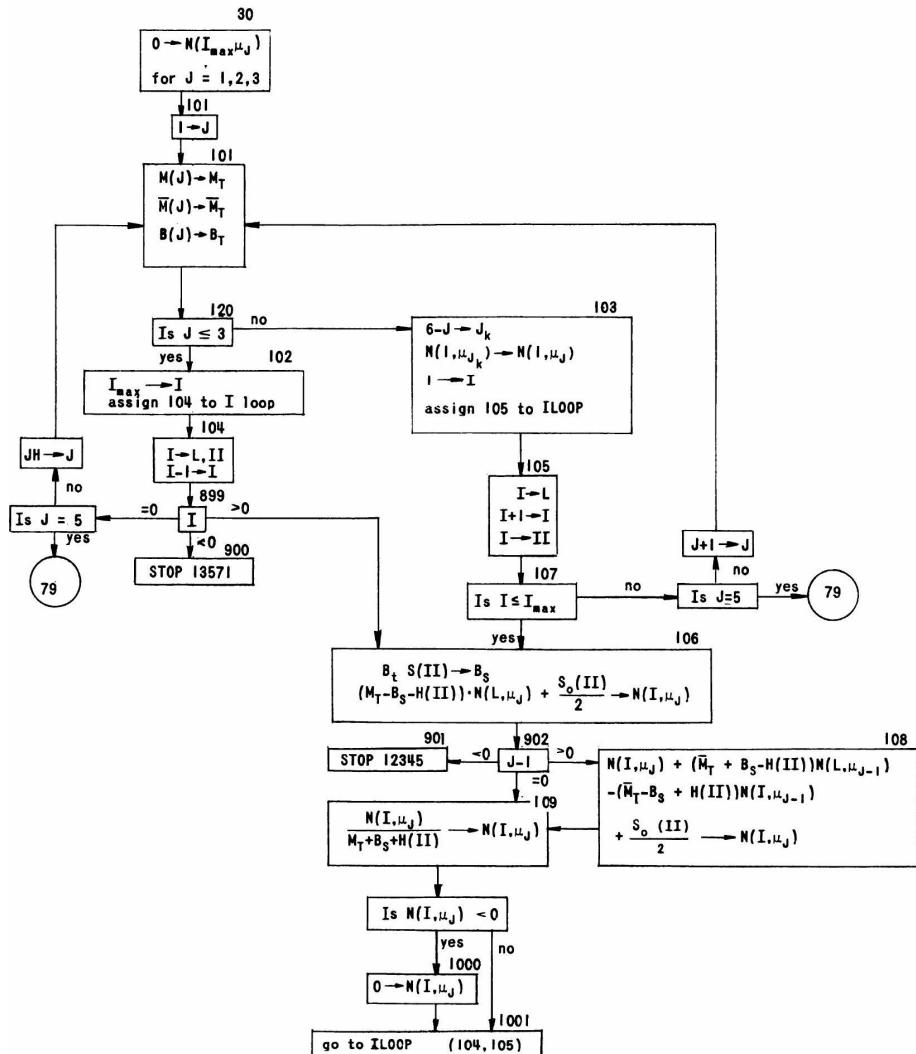


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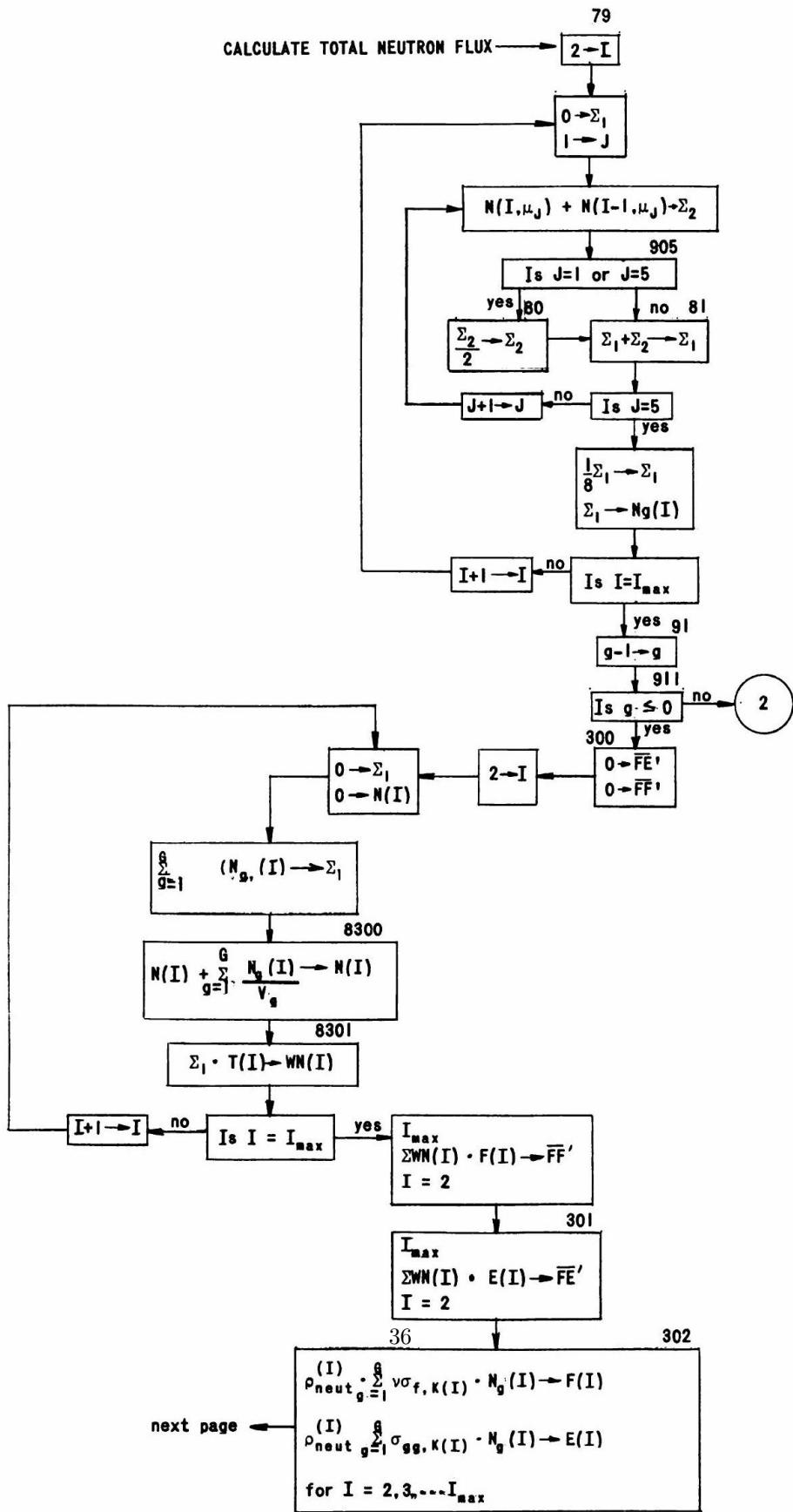
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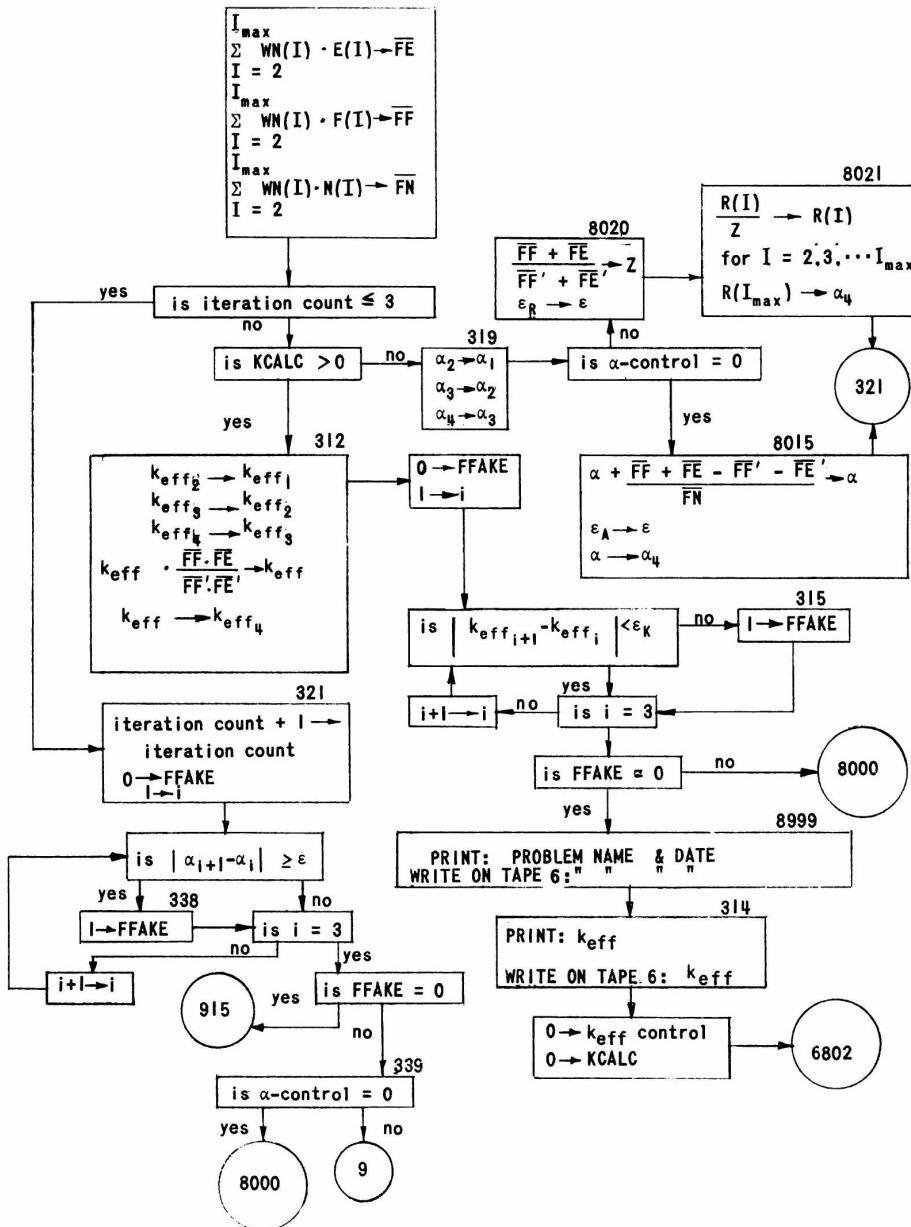


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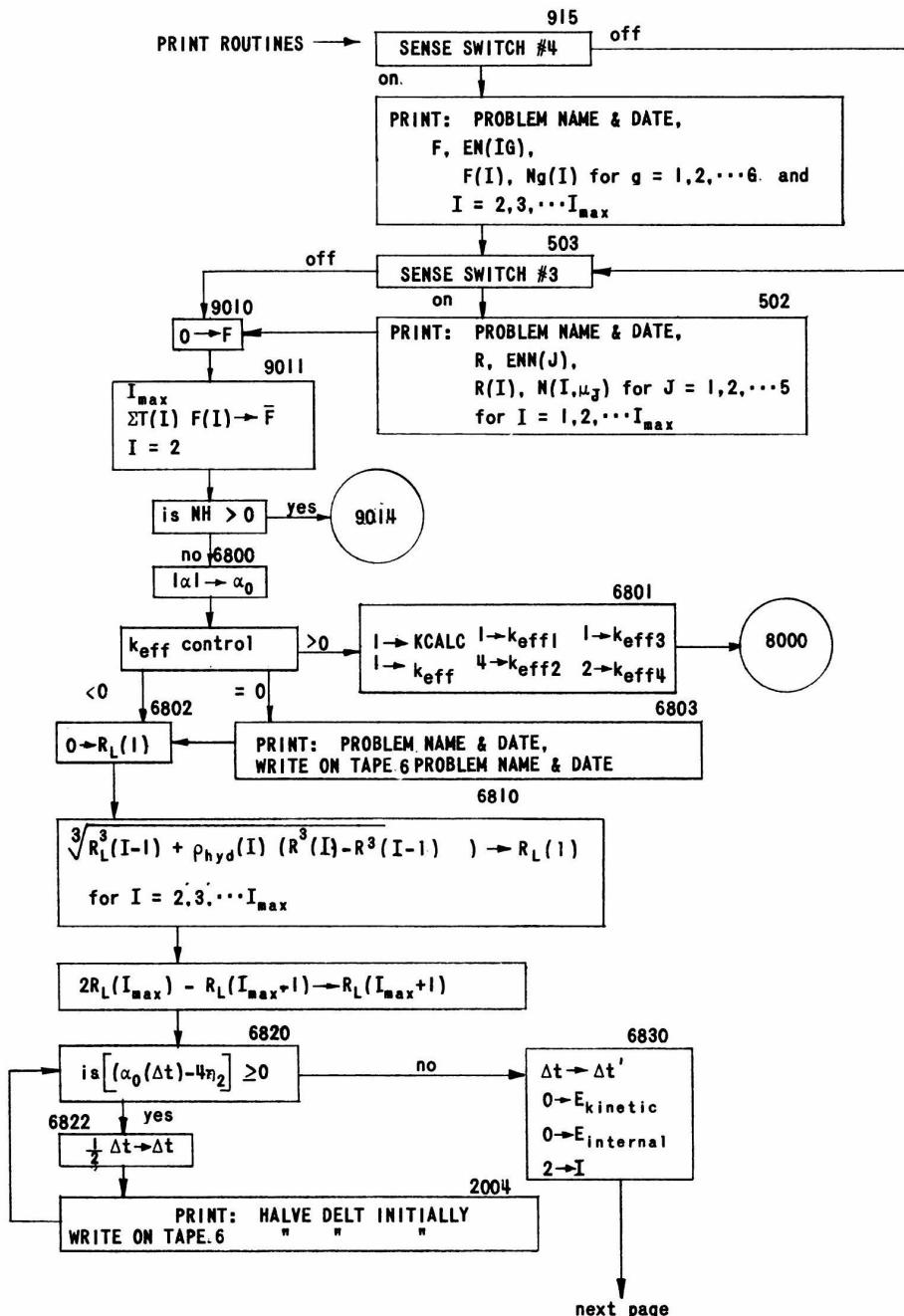


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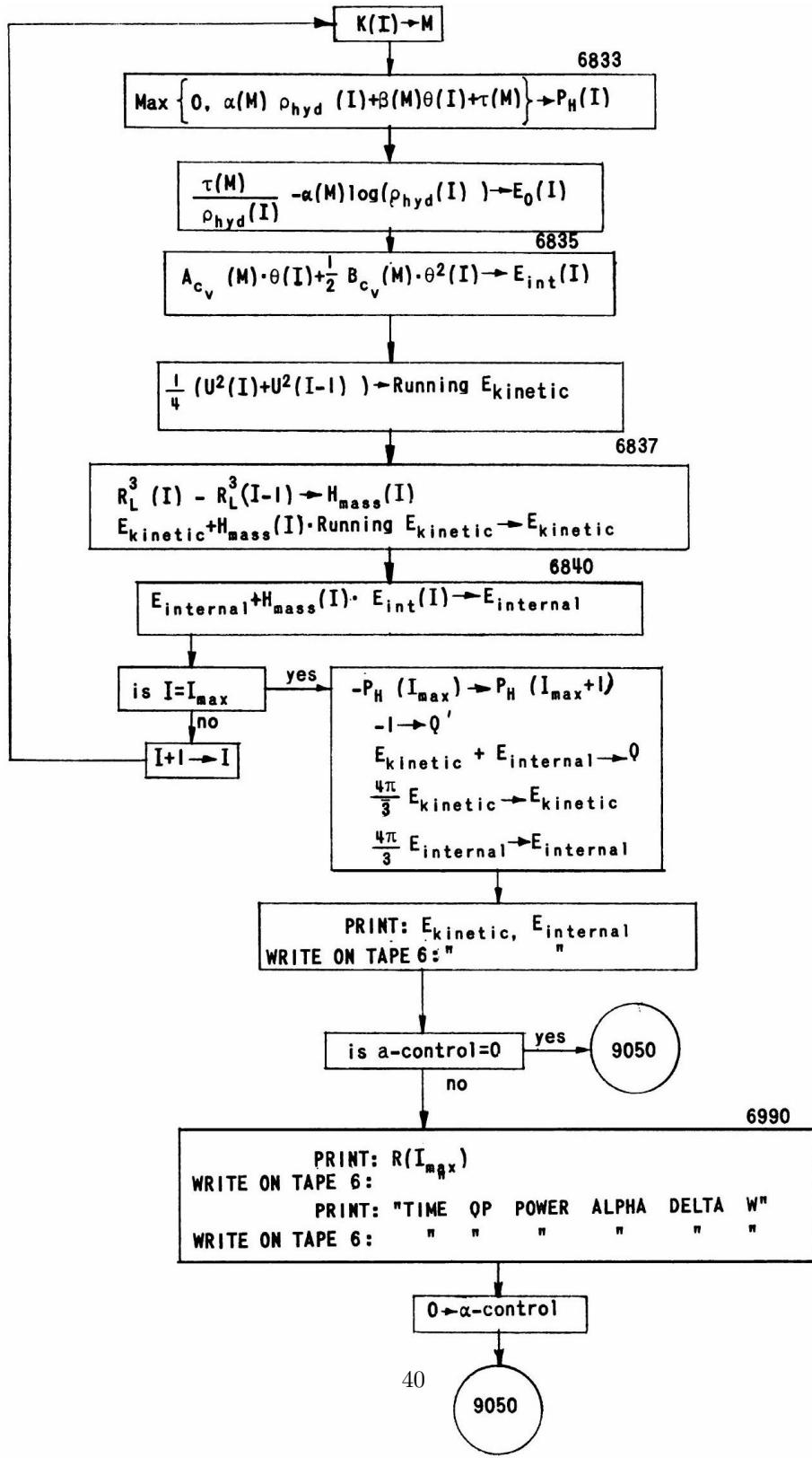


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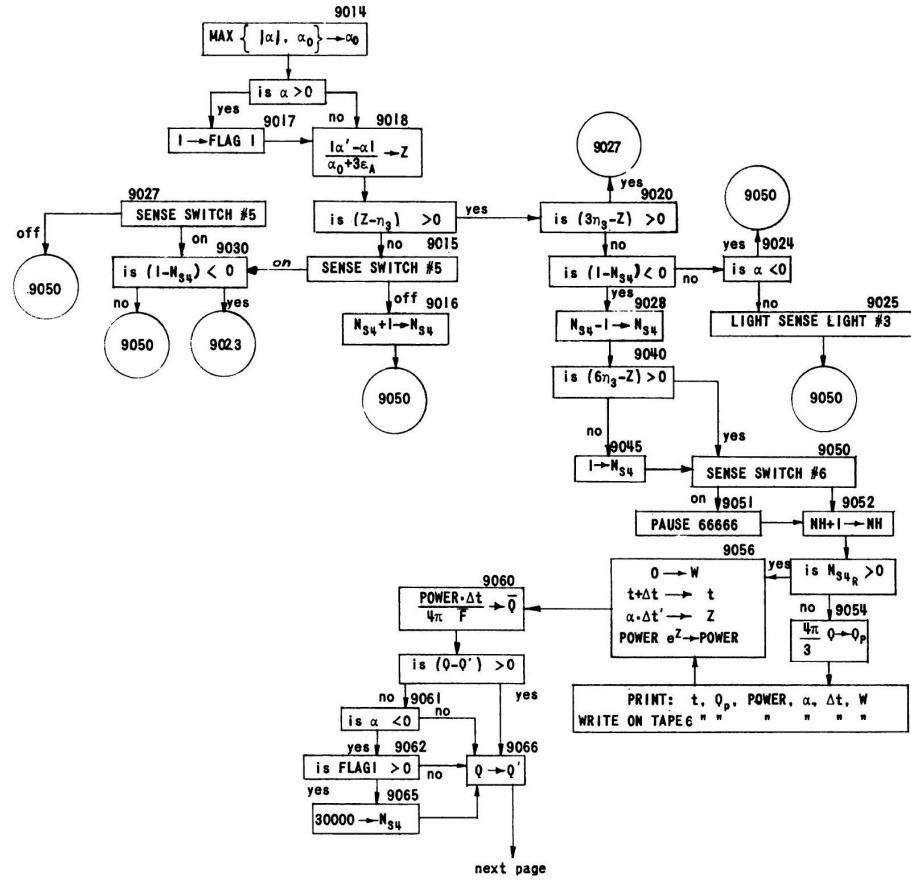


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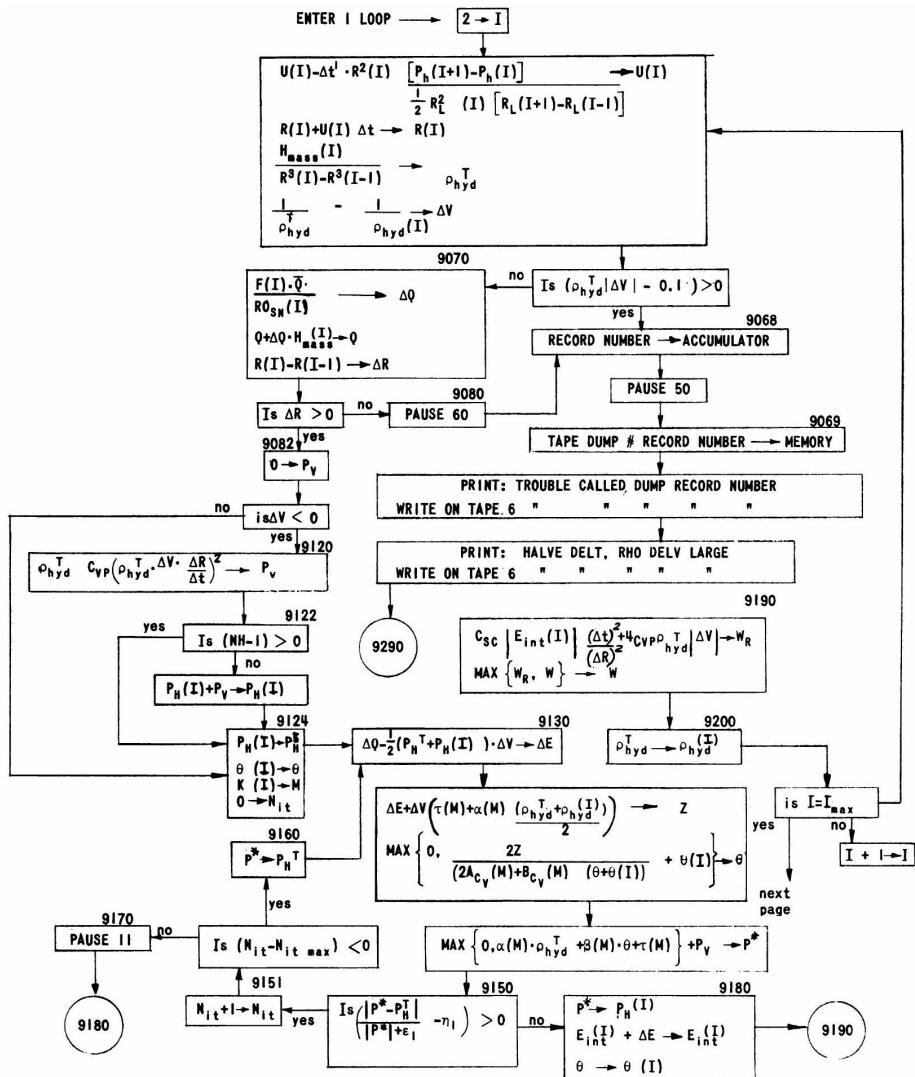
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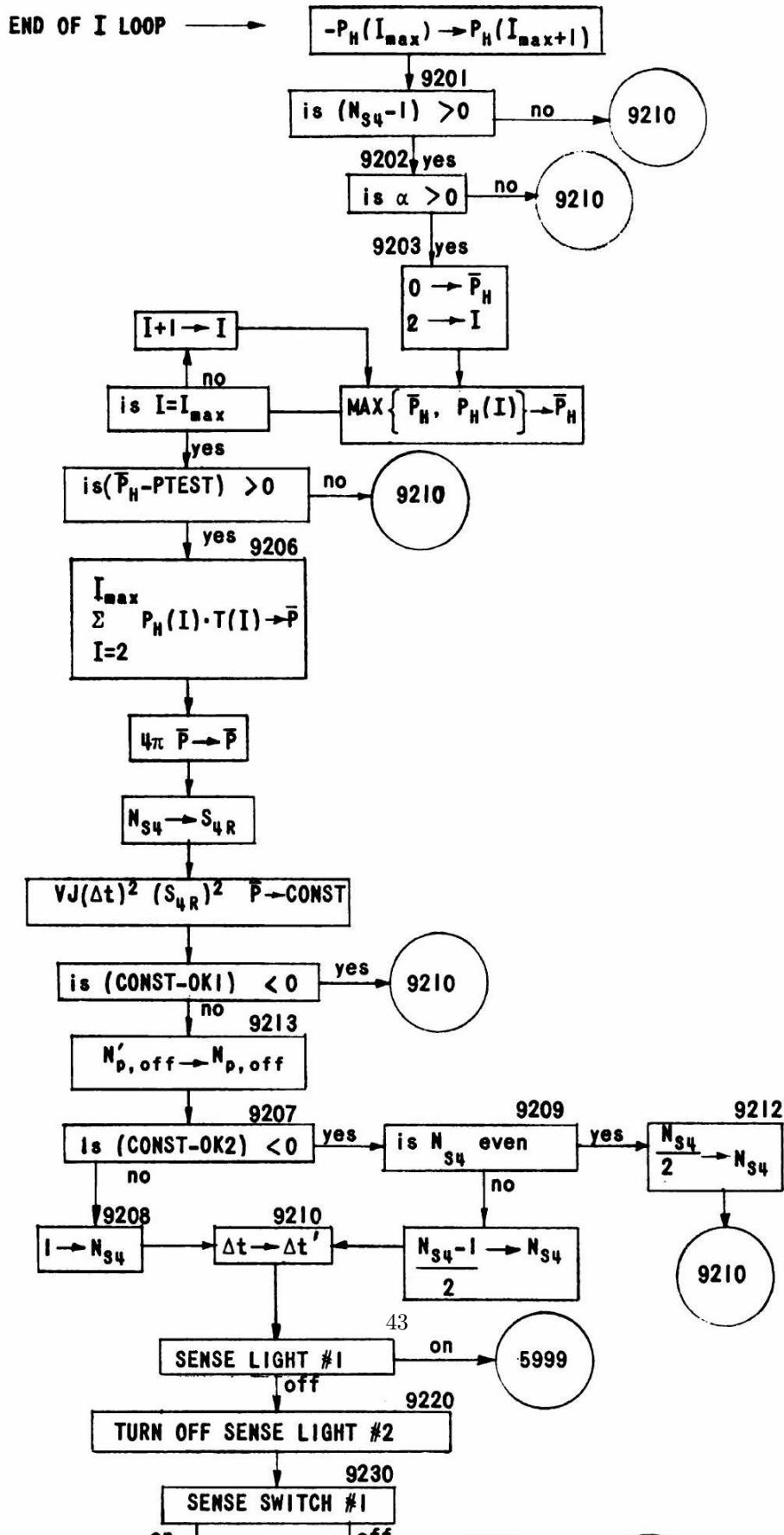
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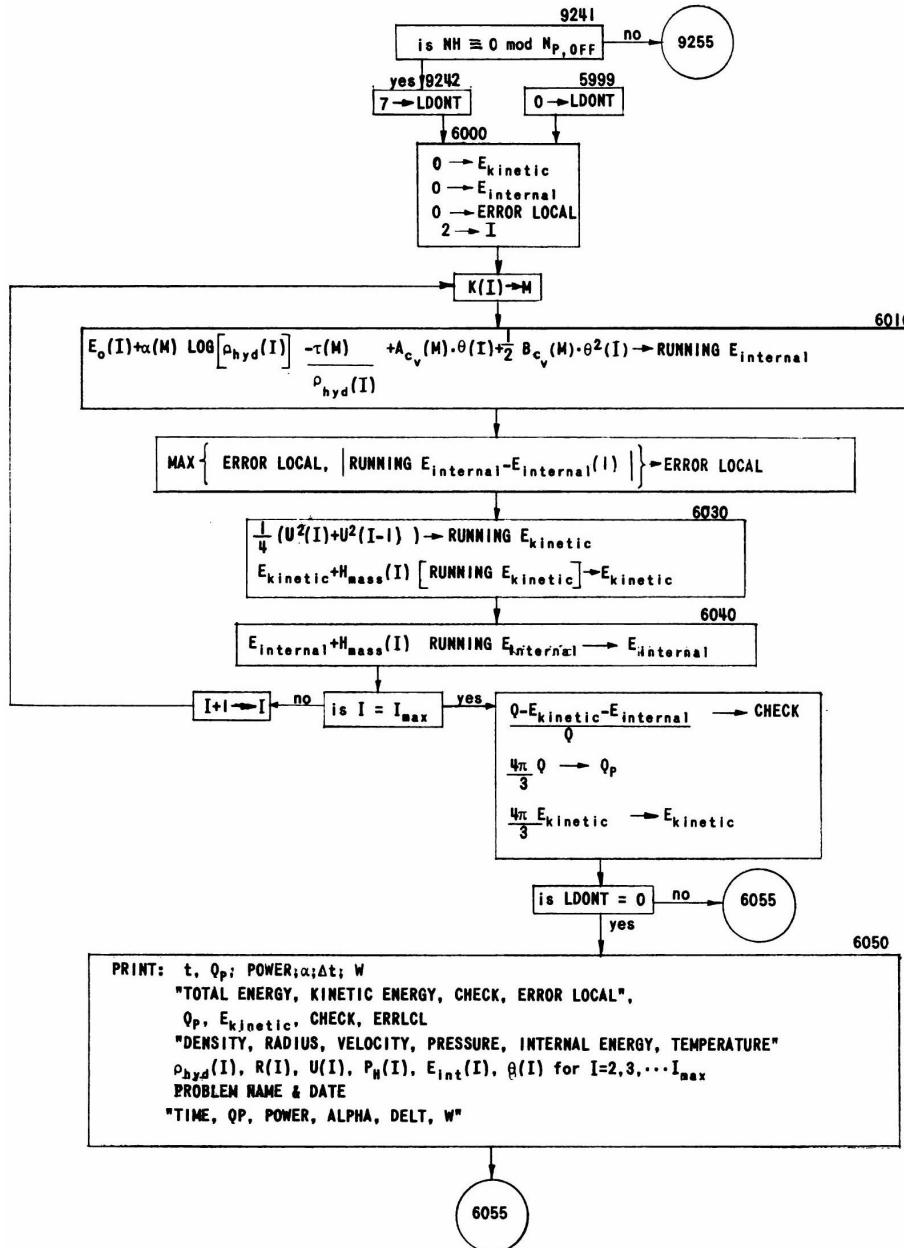


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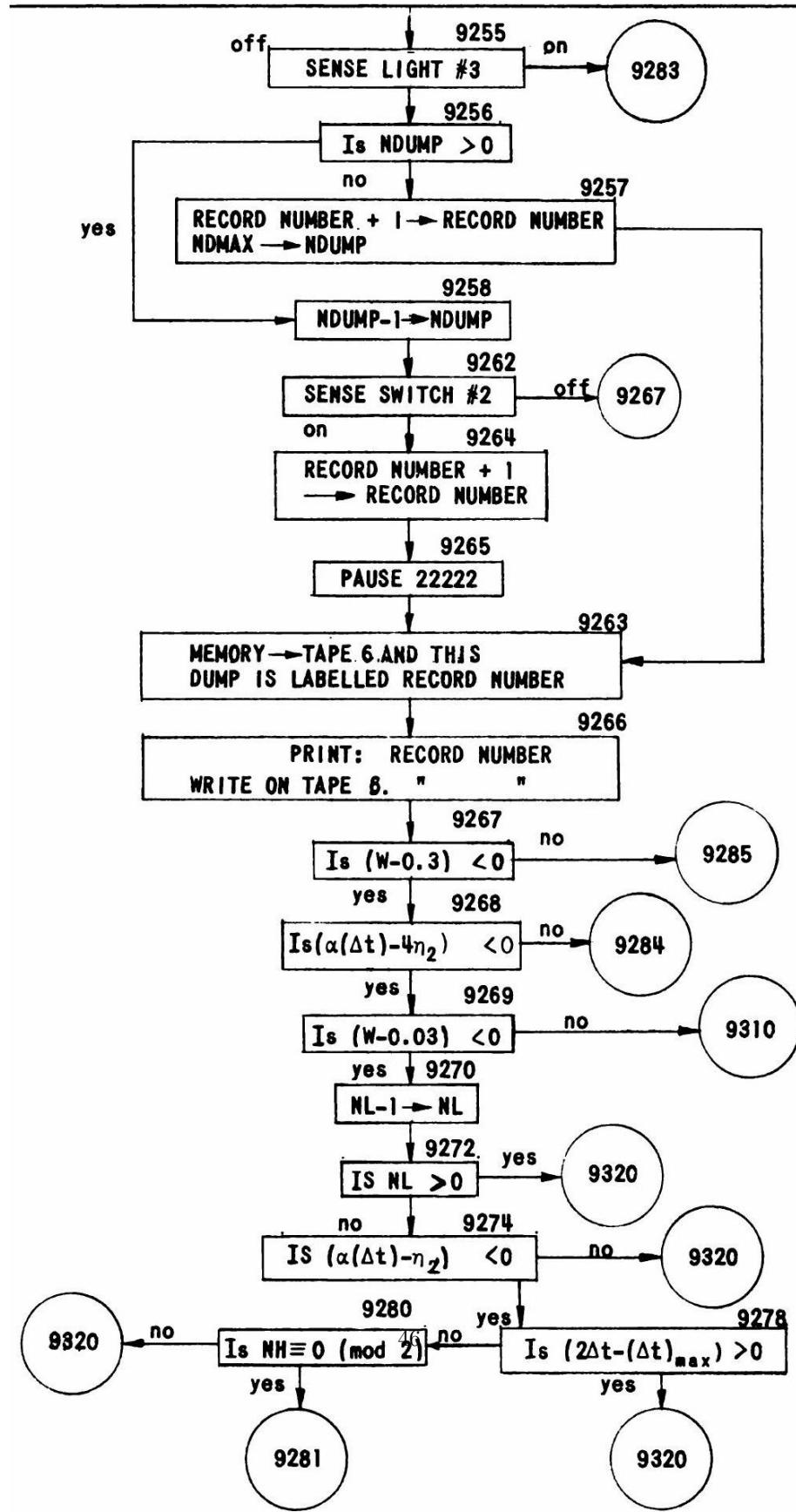
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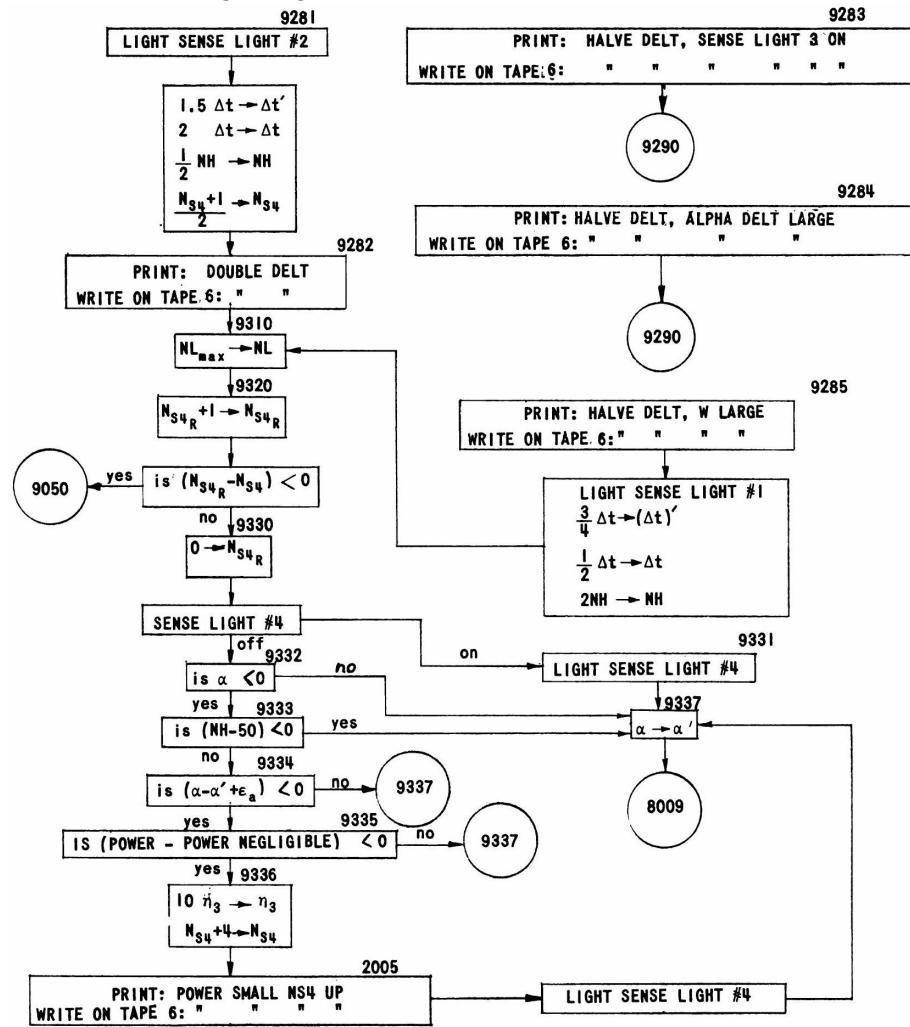




PRINT ON TAPE 6 $t, Q_p, POWER, \alpha, \Delta t, W$

"TOTAL ENERGY, KINETIC ENERGY, CHECK, ERROR LOCAL"
Op, Ekinetic, CHECK, ERRLEL
"DEMSITY, RADIUS, VELOCITY, PRESSURE, INTERNAL ENERGY, TEMPERATURE"
 $\rho_{hyd}(I), R(I), U(I), P_h(I), E_{int}(I), \theta(I)$ for $I = 2, 3, \dots, I_{\max}$
PROBLEM NAVE & DARE
"TIIIE, OP. POWER, ALPIA, DELT. W"
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VI. FORTRAN LISTING OF PROGRAM

C AX-1 MARCH 19,1959

DIMENSION RO(40), R(40), U(40), HP(41), HE(40), THETA(40),
 I RRL(41), K(40), RHO(40), F(40), E(40), RBAR(40),
 2 EN(7,40), DELTA(40), S(40), T(40), H(40), SO(40),
 3 ENN(40,5), ROLAB(8), ALPH(8), BETA(8), TAU(8),
 4 ACV(8), BCV(8), KP(8), V(7), ANU(7), SUM(7),

5 WN(40), ANUSIG(7,8), SIG(7,8), SIGMA(7,7,8),
 6 P(8,8), MN(8,9), A(4), AM(5), AMBAR(5),
 7 B(5), ENNN(40), HEO(40), HMASS(40), AK(4), ROSN(40)
 9900 FORMAT(54H1PROBLEM NAME 25 DECEMBER 1957
 9910 FORMAT (1P6E12.6)
 9911 FORMAT (1H 1P6E15.6)
 9915 FORMAT (1H 9I6)
 9920 FORMAT (36I2)
 9921 FORMAT (1H 3613)
 9922 FORMAT (1814)
 9930 FORMAT (9F8.7)
 9931 FORMAT (1H 9F11.7)
 9940 FORMAT (918)
 9941 FORMAT (1H 9II1)
 9942 FORMAT (18H K EFFECTIVE = 1P1E15.6)
 9943 FORMAT (27H TOTAL KINETIC ENERGY = 1P1E15.6, 28H TOTAL INTER
 1NAL ENERGY = 1PIE15.6)
 9944 FORMAT (29H INITIAL MAXIMUM RADIUS = 1PIE15.6)
 9980 FORMAT (10HOF, EN(IG))
 9981 FORMAT (1P9E13.5)
 9982 FORMAT (6OHO TOTAL ENERGY KINETIC ENERGY CHECK ERROR
 1LOCAL)
 9983 FORMAT 190H0 DENSITY RADIUS VELOCITY PRES
 ISURE INTERNAL ENERGY TEMPERATURE)
 9984 FORMAT (6H DUMP I2)
 9985 FORMAT (10HOR, ENN(J))
 9986 FORMAT 185H TIME QP POWER ALP
 1HA DELT W)
 9987 FORMAT (22H TROUBLE. CALLED DUMP I2)
 7000 READ 9900
 7005 READ 9920, IRCNBR
 IF(IRCNBR) 7020, 7020, 7010
 7010 PAUSE7010
 PRINT 9900
 SENSE LIGHT O
 IF(SENSE SWITCH 1) 7015, 9266
 7015 PAUSE 111
 GO TO 9266
 7020 READ 9920, ICNTRL
 READ 9910, ALPHA
 READ 9910, POWER
 READ 9920, IMAX
 7025 KCALC = 0
 R(1)=0.0
 DO 7030 I =2,IMAX
 7030 READ 9910, R(I), RO(I), F(I), U(I), THETA(I)

```
    READ 9920, (K(I), I=2,IMAX)
    READ 9920, IGMAX
    READ 9920, NMAX, MMAX
    IF(MMAX) 7050, 7050, 7040
    7040 DO 7045 M=1,MMAX
        READ 9930, (P(M,IS), IS = 1,8)
    7045 READ 9940, (MN(M,IS), IS=1,9)
    7050 READ 9910, (V(IG), IG=1,IGMAX), (ANU(IG), IG=1,IGMAX)
    7060 DO 7070 N=1,NMAX
        DO 7070 IG=1,IGMAX
    7070 READ 9910, ANUSIG(IG,N), SIG(IG,N), (SIGMA(IG,IH,N), IH=1,IGMAX)
```

7080 KP(1)=K(2)

```
JMAX = 1
DO 7170 I=2,IMAX
M = K(1)
DO 7090 J=1,JMAX
IF(M-KP(J)) 7090, 7100, 7090
7090 CONTINUE
JMAX = JMAX+1
KP(JMAX)=M
GO TO 7110
7100 IF(I-2) 7120, 7110, 7120
7110 READ 9910, (ROLAB(M), ALPH(M), BETA(M), TAU(M), ACV(M), BCV(M))
7120 CONTINUE
    READ 9910, EPSR, EPSA, EPS1, ETA1, ETA2, ETA3
    READ 9910, CVP, CSC
    READ 9910, DELT, DTMAX
7130 READ 9922, NP, NPOFF, NPOFFP, KCNTRL
7135 READ 9910, VJ,OK1, OK2, PTEST, EPSK, POWNGL
    AITCT = 0
    A(4)=ALPHA
    EPS = EPSA
    IF(ICNTRL) 7140, 7150, 7140
7140 EPS = EPSR
    A(4) = R(IMAX)
7150 A(3)=A(4)+10.0*EPS
    AM(1) =1.0
```

```

AM(2)=0.6666667
AM(3) = 0.1666667
AM(4)=0.3333333
AM(5)=0.8333333
AMBAR(1)=0.0
AMBAR(2)=0.8333333
AMBAR(3)=0.3333333
AMBAR(4) =0.1666667
AMBAR(5)=0.6666667
B(1)=0.0
B(2)=1.6666667
B(3)=3.6666667
B(4)=3.6666667
B(5)=1.6666667
PRINT 9900

IF (SENSE SWITCH 6) 9000, 7155
7155 PRINT 9921,ICNTRL
PRINT 9911, ALPHA
PRINT 9911, POWER
PRINT 9921, IMAX
DO 7160 I = 2, IMAX
7160 PRINT 9911, R(I), RO(I), F(I), U(I), THETA(I)
PRINT 9921, (K(I), I=2, IMAX)
PRINT 9921, IGMAX
PRINT 9921, NMAX, MMAX
IF (MMAX) 7172, 7172, 7168
7168 DO 7170M = 1, MMAX
PRINT 9931, (P (M,IS),I S = 1,8 )
7170 PRINT 9941, (MN(M,IS), IS=1,9)
7172 PRINT 9911, (V(IG), IG = 1 , IGMAX), (ANU (IG), IG = 1 , IGMAX)
DO 7180 N = 1, NMAX
DO 7180 IG = 1, IGMAX
7180 PRINT 9911, ANUSIG(IG,N), SIG(IG,N), (SIGMA(IG,IH,N), IH=1,IGMAX)
DO 7190 J = 1,JMAX
M = KP (J)
7190 PRINT 9911, (ROLAB(M), ALPH(M), BETA(M), TAU(M), ACV(M),
BCV(M))
PRINT 9911, EPSR, EPSA, EPS1, ETA1, ETA2, ETA3
PRINT 9911, CVP, CSC
PRINT 9911, DELT, DTMAX
PRINT 9915, NP, NPOFF, NPOFFP, KCNTRL
PRINT 9911, VJ, OK1, OK2, PTEST, EPSK, POWNGL
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```

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PRINT 9911, VJ, OK1, OK2, PTEST, EPSK, POWNGL
9000 TIME = 0 •
NH=0
ALPHAP=0.0
SENSE LIGHT O
AKEFF = 1.0
NITMAX = 300
FLAG1 = 0.0
NDMAX = 64
NLMAX = 64
NDUMP = NDMAX
DELTP=DELT
IF(SENSE SWITCH 1) 9002, 9003
9002 PAUSE 11111
9003 NS4 = 1
NS 4R = 0
C
C MIXTURE CODE
C
208 IF(MMAX) 209,8009,209
209 DO 215M = 1, MMAX
DO 215 IG=1,IGMAX
DO 210 IH=IG,IGMAX
210 SUM(*IH*) = 0.
SUM1 = 0.
SUM2 = 0.
DO 217 IS = 1,8

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MA = MN(M,IS)
DO 211 IH=IG,IGMAX
211 SUM(IH) = SUM(IH) + P(M,IS)*SIGMA(IG,IH,MA)
SUM1 = SUM1 + P(M,IS)*ANUSIG(IG,MA)
SUM2 = SUM2 + P(M,IS)*SIG(IG,MA)
207 IF(MN(M,IS+2)) 212, 213, 212
212 CONTINUE
213 MA = MN(M,IS+1)
DO 214 IH=IG,IGMAX
214 SIGMA(IG,IH,MA) = SUM(IH)
ANUSIG(IG,MA) = SUMI
215 SIG(IG,MA) = SUM2
C

```

C PRELIMINARY CALCULATION
C
 8009 DO 8010 I=2,IMAX
    M=K(I)
    ROSN(I)=RO(I)
 8010 RHO(I)=RO(I)/ROLAB(M)
    9 \text { DO 13 I =2,IMAX}
      RBAR(I) = (R(I) + R(I-1))/2.
      DELTA(I) = RBAR(I) - R(I-1)
      S(I) = DELTA(I)/RBAR(I)
    13 T(I) = ( R(I) ** 3 - R(I-1) ** 3 ) / 3 . 0
C
C START BIG G LOOP
C
 8000 IG=IGMAX
    2 DO 11 I=2,IMAX
      N = K(I)
      IF(KCALC) 5, 5,8
      5 H(I)=DELTA(I)*(SIG(IG,N)*RHO(I)+ALPHA/V(IG))
        GO TO 7
      8 H(I) = DELTA(I)*SIG(IG,N)*RHO(I)
        IF(H(I)) 14, 15, 15
      14 \text { PAUSE 14}
        H(I) = 0.
      15 \text { SUM1 = 0.}
        IF(AITCT) 3, 3, 40
      40 DO 4 IH=IG,IGMAX
        SUM1 = SUM1 + EN(IH,I)*SIGMA(IG,IH,N)
        IF(KCALC) 3, 3, 10
      10 SO(I) = 4.0*DELTA(I)*(ANU(IG)*F(I)/AKEFF + RHO(I)*SUMI)
        GO TO 11
        SO(I) = 4.*DELTA(I)*(ANU(IG)*F(I) + RHO(I)*SUMI)
      11 CONTINUE
        DO 30 J=1,3
      30 ENN(IMAX,J) = 0.
    101 \text { DO 110 J=1,5}
      AMT = AM(J)
      AMBART = AMBAR(J)
      BT = R(J)

```

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120 IF(J - 3) 102, 102, 103

```

IO2 I = IMAX
ASSIGN 104 TO ILOOP
104 \mathrm{L} \mathrm{=} \mathrm{I}
\mathrm{I} \mathrm{=} \mathrm{I} - 1
899 IF(I) 900, 110, 106
900 STOP 13571

```

$$103 \quad JK = 6 - J$$

```

ENN(1,J) = ENN(1,JK)
I = 1
ASSIGN 105 TO ILOOP
105 L = I
I ~ = I ~ + I
II = I
107 IF(I - IMAX) 106, 106, 110
I06 BS = RT*S(II)
ENN(I,J) = (AMT - BS - H(II))*ENN(L,J) + SO(II)/2.
902 IF(J - 1) 901, 109, 108
901 \text{STOP 12345}
108 ENN(I,J) = ENN(I,J) + (AMBART + BS - H(II))*ENN(L,J-1)
- (AMBART - BS + H(II))*ENN(I,J-1) + SO(II)/2.
109 ENN(I,J) = ENN(I,J)/(AMT + BS + H(II))
IF(ENN(I,J)) 1000, 1001, 1001
1000 ENN(I,J) = 0
1001 GO TO ILOOP, (104,105)
110 CONTINUE
C
C CALCULATE TOTAL NEUTRON FLUX
C
79 DO 84 I = 2, I MAX
SUM1 = 0.
DO 81 J=1,5
SUM2 = ENN(I,J) + ENN(1-I,J)
905 GO TO (80, 81, 81, 81, 80), J
SO SUM2 = SUM2/2.
81 SUM1 = SUM1 + SUM2
SUM1 = SUM1/8.
84 EN(IG,I) = SUM1
91 ~ I G ~ = ~ I G ~ - ~ 1
911 IF(IG) 300, 300, 2
300 FEBARP = 0.
FFBARD = 0.

```

```

DO 8301 I=2,IMAX
SUMI = 0.0
ENNN(I) = 0.0
DO 8300 IG=1,IGMAX
SUMI = SUMI + EN(IG,I)
8300 ENNN(I) = ENNN(I) + EN(IG,I)/V(IG)
8301 WN(I) = SUM1*T(I)
DO 301 I=2,IMAX
FFBARP = FFBARP + WN(I)*F(I)

```

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```

301 FEBARP = FEBARP + WN(I)*E(I)
307 DO 30? I=2,IMAX
SUM1 = 0.
SUM2 = 0.
N = K(I)
DO 303 IG=1,IGMAX
SUM1 = SUM1 + ANUSIG(IG,N)*EN(IG,I)
303 SUM2 = SUM2 + SIGMA(IG,IG,N)*EN(IG,I)
F(I) = SUM1*RHO(I)
302 E(I) = SUM2*RHO(I)
FEBAR = 0.
FFBAR = 0.
FENBAR = 0.
DO 310 I=2,IMAX
FEBAR = FEBAR + WN(I)*E(I)
FFBAR = FFBAR + WN(I)*F(I)
310 FENBAR = FENBAR + WN(I)*ENNN(I)
913 IF(AITCT-3.) 321, 321, 305
305 IF(KCALC) 319,319,311
3 1 1 \text { DO 317 I=1,3}
3 1 2 A K ( I ) = A K ( I + 1 )
AKEFF = AKEFF*FFBAR*FEBAR/(FFBARP*FEBARP)
AK(4) = AKEFF
FFAKE = 0.0
DO 313 I = 1,3
IF(ABSF(AK(I+1)-AK(I))-EPSK) 313, 315, 315
315 FFAKE = 1.0
313 CONTINUE
IF(FFAKE) 8000, 8999, 8000
8999 PRINT 9900
      WRITE OUTPUT TAPE 6, 9900
314 PRINT 9942, AKEFF

```

```
306 WRITE OUTPUT TAPE 6, 9942, AKEFF
  KCNTRL = 0
  KCALC = 0
  GO TO 6802
319 DO 325 I=1,3
  325 A(I) = A(I+1)
    IF(ICNTRL) 8020, 8015, 8020
  8015 ALPHA = ALPHA + (FFBAR + FEBAR - FFBARP - FEBARP)/FENBAR
    EPS = EPSA
    A(4)=ALPHA
    GO TO 321
  8020 Z = (FFBAR + FEBAR)/(FFBARP + FEBARP)
    EPS = EPSR
    DO 8021 I=2,IMAX
  8021 R(I)=R(I)/Z
    A(4)=R(IMAX)
  321 AITCT=AITCT+1.0
    FFAKE = 0.0
    DO 330 I=1,3
      IF(ABSF(A(I+1)-A(I))-EPS) 330, 338, 338
```

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```
  338 FFAKE = 1.0
  330 CONTINUE
    IF(FFAKE) 339, 915, 339
    339 IF(ICNTRL) 9, 8000, 9
C
C PRINT ROUTINES
C
  915 IF(SENSE SWITCH 4) 331, 503
  331 PRINT 9900
    PRINT 9980
    DO 501 I=2,IMAX
  501 PRINT 9981, F(I), (EN(IG,I), IG=1,IGMAX)
  503 IF(SENSE SWITCH 3) 502, 9010
```

502 PRINT 9900

PRINT 9985
PRINT 9911, (R(I), (ENN(I,J), J=1,5), I=1,IMAX)
9 0 1 0 ~ F B A R ~ = ~ 0 . ~ .

```

DO 9011 I=2,IMAX
9 0 1 1 ~ F B A R ~ = ~ F B A R ~ + ~ T ( I ) * F ( I ) ~
   IF(NH) 6800, 6800, 9014
6800 ALPHAO=ABSF(ALPHA)
   IF(KCNTRL) 6802, 6803, 6801
6801 KCALC = 1
   AKEFF = 1.0
   AK(1) = 1.0
   AK(2) = 4.0
   AK(3) = 1.0
   AK(4) = 2.0
   GO TO 8000
6803 PRINT 9900
   WRITE OUTPUT TAPE 6, 9900
6802 RL(1) = 0.0
   DO 6810 I=2,IMAX
6 8 1 0 ~ R L ( I ) = C U B E R T F ( R L ( I - 1 ) ** 3 + R O ( I ) * ( R ( I ) ** 3 -
R ( I - 1 ) ** 3 ) ) ~
   RL(IMAX+1)=2.0*RL(IMAX)-RL(IMAX-1)
6820 IF(ALPHAO*DELT-4.0*ETA2) 6830, 6822, 6822
6822 DELT=0.5*DELT
2004 FORMAT(21H HALVE DELT INITIALLY)
   PRINT 2004
   WRITE OUTPUT TAPE 6, 2004
   GO TO 6820
6830 DELTP=DELT
   TOTKE=0.0
   TOT IEN=0.0
   DO 6840 I =2,IMAX
   M=K(I)
6833 HP(I)=MAXIF(0.0,(ALPH(M)*RO(I)+BETA(M)*THETA(I)+TAU(M)))
   HEO(I)=TAU(M)/RO(I) - ALPH(M)*LOGF(RO(I))
6835 HE(I)=ACV(M)*THETA(I)+0.5*BCV(M)*THETA(I)**2
   RKE = 0.25*(U(I)**2 + U(I - 1)**2)
6837 HMASS(I)=RL(I)**3 - RL(I-1)**3
   TOTKE = TOTKE + HMASS(I)*RKE

```

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```

6840 TOTIEN=TOTIEN + HMASS(I)*HE(I)
   HP(IMAX+1)=-HP(IMAX)
   QPRIMF = -1.0
   Q=TOTKE + TOTIEN

```

```

TOTKE=4.18879*TOTKE
TOTIEN=4.18879*TOTIEN
PRINT 9943, TOTKE, TOTIEN
WRITE OUTPUT TAPE 6,9943, TOTKE, TOTIEN
IF(ICNTRL) 6990, 9050, 6990
6990 PRINT 9944, R(IMAX)
    WRITE OUTPUT TAPE 6,9944, R(IMAX)
    PRINT 9986
    WRITE OUTPUT TAPE 6, 9986
    ICNTRL = 0
    GO TO 9050
9 0 1 4 \text { ALPHA0 = MAXIF(ABSF(ALPHA), ALPHA0)}
    IF(ALPHA) 9018, 9018, 9017

```

9017 FLAG1 = 1•0

```

9 0 1 8 ~z~ = ~A R S F (ALPHAP-ALPHA)/(ALPHA0~ + ~3.0*EPSA)
    IF(Z-FTA3) 9015, 9015, 9020
9015 IF(SENSE SWITCH 5) 9030, 9016
9 0 1 6 \text { NS4=NS4+1}
    GO TO 9050
9020 IF(3.0*ETA3-Z) 9022, 9022, 9027
9022 IF(1-NS4) 9023, 9024, 9024
9 0 2 3 \text { NS4=NS4-1}
    GO TO 9040
9024 IF(ALPHA) 9050, 9025, 9025
9025 SENSE LIGHT 3
    GO TO 9050
9027 IF(SENSE SWITCH 5) 9030, 9050
9030 IF(1-NS4) 9023, 9050, 9050
9040 IF(6.0*ETA3-Z) 9045, 9045, 9050
9 0 4 5 \text { NS4=1}
9050 IF(SENSE SWITCH 6) 9051,9052
9 0 5 1 ~ P A U S E ~ 6 6 6 6 \}
9 0 5 2 ~ N H = N H + 1 \}
    IF(NS4R) 9054, 9054, 9056
9 0 5 4 \text { QP=4.18879*Q}
    PRINT 9911, TIME, QP, POWER, ALPHA, DELT,W
    WRITE OUTPUT TAPE 6, 9911, TIME, QP, POWER, ALPHA, DELT, W
9 0 5 6 \text { W } = 0 . 0
    TIME=TIME+DELT
    Z=ALPHA*DELTP
    POWER=EXP(Z)*POWER

```

9 0 6 0 ~ Q B A R = P O W E R * D E L T / (1 2 . 5 6 6 3 7 * F B A R)
IF(Q-QPRIME) 9061, 9061, 9066
9061 IF(ALPHA) 9062, 9066, 9066

9062 IF(FLAG1) 9066, 9066, 9065
9065 NS4 = 30000

9 0 6 6 ~ Q P R I M F ~ = ~ Q
C

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C ENTER I LOOP
C
DO 9200 I =2,IMAX
U(I)=U(I) - DELTP*R(I)**2*(HP(I+1)-HP(I))/
X (0.5*RL(I)**2*(RL(I+1)-RL(I-1)))
R(I)=R(I)+U(I)*DELT
RHOT=HMASS(I)/(R(I)**3-R(I-1)**3)
DELV=1.0/RHOT-1.0/RO(I)
IF(RHOT*ABSF(DELV)-0.1) 9070, 9070, 9068
9068 IRCNBR = IRCNBR
PAUSE 50

9069 PAUSE

PRINT 9987, IRCNBR
WRITE OUTPUT TAPE 6, 9987, IRCNBR
2003 FORMAT(27H HALVE DELT, RHO DELV LARGE)
PRINT 2003
WRITE OUTPUT TAPE 6, 2003
GO TO 9290
9 0 7 0 ~ D E L Q = F (I) * Q B A R / R O S N (I) \}) \mp@code { ~ }
Q = Q + DELQ*HMASS(I)
DELR=R(I)-R(I-1)
IF(DELR) 9080, 9080, 9082
9 0 8 0 ~ P A U S E ~ 6 0 \}
GO TO 9068

9082 VP=0.0

IF(DELV) 9120, 9124, 9124
9120 VP=(VP*RHOT*(RHOT*DELV*DELR/DELT)**2
9122 IF(NH-1) 9123, 9123, 9124

9123 HP(I)=HP(I)+VP
9124 HPT=HP(I)

THET=THETA(I)
M=K(I)
NIT=0
9130 DELE=nELQ-0.5*(HPT+HP(I))*DELV
Z=DELF+DELV*(TAU(M)+ALPH(M)*0.5*(RHOT+RO(I)))
THET =MAXIF (0.0, (THETA(I)+2.0*Z/(2.0*ACV(M)+
X BCV(M)*(THET+THETA(I))))
9140 PSTAR=MAXIF(O.O, (ALPH(M)*RHOT+BETA(M)*THET+TAU(M)))+VP
9150 IF(ABSF(PSTAR-HPT)/(ABSF(PSTAR)+EPS1)-ETA1)9180,9180,9151

9151 NIT=NIT+1

IF(NIT-NITMAX) 9160,9170,9170
9160 ~ HPT=PSTAR
GO TO 9130
9170 ~ PAUSE ~ 11 ~
9180 ~ HP(I)=PSTAR
HE(I)=HE(I)+DELE
THETA(I)=THET
9190 WR ~ = ~ CSC*ABSF(HE(I))*DELT**2/DELR**2 + 4.0*CVP*RHOT*ABS
W = MAXIF(WR,W)
9200 RO(I)=RHOT
C
C END OF I LOOP
C
HP(IMAX+1)=-HP(IMAX)
9201 IF(NS4-1) 9210, 9210, 9202
9202 IF(ALPHA) 9210, 9210, 9203
9203 ~ HPBAR ~ = ~ 0 . ~ + ~
DO 9204 I=2,IMAX
9204 HPBAR = MAXIF(HPBAR,HP(I))
IF(HPRAR-PTEST) 9210, 9210, 9205

9205 PBAR = 0.

```
DO 9206 I=2,IMAX
9206 ~ P B A R ~ = ~ P B A R ~ + ~ H P(I)*T(I) ~ 1 )
PBAR = PBAR*12.56637
S4R = NS4
CONST = VJ*DELT**2*S4R**2*PBAR
IF(CONST-OK1) 9210, 9213, 9213
```

9213 NPOFF = NPOFFP

```
9207 IF(CONST-OK2) 9209, 9208, 9208
9208 ~ N S 4 ~ = ~ 1
GO TO 9210
9209 IF(XMODF(NS4,2)) 9211, 9212, 9211
```

9211 NS4 = (NS4-1)/2

```
GO TO 9210
9212 NS4 = NS4/2
9210 DELTP=DELT
IF(SENSE LIGHT 1) 5999,9220
9220 IF(SENSE LIGHT 2) 9230, 9230
9230 IF(SENSE SWITCH 1) 5999, 9240
9240 IF(XMODF(NH,NP)) 5999, 5999, 9241
9241 IF(XMODF(NH,NPOFF)) 9242, 9242, 9255
9242 \text { LDONT = 7}
GO TO 6000
```

5999 LDONT = 0

```
6000 TOTKE = 0.0
TOT IEN=0.0
ERRLCL=0.0
DO 6040 I =2,IMAX
M=K(I)
6010 RIE=HFO(I)+ALPH(M)*LOGF(RO(I))-TAU(M)/RO(I)+
```

```

X ACV(M)*THETA(I)+0.5*BCV(M)*THETA(I)**2
6020 ERRLCL=MAXIF(ERRLCL, ABSF(RIE-HE(I)))
6030 RKE = 0.25*(U(I)**2 + U(I-1)**2)
    TOTKE = TOTKE +HMASS(I)*RKE
6040 TOTIEN=TOTIEN+HMASS(I)*RIE
    CHECK = (Q-TOTKE-TOTIEN)/Q
    QP=4.18879*Q
    TOTKE=4.18879*TOTKE
    IF(LDONT) 6055, 6050, 6055
6050 PRINT 9911, TIME, QP, POWER, ALPHA, DELT, W
    PRINT 9982
    PRINT 9911, QP, TOTKE, CHECK, ERRLCL
    PRINT 9983
9250 PRINT 9911, (RO(I),R(I),U(I),HP(I),HE(I),THETA(I),I=2,IMAX)

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    PRINT 9900
    PRINT 9986
6055 WRITE OUTPUT TAPE 6, 9911, TIME, QP, POWER, ALPHA, DELT, W
    WRITE OUTPUT TAPE 6, 9982
    WRITE OUTPUT TAPE 6, 9911, QP, TOTKE, CHECK, ERRLCL
    WRITE OUTPUT TAPE 6, 9983
    WRITE OUTPUT TAPE 6, 9911, (RO(I),R(I),U(I),HP(I),HE(I),THETA(I),I
    I=2,IMAX)
    WRITE OUTPUT TAPE 6, 9900
    WRITE OUTPUT TAPE 6, 9986
9255 IF(SENSE LIGHT 31 9283, 9256
9256 IF(NDUMP) 9257, 9257, 9258
9 2 5 7 ~ I R C N B R ~ = ~ I R C N B R ~ + ~ 1
    NDUMP = NDMAX
    GO TO 9263
9258 NDUMP = NDUMP-1
9262 IF(SENSE SWITCH 2) 9264, 9267
9264 IRCNBR=IRCNBR+1

```

9265 PAUSE?2222

9 2 6 3 \text { PAUSE}
9266 PRINT 9984, IRCNBR
 WRITE OUTPUT TAPE 6, 9984, IRCNBR
9267 IF(W-N.3) 9268, 9285, 9285
9268 IF(ALPHA*DELT-4.0*ETA2) 9269, 9284, 9284
9269 IF(W-0.03) 9270, 9310, 9310

9270 NL = NL-1

9272 IF(NL) 9274,9274,9320
9274 IF(ALPHA*DELT-ETA2) 9278, 9320, 9320
9278 IF(2.0*DELT-DTMAX) 9280, 9280, 9320
9280 IF(XMODF(NH,2)) 9320,9281,9320
9281 SENSE LIGHT 2
 DELTP = 1.5*DELT
 DELT=2.0*DELT
 NH=NH/2
 NS4=(NS4+1)/2
9282 FORMAT(12H DOUBLE DELT)
 PRINT 9282
 WRITE OUTPUT TAPE 6, 9282
 GO TO 9310
2000 FORMAT(29H HALVE DELT, SENSE LIGHT 3 ON)
9 2 8 3 \text { PRINT 2000}
 WRITE OUTPUT TAPE 6, 2000
 GO TO 9290
2001 FORMAT(28H HALVE DELT, ALPHADELT LARGE)
9 2 8 4 \text { PRINT 2001}
 WRITE OUTPUT TAPE 6, 2001
 GO TO 9290
2002 FORMAT(20H HALVE DELT, W LARGE)
9 2 8 5 \text { PRINT 2002}
 WRITE OUTPUT TAPE 6, 2002
9290 SENSE LIGHT 1
 DELTP=0.75*DELT

 DELT=0.5*DELT
 NH=2*NH

9310 NL=NLMAX

9 3 2 0 ~ NS4R = NS4R + 1

```
IF(NS4R-NS4) 9050,9330,9330
9 3 3 0 ~ N S 4 R = 0
    IF(SENSE LIGHT 4) 9331, 9332
9331 SENSE LIGHT 4
    GO TO 9337
9332 IF(ALPHA) 9333, 9337, 9337
9333 IF(NH-50) 9337, 9334, 9334
9334 IF(ALDHA-ALPHAP+EPSA) 9335, 9337, 9337
9335 IF(POWER-POWNGL) 9336, 9337, 9337
9 3 3 6 \text { ETA3 = 10.0*ETA3}
    NS4 = NS4+4
2005 FORMAT(19H POWER SMALL NS4 UP)
    PRINT 2005
    WRITE OUTPUT TAPE 6, 2005
    SENSE LIGHT 4
9 3 3 7 ~ A L P H A P ~ = ~ A L P H A \}
    GO TO 8009
```

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In the preparation of this report certain superfluous material was inadvertently included as pages 62, 63, and 64. This has been deleted, but the page numbers from 65 on have been maintained to expedite publication.

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VII. ROLE OF SENSE SWITCHES, SENSE LIGHTS AND FLAGS

Sense Switch No. 1

At Order No. 7010, this switch, if on (depressed), calls for Pause 111 to allow time for modifications in a problem being rerun from a dump. Again at Order 9000, depressing this switch produces Pause 11111 after the print-out of input data and before the beginning of the mixture code. Finally, at Order 9230, if this switch is depressed, an on-line and off-line print-out of t, Q_p , power, alpha, etc., is provided independent of whether $NH \equiv 0 \pmod{N_p}$.

Sense Switch No. 2

At Order No. 9262, depressing this switch produces a dump of the memory on Tape 6.

Sense Switch No. 3

At Order No. 503, following Order No. 915, depressing this switch provides an on-line print-out of the radii and of ENN(I,J), the angular flux distribution for Group 1, the lowest energy group (or, in a one-group problem, the only group).

Sense Switch No. 4

At Order No. 915, depressing this switch provides an on-line printout of $F(I)$, the fission source, for all mass points and of $EN(IG, I)$, the flux, for all groups and mass points.

Sense Switch No. 5

At Order No. 9015, depressing this switch sends the computation to Order No. 9023 where N_{S4} is reduced by one if it is not already unity.

Sense Switch No. 6

At Order No. 7150, this switch bypasses the normal on-line printout of input data if depressed. At Order No. 9050, this switch, if depressed, produces Pause 66666 before beginning the next series of hydrocycles.

Sense Light No. 1

At Order No. 9210, if this sense light is on, an energy balance is made and an on-line and off-line print-out of t, Q_p , power, $\alpha, \Delta t$, etc. is provided, independent of whether $NH = 0 \bmod N_p$. This light is lit at Order No. 9290 where Δt is halved.

Sense Light No. 2

At Order No. 9281, if the course of the problem permits a doubling of Δt , this sense light is lit. It is automatically turned off at Order No. 9220 following the next hydrocycle.

Sense Light No. 3

At Order No. 9255, this sense light, if on, sends the computation to Order Nos. 9283 and 9290 where Δt will be halved. The light will be turned on at Order No. 9025 if the fractional change in alpha between the last two S_4 calculations exceeds $3\eta_3$.

Sense Light No. 4

At Order No. 2005, if the burst has gone through its peak and has reached a condition of negative alpha and low power, sense light No. 4 is lit and the fact that this condition has been attained is printed.

Flag 1

If alpha becomes negative after having been positive, and if the total energy shows no change or a net decrease during the hydrocycle, this flag sends N_{S4} to 30,000 (Order Nos. 9017, 9062, 9065) terminating any further S_n calculations. At this condition the burst is over, the power is essentially zero. The total energy may therefore actually not

change (within limits of accuracy), and approximations in the solution might even produce a slight wavering in an essentially constant quantity.

VIII. LIST OF PAUSES AND STOPS

Order No.

7010	Pause 7010	This is a dummy pause to provide an address in memory where a transfer card is punched.
7015	Pause 111	Optional pause (Sense Switch No. 1) to allow modification of memory.
9002	Pause 11111	Optional pause (Sense Switch No. 2) following print-out of input data.
14	Pause 14	If $H(I)$ should be negative, this pause results. When problem is continued, Order No. 9068 is instituted.
900	Stop 13571	The problem is stopped if $I < 0$ results somehow.
901	Stop 12345	The problem is stopped if $J = 0$, falling outside the proper range 1 – 5.
9051	Pause 66666	This is an optional pause (Sense Switch No. 6) at the beginning of the problem.
9068	Pause 50	This pause occurs after continuing from Pause 60, or if excessive changes in the hydrocycle calculation occur.
9069	Dummy Pause	If the problem is continued after Pause 50, Order No. 9069 institutes a dummy pause.
9080	Pause 60	This pause indicates radii crossing. Continuing the problem leads to Pauses 11111 and 111.

Order No.

9170	Pause 11	If the hydrocycle calculation of the new pressure, an iterative process, continues, a dummy pause follows.
9265	Pause 22222	This pause follows Order No. 9262, where if Sense Switch No. 2 is on, a dummy pause follows.
9263	Dummy Pause	This is a dummy pause to provide the address in memory where a transfer card is punched.

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IX. OPERATING INSTRUCTIONS

Deck Composition:

1. The FORTRAN compiled binary deck with the transfer card removed and 170_8 punched in row 12 L of the fourth card instead of the usual 140_8 - 255 cards.
2. The "Tape Dump and Recall Routine" - 1 card. (See Appendix F.1)
3. Binary correction cards (transfers to the "Tape Dump and Recall Routine") - 3 cards.

4. Transfer card 170₈ – 1 card.

5. Input data cards.

Reader: 72-72 board.

Punch: Not used.

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Printer: SHARE board No. 2.

Tapes: No. 5 should be blank for routine memory dumps and No. 6 should be blank for output.

Sense Switch Settings: Normally all switches are up. See the section on Sense Switches for details.

Underflow Switch: On

Running Procedure:

1. Ready the card deck in the reader.
2. Ready the printer.
3. Mount and ready tapes No. 5 and 6.
4. Clear and load cards.

Program Stops:

51₈ This occurs if memory and tape transmission differ in the Tape Dump and Recall Routine portion of the program. Continuing will cause the tape unit to backspace one record and come to stop 52.

528 This occurs after the tape has been backspaced one record. Continuing will cause another attempt to execute the "Tape Dump and Recall Routine."

Since this is a FORTRAN compiled program the stops listed under the section "Error Stops in Object Program" of the FORTRAN Preliminary Operator's Manual are applicable. For additional stops see the section on Pauses.

Problem Termination:

The program does not terminate itself. Unless one wishes to observe post-burst phenomena, the appearance of "Power Small NS4 Up" on the on-line output indicates a good stopping point. Tape No. 6 should be printed off-line under program control. Tape No. 5 should be saved if restarting the problem from a dump is anticipated (see Appendix F.2). Neither tape has an end-of-file on it.

Restart Procedure:

To restart a problem from a dump, follow the same procedure as for a new problem with the following exceptions:

1. Tape No. 5 should contain the dump.
2. Input data consist only of a title card and an IRNCNBR card containing the number of the dump from which restart is desired.

Running Time:

The sample problem ran for 40 minutes before being terminated.

X. SAMPLE PROBLEM

A. Input Data

The specification of the problem will be made here in three different forms, all equivalent. First, a set of notes, as might be prepared by a physicist will be presented. The same problem will then be shown on the standard input sheets in slightly more cryptic fashion. Finally, the same data will be listed on the input sheet used by the card puncher in a form similar to that in which it is printed out.

A few general comments precede this presentation. It is first noted that the mass point $I = \text{unity}$ is always reserved for the central point, $R = 0$, and the first real mass point and the first non-zero radius corresponds to $I = 2$.

It is noted that cross sections are stored in barns, necessitating the use of different "densities" in the neutronics and hydrodynamics equations, as was discussed previously in the section "Detailed Flow Diagram and Explanatory Notes." It is also necessary that mixtures be

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specified as atomic fractions, P_i , where $\sum_i P_i = 1$.

It is noted that in the section "Properties of Materials" a material should be listed only once, even if it reappears as one moves outward radially.

The size of the various convergence and comparison criteria specified herein are subject to revision in accordance with the needs and peculiarities of the problem. They generally represent a compromise between the need for accuracy and the desire to minimize the machine time consumed.

EPSR, EPSA, and EPSK are the convergence criteria for the various types of S_n calculations. Running time will be particularly sensitive to EPSA, since this number controls the oft-repeated alpha calculation. ETA 2 limits the maximum fractional change in power per hydrocycle.

Once set, it implies an inverse relationship between the initial alpha and the initial Δt . Unless conditions dictate otherwise, it is reasonable to choose the largest initial Δt which satisfies the ETA 2 test.

Δt_{Max} , NP, NPOFF, and NPOFFP do not directly affect accuracy and, hence, are somewhat arbitrary, depending on the wishes of the problem initiator. ETA 1 and ETA 3 control the accuracy of the solution and, hence, must represent a balance between accuracy and machine time. As with many of the other control criteria, experience and subjective judgment play a major role in fixing these parameters. The numbers used in the test problem have been satisfactory for studies on accidents in fast reactors.

1. Physicist's Specifications

Problem: Geneve 10 Rerun March 20, 1959. Ax-1
 Specify initial alpha = $0.013084\mu\text{sec}^{-1}$. Vary radii to fit.
 Two region problem (Spherical core surrounded by concentric blanket).

Core radius	23.75 cm
Blanket radius	44.70 cm
Core Density	7.92 g/cc
Blanket Density	15.83 g/cc
Core composition (atomic fraction)	0.36 Substance 1 0.64 Substance 2
Blanket composition	1.0 Substance 3

Use 25 uniformly spaced mass points in core, 14 mass points in blanket.

All mass points initially at rest.

Core temp. = 10^{-4} kev.

Blanket temp. = 5×10^{-5} kev.

No fission in blanket. Guess smooth flux curve in core with edge to center ratio = 0.4. Initial power = 10^{12} ergs/ μsec .

Use 1 group cross sections

$V_g = 1.695 \times 10^2 \text{ cm}/\mu\text{sec}$.

Substance 1 = U²³⁵

Substance 2 = U²³⁸

Substance 3 = U²³⁸ with no fission allowed.

Equation of State Parameters

$$\begin{aligned} P &= \alpha\rho + \beta\theta + \tau \\ \alpha &= .02873 \text{ cm}^2/\mu\text{sec}^2 \\ \beta &= 278.46 \text{ g/cm}\mu\text{sec}^2 \end{aligned}$$

For core, set $\tau = -0.3946$. Then the pressure calculated from equation of state will be negative for the original density until $\theta = 6 \times 10^{-4}$

kev. Program will keep pressure zero until this threshold temperature is reached.

For blanket, set $\tau = -0.4687189$, so that pressure initially is exactly zero from the equation of state.

Specific heat parameters:

$$\frac{\partial E}{\partial \theta} = A_{CV} + B_{CV}\theta$$
$$A_{CV} = 12.163 \text{ cm}^2/\mu\text{sec}^2\text{kev}$$
$$B_{CV} = 5.78 \times 10^3 \text{ cm}^2/\mu\text{sec}^2\text{kev}^2$$

Accuracy Criteria

EPSR

EPSA

EPSI

ETA1

ETA2

ETA3

CVP

CSC

3×10^{-6} cm

5×10^{-5} μsec^{-1}

10^{-4} gm/cm μsec^2

10^{-3}

1.5×10^{-2}

3×10^{-2}

2

3 (An estimate of the maximum value of $\gamma(\gamma - 1)$ reached during the burst for the equation of state parameters used.)

Δt

Δt_{Max}

NP

NPOFF

NPOFFP

KCNTRL

VJ

OK1

OK2

PTEST

EPSK

POWNGL

$2\mu\text{sec}$

$16\mu\text{sec}$

100

15

3

01

6.6×10^{-7} (This was guessed from a previous problem and may not conform exactly to present specifications.)

0.01

0.04

10^{-4}

5×10^{-6}

1

2. Formal Presentation of Specifications

INPUT SHEETS - Ax I

Problem Name and Date ____ Geneve 10 Rerun March 20, 1959
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Record Number (choose one)	$\begin{cases} 00 & \text{if beginning new problem} \\ > 0 & \text{if restarting from tape, omit rest of form} \end{cases}$	00
α Control (choose one)		01
$\alpha (\mu\text{sec}^{-1})$		1.3084×10^{-2}
Power ($10^{12}\text{ergs}/\mu\text{sec}$)		1 ____
I Max = Total Number of Zones +1 (I Max ≤ 40)		40

ZONE DATA

The following must be filled out for each i ($2 \leq i \leq I \text{ Max}$)

	RADIUS (cm)	DENSITY (gm/cm ³)	RELATIVE FISSION DENSITY	VELOCITY (cm/ μsec)
i = 2	. 95	7.92	1	0
i = 3	1.90	7.92	1	0
i = 4	2.85	7.92	. 99	0
i = 5	3.80	7.92	. 98	0
i = 6	4.75	7.92	. 97	0
i = 7	5.70	7.92	. 95	0
i = 8	6.65	7.92	. 93	0
i = 9	7.60	7.92	. 91	0
i = 10	8.55	7.92	. 89	0
i = 11	9.50	7.92	. 87	0

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	RADIUS (cm)	DENSITY (gm/cm ³)	RELATIVE FISSION DENSITY	VELOCITY (cm/μsec)
i = 12	10.45	7.92	. 85	0
i = 13	11.40	7.92	. 82	0
i = 14	12.35	7.92	. 79	0
i = 15	13.30	7.92	. 76	0
i = 16	14.25	7.92	. 73	0
i = 17	15.20	7.92	. 70	0
i = 18	16.15	7.92	. 67	0
i = 19	17.10	7.92	. 64	0
i = 20	18.05	7.92	. 61	0
i = 21	19.00	7.92	. 58	0
i = 22	19.95	7.92	. 55	0
i = 23	20.90	7.92	. 52	0
i = 24	21.85	7.92	. 48	0
i = 25	22.80	7.92	. 44	0
i = 26	23.75	7.92	. 40	0
i = 27	24.70	15.83	0	0
i = 28	25.65	15.83	0	0
i = 29	26.60	15.83	0	0
i = 30	27.55	15.83	0	0
i = 31	28.50	15.83	0	0
i = 32	30.30	15.83	0	0
i = 33	32.10	15.83	0	0
i = 34	33.90	15.83	0	0
i = 35	35.70	15.83	0	0
i = 36	37.50	15.83	0	0
i = 37	39.30	15.83	0	0
i = 38	41.10	15.83	0	0
i = 39	42.90	15.83	0	0
i = 40	44.70	15.83	0	0

COMPOSITION

Definitions ;

A Substance has its own cross section cards.

A Mixture is made by the code out of substances.

Materials are those mixtures and/or substances that make up the actual system.

Write material label for each mass point:

$\frac{4}{2}$	$\frac{4}{3}$	$\frac{4}{4}$	$\frac{4}{5}$	$\frac{4}{6}$	$\frac{4}{7}$	$\frac{4}{8}$	$\frac{4}{9}$	$\frac{4}{10}$	$\frac{4}{11}$	$\frac{4}{12}$	$\frac{4}{13}$	$\frac{4}{14}$	$\frac{4}{15}$	$\frac{4}{16}$	$\frac{4}{17}$	$\frac{4}{18}$	$\frac{4}{19}$	$\frac{4}{20}$	
$\frac{4}{21}$	$\frac{4}{22}$	$\frac{4}{23}$	$\frac{4}{24}$	$\frac{4}{25}$	$\frac{4}{26}$	$\frac{4}{27}$	$\frac{4}{28}$	$\frac{4}{29}$	$\frac{4}{30}$	$\frac{4}{31}$	$\frac{4}{32}$	$\frac{4}{33}$	$\frac{4}{34}$	$\frac{4}{35}$	$\frac{4}{36}$	$\frac{4}{37}$	$\frac{4}{38}$	$\frac{4}{39}$	$\frac{4}{40}$

G Max = number of energy groups (≤ 7) 1

NMax 3 MMax 1

N Max = number of different substances for which cross sections are to be read in (≤ 8)

M Max = number of mixtures (≤ 8)

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Label the substances with the integers 1, 2,Max

Label the mixtures with the integers $N \text{ Max} + 1, N \text{ Max} + 2, N \text{ Max} + M \text{ Max}$
If $N \text{ Max} + M \text{ Max} > 8$, some mixtures must be stored at positions previously occupied by substances, wiping out all knowledge of those substances at the time the mixtures are stored therein. The maximum number of materials is 8 .

The proportions, P(M,IS), are stated as atomic fractions, and add up to unity for each mixture.

Proportions:	<input type="checkbox"/>	. 36		. 64	___	___	___	___	___	___	___	___	___	___	___	___	___
Substance Label:	1	2	___	___	___	___	___	___	___	___	___	___	___	___	4	___	Mixture
Proportions:	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___
Substance Label:	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___
Proportions:	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	___	<input type="checkbox"/>

Proportions:

Substance Label: ___

—
—
—
—
—

Proportions: _____

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—
—
—

Substance Label: _____

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—
—

Proportions: _____

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—
—
—
—

Substance Label: _____

—
—
—
—
—

NEUTRON CONSTANTS

Average Neutron Velocity (cm/ μ sec)							Relative Fission Spectrum ν_g ($\sum \nu_g = 1$)						
169.5													1
$\frac{v_g}{g} = 1$	$\frac{v_g}{g} = 2$	$g = 3$	$g = 4$	$g = 5$	$g = 6$	$g = 7$	$\frac{1}{g=1}$	$g = 2$	$g = 3$	$g = 4$	$g = 5$	$g = 6$	$g = 7$

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Cross Sections (barns)

Note: ν = average number of neutrons emitted per fission
 $\sigma_{tr} = \sigma_f + \sigma_{cap} + \sigma_{ol. scat} + \sigma_{inel. scat} = \sigma_{total}$ (if scattering is isotropic)
Substance 1

	$(\nu\sigma_f)_g$	$(\sigma_{tr})_g$	$(\sigma_{scat}) g - 1$	$(\sigma_{scat}) g - 2$	$(\sigma_{scat}) g - 3$	$(\sigma_{scat}) g - 4$	$(\sigma_{scat}) g - 5$
$g = 1$	3.75	7.0	5.3				
$g = 2$							
$g = 3$							
$g = 4$							
$g = 5$							
$g = 6$							
$g = 7$							

Substance 2

	$(\nu\sigma_f)_g$	$(\sigma_{tr})_g$	(σ_{scat})						
			$g - 1$	$g - 2$	$g - 3$	$g - 4$	$g - 5$	$g - 6$	$g - 7$
$g = 1$.25	7.0	6.7						
$g = 2$									
$g = 3$									
$g = 4$									
$g = 5$									
$g = 6$									
$g = 7$									

Substance 3

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	$(\nu\sigma_f)_g$	$(\sigma_{tr})_g$	(σ_{scat})	(σ_{scat})	(σ_{scat})	(σ_{scat})	(σ_{seat})	(σ_{scat})	(σ_{seat})
			$g - 1$	$g - 2$	$g - 3$	$g - 4$	$g - 5$	$g - 6$	$g - 7$
$g = 1$	0	7.0	6.8						
$g = 2$									
$g = 3$									
$g = 4$									
$g = 5$									
$g = 6$									
$g = 7$									

Substance 4

	$(\nu\sigma_f)_g$	$(\sigma_{tr})_g$	(σ_{scat})						
			$g - 1$	$g \leftarrow 2$	$g - 3$	$g - 4$	$g - 5$	$g - 6$	$g - 7$
$g = 1$									
$g = 2$									
$g = 3$									
$g = 4$									
$g = 5$									
$g = 6$									
$g = 7$									

PROPERTIES OF MATERIALS

For each material in order from center outward:

	P_{Lab} (10^{-24} g/ atom)	α ($cm^2/\mu sec^2$)	$\beta(g/cm\mu sec^2 kev)$	$\tau(g/cm\mu sec^2)$
Innermost Material	396	. 02873	278.46	- . 3946
Next New Material	396	. 02873	278.46	- . 4687189

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ACCURACY CRITERIA

Definitions:

EPSR Tolerance for outer radius when α - control $\neq 0$

EPSA Tolerance in α 's found by S_4

EPS1 Largest negligible pressure for equation of state iteration convergence.

ETA1 Fractional pressure tolerance for equation of state iteration convergence.

ETA2 1/4 the maximum tolerated value of $\alpha\Delta t$

ETA3 Tolerance for the change in α between successive S_4 cycles

EPSR (cm)	EPSA (μsec^{-1})	EPSI (g/cm μsec^2)	ETAI	ETA2	ETA3
3×10^{-6}	5×10^{-5}	10^{-4}	10^{-3}	1.5×10^{-2}	3×10^{-2}

C_{vp} Viscous pressure coefficient _____
for shock smearing

Δt (μsec) 2

Courant stability constant 3
equals high estimate for $\gamma(\gamma - 1)$
 $\Delta t \text{ max} (\mu\text{sec})$ 16

NP Number of hydrodynamic cycles between detailed print on primary output.

NPOFF Number of hydrodynamic cycles between detailed print offline.

NPOFFP Revised number of hydrodynamic cycles between detailed print offline; effective when VJ limit on pressure is reached.

KCNTRL 01 if calculation of k_{eff} is desired
00 if calculation of k_{eff} is not desired

$$\frac{100}{NP} \frac{15}{NPOFF} \frac{3}{NPOFFP} \frac{1}{KCNTRL}$$

Limits on alpha change between S_4 calculations

$$VJ \approx \left(\frac{\sqrt{q}}{b} \right)^5 \times \frac{1}{a_{\max} \ell \rho}, \text{ in units of } \text{g}^{-1} \text{ cm}^{-2}$$

where $1 - q = \frac{\text{flux at core edge}}{\text{flux at center}}$

b = core radius, cm

ℓ = neutron lifetime

ρ = density, g/cm 3

OK1 = dimensionless test parameter ($\approx .01$)

OK2 = dimensionless test parameter ($\approx .04$)

PTEST = maximum local pressure allowed without testing for $\frac{d^2(\alpha)}{dt^2}$,
in megabars

EPSK Convergence criterion on k calculation

POWNGL Power following burst after which negligible change in total energy occurs.

$$\frac{6.6 \times 10^{-7}}{VJ} \frac{10^{-2}}{OK1} \frac{4 \times 10^{-2}}{OK2} \frac{10^{-4}}{PTEST} \frac{5 \times 10^{-6}}{EPSK} \frac{1}{POWNGL}$$

For Ax-1', do not fill in POWNGL ; state Ax-1' is to be used.

RE-28 (12-58)

B. Results

The on-line print-out for the complete problem is included herein. First, a complete reproduction of the input data is printed, in exactly the same array as it is presented to the card punchers. Since a calculation of k_{eff} was requested, this number is printed, followed by the initial total kinetic energy, total internal energy and initial maximum radius.

At time equal to zero, a short print-out is made, consisting of Time, Q_p, Power, Alpha, Δt and W. As the calculation progresses, similar short prints are repeated following each S_n calculation. Dumps are noted as they occur during the process.

When a "long" print-out is in order ($NH \equiv 0 \pmod{N_p}$) first the total energy, the kinetic energy and the checks on the energy computation are printed. This is followed by a detailed listing of the density, radius, velocity, pressure, internal energy and temperature of each mass point. This latter print-out is time-consuming, hence, the program was revised to permit infrequent on-line, long prints, coupled with frequent off-line, long prints. The latter are dumped on tape and are available for off-line print-out on separate equipment, if needed.

GENEVE 10 RERUN MARCH 20 1959	
1	1.308400E-02
1	1.000000E+00
40	
9	9.500000E-01
1	9.000000E+00
2	8.500000E+00
3	8.000000E+00
4	7.500000E+00
5	7.000000E+00
6	6.500000E+00
7	6.000000E+00
8	5.500000E+00
9	5.000000E+00
10	4.500000E+00
11	4.000000E+00
12	3.500000E+00
13	3.000000E+00
14	2.500000E+00
15	2.000000E+00
16	1.500000E+00
17	1.100000E+00
18	8.000000E+00
19	5.000000E+00
20	2.000000E+00
21	6.500000E+00
22	2.800000E+00
23	3.750000E+00
24	4.700000E+00
25	3.650000E+00
26	6.600000E+00
27	7.550000E+00
28	8.500000E+00
29	3.030000E+00
30	2.100000E+00
31	3.390000E+00
32	3.570000E+00
33	3.750000E+00
34	3.930000E+00
35	4.100000E+00
36	4.290000E+00
37	7.920000E+00
38	7.920000E+00
39	7.920000E+00
40	7.920000E+00
41	7.920000E+00
42	7.920000E+00
43	7.920000E+00
44	7.920000E+00
45	7.920000E+00
46	7.920000E+00
47	7.920000E+00
48	7.920000E+00
49	7.920000E+00
50	7.920000E+00

GENEVE 10 RERUN MARCH 201959

1.003243E 00

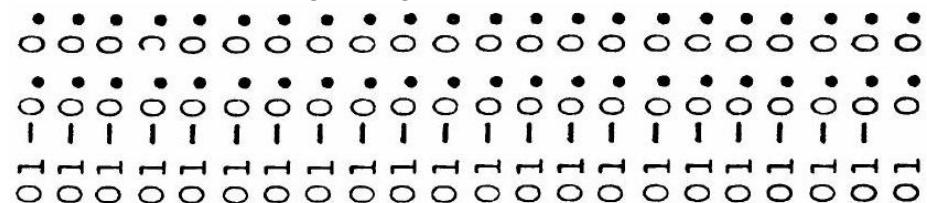
TOTAL INTERNAL ENERGY = 3.484515E03
TOTAL KINETIC ENERGY = 0.

4.400910E 01

					POWER		ALPHA	
0.			3.484515E	03	1.000000E	00	1.308400E-02	
2.000000E	00		3.486570E	03	1.026513E	00	1.306381E-02	
6.000000E	00		3.490840E	03	1.081580E	00	1.306669E-02	
1.200000E	01		3.497678E	03	1.169789E	00	1.306910E-02	
2.000000E	01		3.507671E	03	1.298716E	00	1.307150E-02	
3.000000E	01		3.521725E	03	1.480072E	00	1.307318E-02	
4.200000E	01		3.541205E	03	1.731467E	00	1.307486E-02	
5.600000E	01		3.568153E	03	2.079270E	00	1.307654E-02	
7.200000E	01		3.605640E	03	2.563162E	00	1.307702E-02	
9.000000E	01		3.658339E	03	3.243418E	00	1.307847E-02	
1.100000E	02		3.733451E	03	4.213092E	00	1.307943E-02	
DUMP 1								
1.320000E	02		3.842258E	03	5.617822E	00	1.307967E-02	
1.560000E	02		4.002723E	03	7.689500E	00	1.308039E-02	
1 .820000E	02		4.243975E	03	1.080431E	01	1.308087E-02	
2 .000000E	02		4.466130E	03	1.367270E	01	1•308087E-02	
TOTAL ENERGY			KINETIC ENERGY		CHECK		ERROR LOCAL	
4.466130E 03		0•			-1.378316E-04		2.656016E-06	

DENSITY	RADIUS		VELOCITY	PRESSURE	INTERNAL ENERGY	TEMPERAT
7.920000E 00	9.353166E-01	-O.		0 .	4.609830E-03	3.500994E
7.919999E 00	1.870633E 00	-0.		0.	4 · 603765E – 03	3.496712E
7.919999E 00	2.805949E 00	-0.		0.	4.591511E-03	3.488057 E
7.920000E 00	3.741266E 00	-0.		0.	4.573052E-03	3.475017E
7.919999E 00	4.676582E 00	-0.		0.	4.548420E-03	3.457605E –
7.919999E 00	5.611899E 00	-0.		0.	4.517679 E -03	3.435855E –
7.919999E 00	6.547217E 00	-0.		0.	4.480917E-03	3.409822E
7.919999E 00	7.482533E 00	-0.		0.	4•438245E-03	3.379570E
7.919999E 00	8.417846E 00	-0.	0•		4.389797E-03	3.345174 E
7.919998E 00	9.353163E 00	-0.		0.	4•335721E-03	3.306729E
7.919998E 00	1.028848E 01	-0.		0.	4•276185E-03	3.264334E
7.919999E 00	1.122380E 01	-0.		0.	4•211373E-03	3.218098E
7.919998E 00	1.215911E 01	-0.		0.	4.141483E-03	3.168140E
7.919997E 00	1.309443E 01	-0.		0.	4.066724E-03	3.114589 E
7.919998E 00	1.402975E 01	-0.		0.	3.987319E-03	3.057583E
7.919998E 00	1.496507E 01	-0.		0.	3•903497E-03	2.997261E
7.919998E 00	1.590038E 01	-0.		0.	3.815498E-03	2.933772E

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GENEVE 10 RERUN MARCH 201959

	TIME		QP		POWER		ALPHA	DELT
	2.100000E	02	4.614118E	03	1.558345E	01	1.308135E-02	2.00000
2	.400000E	02	5.194141E	03	2.307269E	01	1.308255E-02	2.00000
DUMP 2								
2	2.620000E	02	5.790050E	03	3.076770E	01	1.307606E-02	2.00000
2	2.700000E	02	6.052932E	03	3.416063E	01	1.291253E-02	2.00000
2	-740000E	02	6.194982E	03	3.597139E	01	1.263538E-02	2.00000
2	-800000E	02	6.422045E	03	3.880450E	01	1.173227E-02	2.00000
2	-820000E	02	6.501495E	03	3.972579E	01	1.123132E-02	2.00000
2	840000E	02	6.582751E	03	4.062824E	01	1.061646E-02	2.00000
2	860000E	02	6.665751E	03	4.150012E	01	9.864639E-03	2.00000
2	.880000E	02	6.750404E	03	4.232701E	01	8.957334E-03	2.00000
2	.900000E	02	6.836587E	03	4.309212E	01	7.876132E-03	2.00000
2	920000E	02	6.924139E	03	4.377629 E	01	6.601209E-03	2•00000
HALVE	DELT,	SENSE	LIGHT 3 ON					
2	-940000E	02	7	03	4.435807E	01	5.114744E-03	1.00000
2	-950000E	02	7	03	4.469970E	01	5.114744E-03	1.00000

TOTAL ENERGY	KINETIC ENERGY	CHECK	ERROR LOCAL
7.057554 E 03	1.252171 E 01	-4.590405E - 04	9.519746E - 06

DENSITY		RADIUS	VELOCITY	PRESSURE	INTERNAL ENERGY	TEM
7.484143E	00	9.531319E-01	2.407454 E -04	4.925818E-02	1.321355E-02	8.21
7.493912E	00	1.905539E 00	1.461096E-03	4•980521E-02	1.319808E-02	8.22
7.493629E	00	2.858224E 00	2.419077E-03	4.903755E-02	1.315292E-02	8.20
7.504321E	00	3.809892E 00	2.837079E-03	4.895018E-02	1.309500E-02	8.18
7.515374E	00	4.760746E 00	3.736507E-03	4.849854 E -02	1.301343E-02	8.15
7.528976E	00	5.710589E 00	4.365463E -03	4.791449E -02	1.291162E-02	8.12
7.549754E	00	6.658724E 00	5.095267E-03	4.764249E-02	1.279374E-02	8.09
7.567464E	00	7.605683E 00	5.717149E-03	4.669176E-02	1.265076E-02	8.03
7.592811E	00	8.550646E 00	6.363582E-03	4.609189E-02	1.249247E-02	7.99
7.617350E	00	9.493879E 00	6.965566E-03	4.503848E-02	1.231175E -02	7.92
7.648377E	00	1.043473E 01	7.512518E-03	4.420762E-02	1.211524E-02	7.88
7.680144E	00	1.137329E 01	8.007845E -03	4.308627E-02	1.189895E-02	7.79
7.716881E	00	1.230911E 01	8.478864E-03	4.204543E-02	1.166610E-02	7.77
7.752517E	00	1.324249E 01	8.894262 E -03	4.054883E-02	1.141318E-02	7.62
7.791894E	00	1.417309E 01	9.367871E -03	3.903099E-02	1.114415E-02	7.53
7.833664E	00	1.510078E 01	9.557108E-03	3.738020E-02	1.085900E-02	7.43
7.881988E	00	1.602497E 01	9.646610E-03	3.593785E-02	1.055997E-02	7.32
7.926625E	00	1.694623E 01	9.939646E-03	3.384898E-02	1.024234E-02	7.20
7.970825E	00	1.786472E 01	9.889098E-03	3.142713E-02	9.909864E-03	7.07
8.023799E	00	1.877955E 01	9.526138E-03	2.938053E-02	9.565789E-03	6.94

6•776275E-04
 6•653063E-04
 6•357862E-04
 5•503850E-04
 4•999998E-05
 4•999999E-05
 4•9999999E-05
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8•058807E 1•969283E 01 9•354209E-03
 8•126535E 2•060099E 01 8•658014E-03
 8•100561E 2•151433E 01 2•032907E-03
 7•936677E 2•244760E 01 2•877922E-10
 7•919998E 2•338291E 01 -0•
 1•583000E 2•431823E 01 -0•
 1•583000E 2•525355E 01 -0•
 1•583000E 2•618887E 01 -0•
 1•583000E 2•712418E 01 -0•
 1•583000E 2•805950E 01 -0•
 1•583000E 2•983168E 01 -0•
 1•583000E 3•160386E 01 -0•
 1•583000E 3•337602E 01 -0•
 1•582999E 3•514820E 01 -0•
 1•582999E 3•692038E 01 -0•
 1•583000E 3•869256E 01 -0•
 1•582999E 4•046474E 01 -0•
 1•582999E 4•223692E 01 -0•
 1•582999E 4•400910E 01 -0•

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GENEVE 10 RERUN MARCH 201959

TIME	QP	POWER	ALPHA	DELT	W
HALVE DELT, SENSE 2•950000E 02	LIGHT 3 ON				
2.955000E 02	7.057554E 03	4.469970E 01	4•275073E-03	5.000000E-01	8.427610E-02
2.955000E 02	7.079975E 03	4.484325E 01	4•275073E-03	5.000000E-01	3.101643E-02

TOTAL ENERGY KINETIC ENERGY CHECK
ERROR LOCAL

9.519630E-06

DENSITY	RADIUS	VELOCITY	PRESSURE	INTERNAL ENERGY	TEM
7.481986E 00	9.532235E-01	1.832310E-04	5.029360E-02	1•328717E-02	8.25
7.483834E 00	1.906310E 00	1.541746E-03	5.007831E-02	1.326452E-02	8.24
7.483896E 00	2.859438E 00	2.428255E-03	4•934222E-02	1•321954E-02	8.22
7.496565E 00	3.811334 E 00	2.884498E-03	4•944069E-02	1•316300E-02	8.21
7.505908E 00	4.762645E 00	3.797786E-03	4.882175E – 02	1•307953E-02	8.17
7.520732E 00	5.712786E 00	4.393979 E -03	4.834875E – 02	1.297824E-02	8.14
7.540719E 00	6.661322E 00	5.194831E-03	4.799533E-02	1.285901E-02	8.11
7.559311E 00	7.608573E 00	5.779899E-03	4•712015E-02	1.271605E-02	8.06
7.584273E 00	8.553883E 00	6.473626E-03	4.647534E – 02	1.255657E-02	8.01
7.609310E 00	9.497405E 00	7.052238E-03	4.545819E-02	1.237529E-02	7.95
7.640404E 00	1.043855E OI	7.629301E-03	4.462197E-02	1.217775E-02	7.89
7.672613E 00	1.137735E OI	8.116051E-03	4.352798E-02	1•196060E-02	7.81
7.709292E 00	1.231343E OI	8.634149E-03	4•246773E-02	1.172641E-02	7.74
7.745423E 00	1.324701E 01	9.051432E-03	4.099948E-02	1.147246E-02	7.65
7.784577E 00	1.417786E 01	9.538440E – 03	3.944508E-02	1•120181E-02	7.55
7.827812E 00	1.510563E 01	9.705800E-03	3.790197E-02	1.091598E-02	7.45
7.876376E 00	1.602990E 01	9.861428E-03	3.645849E-02	1.061536E-02	7.35
7.920403E 00	1.695132E 01	1.018808E-02	3.429620E-02	1.029561E-02	7.23
7.966570E 00	1.786977E 01	1.009850E-02	3.201226E-02	9.962271E-03	7.10
8.020249E 00	1.878451E OI	9.909690E-03	2.999489E-02	9.616482E-03	6.97
8.056527E 00	1.969758E 01	9.505358E-03	2.630742E-02	9.250290E-03	6.80
8.122704E 00	2.060574E 01	9.505549 E -03	2.466803E-02	8.882461E-03	6.67
8.124196E 00	2.151614E 01	3.625286E-03	1.822741E-02	8.481242E-03	6.42
7.951445E 00	2.244760E OI	6.091743E-06	1.910850E-04	8.046777E-03	5.87
7.920021E 00	2.338291E 01	-0.	4.681418E-10	7.602204E-03	5.52
1.583000E 01	2.431823E 01	-0.	0.	6.153750E-04	4.99
1.583000E 01	2.525355E OI	-0.	0.	6.153750E-04	4•9
1.583000E 01	2.618887E 01	-0.	0.	6.153750 E -04	4.99
1.583000E 01	2.712418E 01	-0.	0.	6.153750E-04	4.99
1.583000E 01	2.805950E 01	-0.	0.	6•153750E-04	4.99
1.583000E 01	2.983168E 01	-0.	0.	6.153750E-04	4.99
1.583000E 01	3.160386E 01	-0.	0.	6•153750E-04	4.99
1.583000E 01	3.337602E 01	-0.	0.	6.153750E-04	4•9

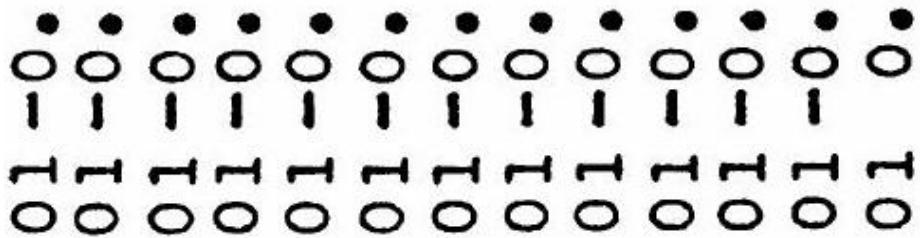
TOTAL ENERGY 7.283048E03	KINETIC ENERGY 2.097754E01	CHECK -4.672505E - 04	ERROR LOCAL 9.519164E - 06
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GENEVE 10 RERUN MARCH 201959

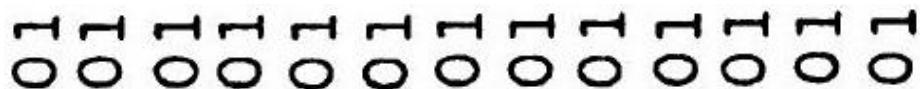
TIME	QP	POWER	ALPHA	DELT	W
2.955000E 02	7.079975E 03	4.484325E 01	3.829388E-03	5.000000E-01	3.101643E-02
2.960000E 02	7.102438E 03	4.492919E 01	3.373051E-03	5.000000E-01	2.742106E-02
2.965000E 02	7•124940E 03	4.500503E 01	2.902788E-03	5•000000E-01	3.258085E-02
2.970000E 02	7.147474 E 03	4.507040E 01	2.416258E-03	5.000000E-01	3.735047E-02
2.975000E 02	7.170036E 03	4.512488 E 01	1.913964E-03	5.000000E-01	4.068206E-02
2.980000E 02	7.192619E 03	4.516808E 01	1.394506E-03	5.000000E-01	4.232702E-02
2.985000E 02	7.215218E 03	4.519958E 01	8.567256E-04	5.000000E-01	4.214406E-02
2.990000E 02	7.237827E 03	4.521895E 01	3.018303E-04	5.000000E-01	4.009234E-02
2.995000E 02	7.260439E 03	4.522577E 01	-2.711039E-04	5.000000E-01	3.624670E-02
3.000000E 02	7•283048E 03	4.521964E 01	-2.711039E-04	5.000000E-01	3.206001E-02

DENSITY		RADIUS	VELOCITY	PRESSURE	INTERNAL ENERGY	TEM
7.401031E 00		9.566864E-01	1.424552E-03	5.353012E-02	1•389095E-02	8.49
7.393915E 00		1.913910E 00	1.696909E-03	5.248137E-02	1•386256E-02	8.41
7.404357E 00		2.869995E 00	2.315887E-03	5•273834E-02	1.382527E-02	8.42
7.412364E 00		3.825582E 00	3.379210E -03	5.234674E-02	1.376084E-02	8.40
7.425086E 00		4.780163E 00	3.948628E-03	5.203104E-02	1•367740E-02	8.37
7.441152E 00		5.733496E 00	4.823062E -03	5.162633E-02	1.357202E-02	8.34
7.457356E 00		6.685685E 00	5.528755E-03	5.086122E-02	1•344403E-02	8.30
7.481923E 00		7.635847E 00	6.323115E-03	5.048868E-02	1.329935E-02	8•2
7.504809E 00		8.584374E 00	6.975247E-03	4.957673E-02	1.313071E-02	8.20
7.534809E 00		9.530544E 00	7.631582E-03	4.893916E-02	1•294487E-02	8.15
7.565585E 00		1.047445E 01	8.233802E-03	4.797767 E -02	1.273753E-02	8.08
7.600967E 00		1.141568E 01	8.869514 E -03	4.706591E-02	1.251226E-02	8.03
7.636243E 00		1.235442E 01	9.463822E-03	4.575969 E -02	1.226570E-02	7.93
7.676543E 00		1.329021E 01	1.002161E-02	4.453489 E -02	1•200253E-02	7.84
7.720246E 00		1.422281E 01	1.030141E-02	4.324137E-02	1.172205E-02	7.75
7.769700E 00		1.515174E 01	1.072612E-02	4.207328E-02	1.142572E-02	7.66
7.814853E 00		1.607768E 01	1.120278E-02	4.015730E-02	1.110779E-02	7.54
7.865319E 00		1.700015E 01	1.130235E-02	3.835686E-02	1.077639E-02	7.43
7.922419E 00		1.791856E 01	1.149764E-02	3.676734 E -02	1.043189E-02	7.33
7.973327E 00		1.883378E 01	1.156862E-02	3.429114E-02	1.006687E-02	7.11
8.037897E 00		1.974442E 01	1.140977E-02	3.262382E-02	9.695081E-03	7.04
8.077105E 00		2.065343E 01	1.096143 E -02	2.858021E-02	9.296469E-03	6.88
8.148068E 00		2.155735E 01	1.197423E-02	2.671503E-02	8.896784E-03	6.72
8.215868E 00		2.245678E 01	6.082644E-03	2.466825 E -02	8•480696E-03	6.56
7.995130E 00		2.338293E 01	2.579092E-05	5.399298E-04	7•963973E-03	5.89
1.583035E 01		2.431823E 01	1.911376E-07	1.040176E-05	6.153750E-04	5•0

0. 6. 153750E-04 4. 9999998E-05
0. 6. 153750E-04 4. 9999999E-05
0. 6. 153750E-04 4. 9999998E-05
0. 6. 153750E-04 4. 9999997E-05
0. 6. 153750E-04 4. 9999997E-05



شش	ش	س	س	س	ش	ش	ش	ش	ش	ش	ش
In	∞	∞	0	N	0	∞	o	v	N	0	
In ∞	- μ	0	∞	0	N	m	n	N	の	σ	
$m\infty$	t	-	m	0	∞	0	N	+	0	の	
$n\infty$	N	m	0	N	v	N	の	b	m	0	
Ne-	T	∞	0	m	-1	の	o	t	N	0	
000	N	の	-	m	In	0	∞	0	N	+	
NNNNNmmytt											



ش	W	ش	ش	ش	ش	ش	س	ش	لسا	ش	ش
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
M	M	m	m	m	m	N	N	m	N	N	N
∞	0	0	0	ou	ou	0	∞	0	∞	∞	∞
th	n	in	,	tn	μ	In	n	"	in	in	,
-	-	•	•	-	-	-	-	-	-	-	-
-1											

3•200000E 02	8•095437E 03	3•220320E 01	-3•786118E-02	5•000000E-01	3•297700E-02
3•205000E 02	8•1111236E 03	3•159931E 01	-3•904422E-02	5•000000E-01	3•336086E-02
3•210000E 02	8•126729E 03	3•098841E 01	-4•023603E-02	5•000000E-01	3•287899E-02
3•220000E 02	8•156796E 03	2•976631E 01	-4•260405E-02	5•000000E-01	2•962761E-02
3•230000E 02	8•185626E 03	2•852374E 01	-4•508476E-02	5•000000E-01	2•618562E-02
3•240000E 02	8•213201E 03	2•726631E 01	-4•756128E-02	5•000000E-01	2•910206E-02
3•250000E 02	8•239512E 03	2•599985E 01	-5•006933E-02	5•000000E-01	3•343638E-02
3•260000E 02	8•264554E 03	2•473011E 01	-5•260200E-02	5•000000E-01	3•227879E-02
3•270000E 02	8•288328E 03	2•346287E 01	-5•515871E-02	5•000000E-01	2•701019E-02
3•280000E 02	8•310841E 03	2•220374E 01	-5•773410E-02	5•000000E-01	3•003798E-02
3•290000E 02	8•332104E 03	2•095813E 01	-6•032818E-02	5•000000E-01	3•424720E-02
3•300000E 02	8•352136E 03	1•973115E 01	-6•293555E-02	5•000000E-01	3•321113E-02
3•310000E 02	8•370958E 03	1•852762E 01	-6•555734E-02	5•000000E-01	3•166332E-02
3•320000E 02	8•388859E 03	1•735196E 01	-6•818837E-02	5•000000E-01	3•170859E-02
3•330000E 02	8•405085E 03	1•620820E 01	-7•082857E-02	5•000000E-01	3•451502E-02
3•340000E 02	8•420455E 03	1•509991E 01	-7•347678E-02	5•000000E-01	3•247912E-02
3•350000E 02	8•434747E 03	1•403019E 01	-7•612848E-02	5•000000E-01	2•951676E-02
3•360000E 02	8•447799E 03	1•300174E 01	-7•878513E-02	5•000000E-01	3•324070E-02
3•370000E 02	8•460255E 03	1•201671E 01	-8•144622E-02	5•000000E-01	3•413450E-02
3•380000E 02	8•471561E 03	1•107685E 01	-8•407400E-02	5•000000E-01	3•229823E-02
3•390000E 02	8•481961E 03	1•083455E 01	-8•674214E-02	5•000000E-01	3•322019E-02
3•400000E 02	8•491504E 03	9•337340E 00	-8•938380E-02	5•000000E-01	3•429283E-02
3•415000E 02	8•504318E 03	8•165727E 00	-9•332411E-02	5•000000E-01	3•088998E-02
3•430000E 02	8•515481E 03	7•099040E 00	-9•72935E-02	5•000000E-01	3•361961E-02
3•445000E 02	8•525148E 03	6•135555E 00	-1•011212E-01	5•000000E-01	3•313833E-02
3•460000E 02	8•533471E 03	5•272048E 00	-1•049455E-01	5•000000E-01	3•209773E-02
3•475000E 02	8•540595E 03	4•504028E 00	-1•087615E-01	5•000000E-01	3•437118E-02
3•490000E 02	8•5466659E 03	3•826038E 00	-1•125067E-01	5•000000E-01	3•621689E-02
3•500000E 02	8•550175E 03	3•418915E 00	-1•125067E-01	5•000000E-01	3•528061E-02
TOTAL ENERGY	KINETIC ENERGY	CHECK	ERROR LOCAL		
8•550175E 03	1•368729E 02	-5•476842E-04	9•557465E-06		
DENSITY	RADIUS	VELOCITY	PRESSURE	INTERNAL ENERGY	TEMPERATURE
6•314519E 00	1•008679E 00	1•903546E-03	2•256632E-04	1•716892E-02	7•663890E-04
6•331030E 00	2•015825E 00	2•738945E-03	1•789532E-03	1•714454E-02	7•702328E-04
6•332251E 00	3•023369E 00	3•405926E-03	1•072511E-03	1•079448E-02	7•676037E-04
6•348160E 00	4•029092E 00	4•107742E-03	1•676030E-03	1•701922E-02	7•681297E-04
6•367559E 00	5•032946E 00	5•150840E-03	2•241811E-03	1•691839E-02	7•681782E-04
6•3788336E 00	6•036252E 00	6•556652E-03	1•397774E-03	1•679133E-02	7•639860E-04
6•405661E 00	7•036680E 00	7•342406E-03	1•981394E-03	1•664034E-02	7•633132E-04
6•442238E 00	8•033304E 00	7•712783E-03	3•203344E-03	1•646434E-02	7•639081E-04
6•491994E 00	9•024756E 00	7•854918E-03	5•464867E-03	1•626532E-02	7•668960E-04

		MARCH 201959	POWER		
GENEVE 10 RERUN TIME			ALPHA		
3.505000E 02		8.551790E 03	3.231899E 00	-1.16E070E-01	5.000000E-01
			DUMP 4		
3.520000E 02		8.556109E 03	2.714952E 00	-1.198263E-01	5.000000E-01
3.535000E 02		8.559723E 03	2.268310E 00	-1.233918E-01	5.000000E-01
3.555000E 02		8.563617E 03	1.772253E 00	-1.280392E-01	5.000000E-01
3.575000E 02		8.566642E 03	1.371868E 00	-1.325590E-01	5.000000E-01
3.595000E 02		8.568970E 03	1.052381E 00	-1.369468E-01	5.000000E-01
POWER SMALL NS4 UP					
3.615000E 02		8.570745E 03	8.002442E-01	-1.412027E-01	5.000000E-01
3.660000E 02		8.573310E 03	4.239031E-01	-1.503135E-01	5.000000E-01
3.710000E 02		8.574737E 03	1.999240E-01	-1.597197E-01	5.000000E-01
3.765000E 02		8.575432E 03	8.305300E-02	-1.691910E-01	5.000000E-01
3.825000E 02		8.575722E 03	3.009422E-02	-1.784988E-01	5.000000E-01
DUMP 5					
3.890000E 02		8.575824E 03	9.431836E-03	-1.876245E-01	5.000000E-01
3.960000E 02		8.575850E 03	2.536333E-03	-1.967015E-01	5.000000E-01
4.000000E 02		8.575852E 03	1.154784E-03	-1.967015E-01	5.000000E-01

TOTAL ENERGY KINETIC ENERGY CHECK ERROR LOCAL
 8.575852 E 03 1.414158 E 02 -5.208532E - 04 2.470845E - 05

DENSITY	RADIUS	VELOCITY	PRESSURE	INTERNAL ENERGY	TEMP
4.917073E 00	1.096389E 00	1.753956E-03	0 .	1.725101E-02	4.417
5.205647E 00	2.156736E 00	2.818523E-03	0.	1.722617E-02	2.572
5.499321E 00	3.188685E 00	3.305828E-03	0 .	1.717615E-02	4.281
5.537857E 00	4.230596E 00	4.029824E - 03	0.	1.710035E-02	4.433
5.419751E 00	5.297382E 00	5.289495E-03	0.	1.699883E-02	3.721
5.439850E 00	6.358381E 00	6.441835E - 03	0.	1.687154E-02	3.745
6.025999E 00	7.328801E 00	5.509934E-03	0•	1.671965E-02	6.370
6.094808E 00	8.307465E 00	5.501657E - 03	0.	1.654206E-02	6.518
6.331326E 00	9.265503E 00	4.705751E-03	0.	1.633964E-02	7.214
5.812325E 00	1.031525E 01	6.145067E-03	0•	1.611205E-02	5.094
5.605493E 00	1.139668E 01	8.310706E-03	0.	1.586059E-02	3.934
6.437482E 00	1.234178E 01	7.164884E-03	0.	1.558564E-02	7.089
6.060120E 00	1.335402E 01	8.256142E-03	0•	1•528728E-02	5.586
6.334372E 00	1.432737E 01	7.440804E-03	0•	1.496597E-02	6.371
6.329760E 00	1.530778E 01	8.697620E-03	0.	1.462263E-02	6.138
6.527848E 00	1.626487E 01	7.460192E-03	8.721617E-07	1.425737E-02	6.543
6.711025E 00	1.720369E 01	6.942592E-03	0.	1.387102E-02	6.833
6.821918E 00	1.813551E 01	6.589408E-03	0 .	1.346437E-02	6.883
6.773332E 00	1.908118E 01	8.033070E-03	0 •	1•303804E-02	6.486

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34E	01	7•377634E-03	0•	1•259182E-02	6•739882E-04
08E	01	4•673943E-03	6•565979E-05	1•212834E-02	6•589158E-04
70E	01	7•127221E-03	6•102771E-04	1•164701E-02	6•737058E-04
2E	01	5•481286E-03	1•880346E-05	1•114650E-02	6•599739E-04
96E	01	6•677044E-03	0•	1•062398E-02	6•399492E-04
31E	01	6•270953E-03	0•	1•005223E-02	6•348003E-04
23E	01	4•572521E-03	5•531476E-05	6•246356E-04	5•031701E-05
.2E	01	5•868169E-03	3•378190E-03	6•212036E-04	5•089614E-05
04E	01	5•013392E-03	1•277981E-03	6•191517E-04	5•047225E-05
3E	01	6•122503E-03	4•330344E-03	6•196177E-04	5•087734E-05
92E	01	6•870994E-03	4•837479E-03	6•199504E-04	5•095500E-05
60E	01	7•821550E-03	1•095472E-02	6•290912E-04	5•209313E-05
21E	01	9•812453E-03	1•652120E-02	6•362296E-04	5•271491E-05
71E	01	9•618474E-03	2•135148E-02	6•464864E-04	5•333774E-05
05E	01	1•090850E-02	2•322140E-02	6•509714E-04	5•356141E-05
.8E	01	1•111459E-02	2•947552E-02	6•702914E-04	5•443109E-05
98E	01	7•408754E-03	2•577956E-02	6•569390E-04	5•383090E-05
33E	01	3•136491E-03	1•409954E-02	6•276976E-04	5•204429E-05
5E	01	8•856262E-04	4•775890E-03	6•168221E-04	5•069100E-05
74E	01	3•281066E-04	8•954424E-04	6•154275E-04	5•013203E-05

APPENDIX A

DETAILS OF THE VJ-OK-1 TEST

Before the addition of the VJ-OK-1 test to the program it was observed that in the typical problem having a step function reactivity input at zero time and low power, N_{S_4} would build up appreciably by the time high power and the accompanying shutoff mechanism were reached. As a result alpha would change considerably from S_4 calculation to S_4 calculation during shutoff. Since alpha is held constant between such neutronic calculations, some error in the time variation of power would result.

It was desirable that N_{S_4} be large before the burst to conserve machine time. A means of reducing its size at the beginning of the burst was needed. It was decided to obtain the necessary signal by observing $\ddot{\rho}$, the time rate of change of the reactivity inserted per unit time by the feedback mechanism. When the ratio $\frac{\ddot{\rho}}{\dot{\rho}}$ became large, alpha would start changing rapidly and N_{S_4} should be reduced.

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Thus, in a power series expansion of reactivity,

$$\rho = \rho_0 + \dot{\rho}\Delta t + \frac{1}{2}\ddot{\rho}(\Delta t)^2 + \dots,$$

the term in the second derivative is watched, and when

$$\frac{\frac{1}{2}\ddot{\rho}(\Delta t)^2}{\rho_{\text{initial}}} > \text{OK}_1$$

N_{S_4} is modified.

Equation 14 from Appendix C of reference 1 provides the relation

$$\begin{aligned}
\ddot{\rho} &= \frac{-5}{2.54} \frac{\sqrt{q}}{b} \int \ddot{u} \left(\frac{d\phi}{dr} \right)^2 r dr \\
&= + \frac{5}{2.54} \frac{\sqrt{q}}{b} \int \left(\frac{1}{s} \frac{\partial p}{\partial r} \right) \left(-\frac{2qr}{b^2} \right)^2 r dr \\
&= \frac{5}{2.54} \frac{1}{s} \left(\frac{\sqrt{q}}{b} \right)^5 [pr^3 - p \cdot 3r^2 dr]_0^\infty \\
&= - \frac{20}{2.54} \frac{3}{s} \left(\frac{\sqrt{q}}{b} \right)^5 \frac{1}{4\pi} \int pr^2 dr \cdot 4\pi \\
&= \frac{-60}{10.16\pi} \frac{1}{s} \left(\frac{\sqrt{q}}{b} \right)^5 \int pdV
\end{aligned}$$

where

\phi is the flux,
u is the displacement,
r is the radial position
p is the pressure, and
b, q, and s are defined below.

Then

$$\frac{\frac{1}{2}\ddot{\rho}(\Delta t)^2}{\rho_{\text{initial}}} = \frac{(N_{S_4})^2 (\Delta t)^2}{\rho_{\text{initial}}} \cdot \frac{30}{10.16\pi} \left(\frac{\sqrt{q}}{b} \right)^5 \frac{1}{s} \int pdV < OK_1$$

Thus this ratio is proportional to a constant which is a function of the particular reactor, multiplied by the integral of the pressure over the reactor volume. This relation was derived by V. Jankus and has been previously reported in slightly different form in reference 2. (See equation #23.)

The last equation may be rewritten in the form

$$VJ \cdot (\Delta t)^2 \cdot (N_{S_4})^2 \int pdV < OK_1$$

where

$$\begin{aligned}
VJ &= \left(\frac{\sqrt{q}}{b} \right)^5 \times \frac{1}{\rho_{\text{max}} s} \\
&= \left(\frac{\sqrt{q}}{b} \right)^5 \times \frac{1}{\alpha_{\text{max}} \cdot \ell \cdot s}
\end{aligned}$$

and

$I-q$ = ratio of flux at core edge to center
b = core radius, cm

α max = maximum alpha anticipated, $\delta \text{textrm{k}}/\mu \text{ sec}$
 s = core density, grams/cm 3
 I = prompt neutron lifetime, $\mu \text{ sec}$

Generally OK-1 has been set equal to .01. If the fractional change in reactivity in time $N_{S_4} \cdot \Delta t$ exceeds this amount, steps are taken to reduce N_{S_4} . To improve the efficiency of the over-all program, the test is not imposed until the local pressure at some point exceeds PTEST, an adjustable parameter.

APPENDIX B

THE TIME SCALE

The continuous time variable of the burst is approximated by a series of small, finite steps, Δt . From any point t in the course of the solution, the time is given by $t + n\Delta t$, assuming constant time increments. A superscript notation is used herein to label other parameters which vary with time. Thus, the radius for mass point I may be written as $R(I)^n, R(I)^{n+1}$, etc.

When the problem begins, the radii are specified at time $t = 0$. Alpha is calculated for this configuration, so that alpha is known at $t = 0$. The acceleration is calculated at this time, requiring a knowledge of the pressure (and hence the energy) at $t = 0$. To find the radii at $t + \Delta t, (R^{n+1})$ the average velocity during the interval of $U^{n+1/2}$ is needed. This may be calculated, provided that $U^{n-1/2}$ and the average acceleration during the time interval between $t + 1/2\Delta t$ are known.

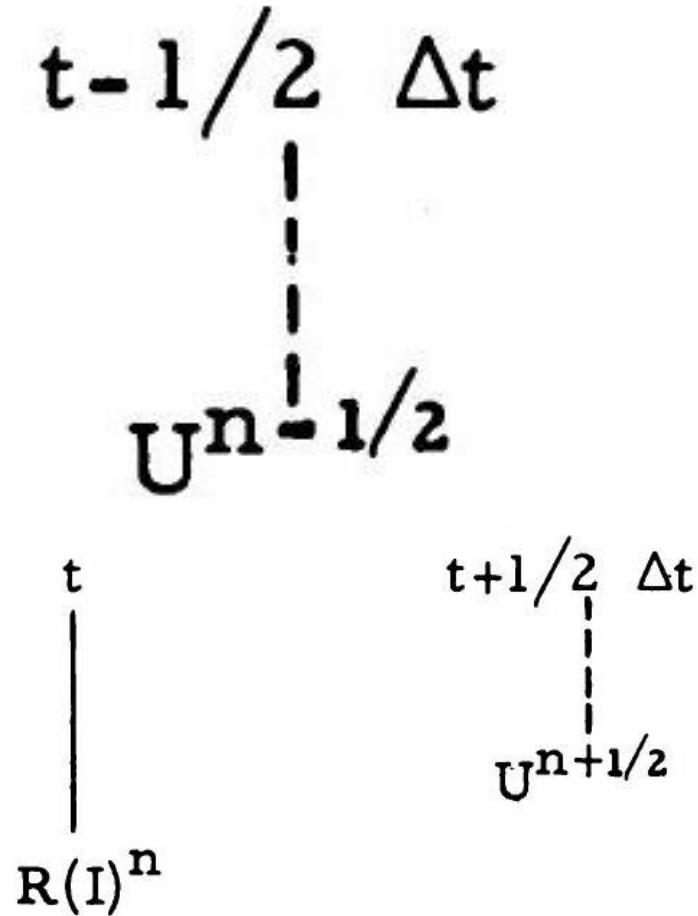
To find the internal energy (and thus the pressure) at $t + \Delta t$ requires the internal energy at t , plus the average power during Δt , or $POWER^{n+1/2}$. The latter may be calculated from the power at $t - 1/2\Delta t$, and the average rate of rise during the period $t - \frac{\Delta t}{2}$ to $t + \frac{\Delta t}{2}$, $ALPHA^n$.

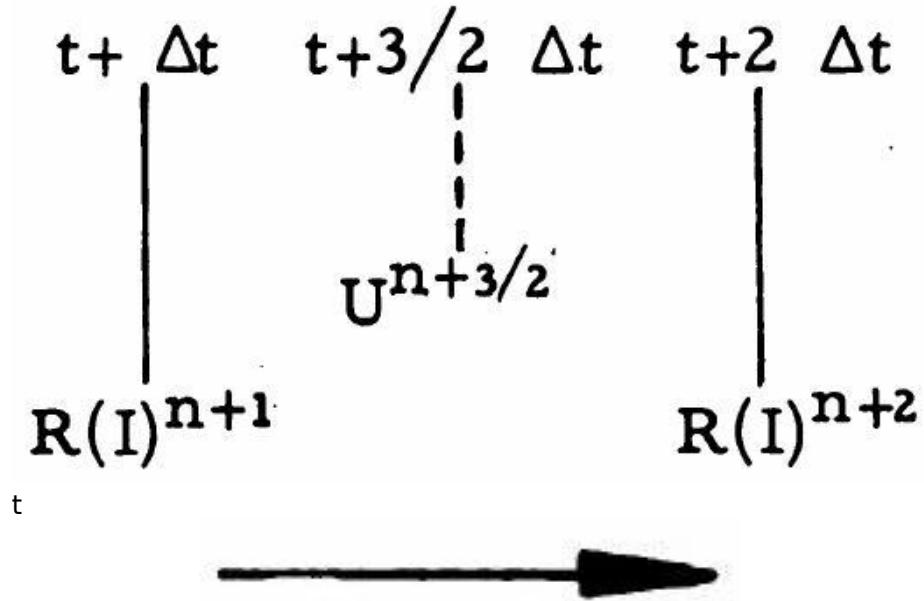
The positions in time at which the various variables must be computed are summarized in the following time chart.

$U^{n-1/2}$	$R(I)^n$	$U^{n+1/2}$	$R(I)^{n+1}$	$U^{n+3/2}$	$R(I)^{n+2}$
$POWER^{n-1/2}$	p^n	$POWER^{n+1/2}$	p^{n+1}	$POWER^{n+3/2}$	p^{n+2}
	ΔQ^n		ΔQ^{n+1}		ΔQ^{n+2}
	$E_{internal}^n$		$E_{internal}$		$E_{internal}^{n+2}$
	α^n				α^{n+2}

The time chart helps to explain the steps taken when Δt is halved or doubled. When, as per order 9290, $\frac{\Delta t}{2} \rightarrow \Delta t$, one notes $\frac{3}{4}\Delta t' \rightarrow \Delta t'$. In

the solution parameters specified on the half interval station change in accordance with $\Delta t'$, while the others vary with Δt . Except during a change in time interval, $\Delta t' = \Delta t$. At a time interval change, the variables U and POWER should be maintained at their half interval position. Thus, if at time $t + \Delta t$, the time interval is halved, the time chart for $R(I)$ and U would look as follows.





Thus the time interval between $R(I)^{n+1}$ and $R(I)^{n+2}$ is half the old Δt , while the time interval between $U^{n+1/2}$ and $U^{n+3/2}$ is $3/4$ the old Δt . On the other hand, on a doubling of Δt , $\Delta t'$ increases only by a factor of 1.5. This arbitrary procedure maintains the velocities and radii in the proper relative positions. A small error in computation is produced in that during a halving of Δt , the increment in U is computed using as average acceleration the value at $2/3$ the interval instead of midway.
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APPENDIX C

DISCUSSION OF HYDRODYNAMIC STABILITY CRITERIA AND SHOCK WAVE TREATMENT

If c is the velocity of sound in the material, then for stability of the finite-difference scheme $c \Delta t < \Delta R$ must hold. (See Ch. II, Sections 2 and 3 of reference (10); also, see Ch. X, Section 11, p. 221 of (9).)

Let $p = p(\rho, s)$ be the caloric equation of state, where p is pressure, ρ is density, and s is specific entropy. Then $c^2 = \frac{\partial p}{\partial \rho}$. (See (11), Ch. III, Section 35; or (12) p. 111, Section 6.10.) The material is treated as a polytropic gas, so that $p = f(s)\rho^\gamma$ and $\frac{\partial p}{\partial \rho} = \gamma \frac{p}{\rho}$, where γ is the adiabatic exponent. But $\frac{p}{\rho} = (\gamma - 1)E$, where E is the specific internal energy (see p. 7 of (11)), so that the stability criterion becomes $(\frac{\Delta R}{\Delta t})^2 >$

$\gamma(\gamma - 1)E$. Then, if one defines a "Courant stability constant" by $C_{sc} = \gamma(\gamma - 1)$, $C_{sc}E\frac{(\Delta t)^2}{(\Delta R)^2} < 1$ must hold.

Actually, the stronger criterion

$$C_{sc}E\frac{(\Delta t)^2}{(\Delta R)^2} + 4C_{vp}\frac{|\Delta V|}{V} < .3$$

is imposed. (When it fails, Δt is halved.) The second term (due to George N. White, Jr.) will ordinarily dominate only in the vicinity of a shock. C_{vp} is the "shock-width constant," and is usually taken to be between 1.5 and 2. It is related to the number of mesh-widths by which the shock is artificially broadened in the von Neumann-Richtmyer method for the numerical calculation of hydrodynamic shocks. (See Ref. 8, also Ref. 9, Chap. 10.) They add a fictitious "pseudo-viscosity pressure" $P_v = C_{vp\rho}\rho^3 (\Delta R \frac{\partial V}{\partial t})^2$ to the real physical pressure in all dynamical equations. This imitates the shocksmearing effect of ordinary physical viscosity, and the differential equations need not be interrupted by troublesome boundary conditions (given by the Rankine-Hugoniot equations) at moving surfaces of internal discontinuity.

P_v is quadratic in $\frac{\partial V}{\partial t}$ so that the transition layer will have width independent of shock strength. (In the case of physical viscosity, the term is linear and the width goes to zero with increasing strength.) For further discussion of this method, see Ch. X, Sections 8-12, of (9).

APPENDIX D

THERMODYNAMIC CONSIDERATIONS

The equation of state has been taken as

$$p = \alpha\rho + \beta\theta + \tau$$

with the accompanying relation

$$\left(\frac{\partial E}{\partial \theta}\right)_v = c_v = A_{cv} + B_{cv}\theta$$

The first law of thermodynamics provides the relation

$$dE = dQ - pdv = \left(\frac{\partial E}{\partial \theta}\right)_v d\theta + \left(\frac{\partial E}{\partial v}\right)_\theta dv$$

Further thermodynamic considerations (Ref. 12, See Chap. XIII) lead to the additional relation,

$$\left(\frac{\partial E}{\partial v}\right)_\theta = \theta \left(\frac{\partial p}{\partial \theta}\right)_v - p.$$

Hence

$$\begin{aligned} d\theta &= \frac{\{dE - (\frac{\partial E}{\partial v})_\theta dv\}}{(\frac{\partial E}{\partial \theta})_V} \\ &= \frac{\{dE - [\theta (\frac{\partial p}{\partial \theta})_V - p] dv\}}{(\frac{\partial E}{\partial \theta})_V} \\ &= \frac{dE + (\alpha\rho + \tau)dV}{A_{cv} + B_{cv}\theta} \end{aligned}$$

This leads to the formula under Order #9130, which in effect reads

$$\Delta\theta = \frac{\{\Delta E + (\frac{\alpha}{2} [\rho^n + \rho^{n+1}] + \tau) \Delta v\}}{A_{cv} + \frac{B_{cv}}{2} (\theta^n + \theta^{n+1})}$$

For the alternate computation of energy a similar starting point is taken, namely,

$$\begin{aligned} \left(\frac{\partial E}{\partial v}\right)_\theta &= \theta \left(\frac{\partial p}{\partial \theta}\right) - p \\ &= -\frac{\alpha}{v} - \tau \text{ for the assumed equation of state.} \end{aligned}$$

Integrating, one gets

$$\begin{aligned} E &= -\alpha \ln v - \tau v + \mathbf{f}(\theta) \\ &= \alpha \ln \rho - \frac{\tau}{\rho} + \mathbf{f}(\theta) \end{aligned}$$

Since $(\frac{\partial E}{\partial \theta})_v = C_v = \frac{\partial f(\theta)}{\partial \theta}$, integration of the specific heat equation, yields the result

$$f(\theta) = A_{cv}\theta + \frac{1}{2}B_{cv}\theta^2 + E_0,$$

and thus

$$E = \alpha \ln \rho - \frac{\tau}{\rho} + A_{cv}\theta + \frac{1}{2} B_{cv}\theta^2 + E_0 = \text{Running } E_{\text{internal}}$$

If

$$E|_{t=0} = A_{cv}\theta + \frac{1}{2}B_{cv}\theta^2 \Big|_{t=0}$$

then

$$E_0 = \frac{\tau}{\rho} - \alpha \ln \rho \Big|_{t=0}$$

The so-called error local is obtained by comparing the running E_{internal} , computed as above for each mass point with the value obtained at Order #9180, which represents the sum of the initial energy and all the succeeding ΔE values resulting from the corresponding iterative solutions for pressure.

The second energy balance or "check" involves summing the kinetic and internal energies for all mass points and comparing it with the total energy Q , as determined directly from the integral of power over time.

APPENDIX E

POSSIBLE VARIATIONS IN THE PROGRAM - Ax-1'

For Ax-1, a simple form of the equation of state was chosen, with the explicit intent of making modifications therein simple to accomplish. For example, another simple equation of state would be that employed by Bethe and Tait, $(^3) = (\gamma - 1)\rho E_{\text{int}}$, wherein a direct calculation of temperature is bypassed, and a different dependence of pressure on density results. Considerably more elaborate equations might also be utilized. Work is continuing in this area to determine that form which might be most satisfactory for problems in fast reactor safety.

One modification of Ax-1 has already been made. It has been customary in previous analytical calculations to make a pair of partially compensating assumptions, for simplicity of analysis. (3) First, during the burst alpha was held constant up till the time sufficient reactivity had been inserted by the shut off mechanism to balance the input reactivity exactly. This procedure kept the power rising too fast. Secondly, the energy developed in the burst was computed up to this point of reactivity balance, neglecting that portion generated while the power fell from its peak during the time of negative alpha. To check the effect of these assumptions, Ax-1 was modified so that it followed the course of the explosion in the above manner. The power distribution at zero time was used as that valid for computing the distribution of energy. The S_n section was allowed to go on computing new alphas, but they were used only to terminate the calculation when $\alpha < 0$. The recomputed fluxes and alphas did not enter the hydrodynamic calculation. The computation was accomplished by the following list of modifications:

- (1) Insert " FOD(40) " in dimension statements.
- (2) Omit "POWNGL" from (7135) and from print statement.

- (3) Insert "FBAR" = 0 after (7135)
 "FALPHA = 0"
 (4) In (9010) omit "FBAR = 0", and move up to insert the order "IF(NH)6800,
 6800, 9014," now after (9011), in its place keeping the number (9010)
 for the moved order.

Move the two orders

```
"DO 9011I = 2,IMAX "
"9011 FBAR = FBAR + T(I) * F(I) "
```

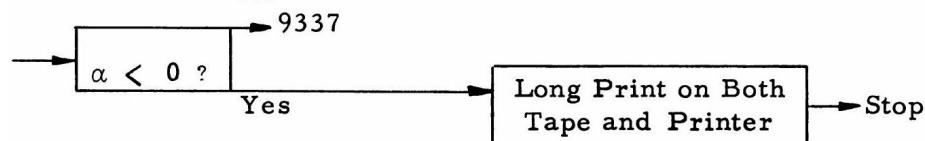
down to just beyond 6800. Then insert "FALPHA" ALPHA"

- (5) Just beyond (6835), insert FOD (I) = F(I)/RO(I)
 (6) In (9070), replace formula for DELQ by "DELQ = FOD(I)*QBAR"
 (7) Omit (9060) +1 through (9065).
 (8) Omit " Z = ALPHA * DELTP"

Insert " Z = FALPHA * DELTP" from just before (9060).

- (9) Between (9330) and (9337), take everything out and replace it by

No



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APPENDIX F. 1

Ax-1 TAPE DUMP AND RECALL ROUTINE

A periodic dumping of the memory from 10000_8 through 17777_8 onto tape #5 has been provided. In case of machine failure, lack of sufficient machine time to complete a problem, a desire to change control parameters, or a desire to continue past the original termination point, a previous dump can be selected and the problem continued from that point. The Tape Dump and Recall Routine occupies positions 140_8 through 165_8 in memory and is loaded by the FORTRAN loader. It was necessary to arrange transfers at appropriate addresses in the main body of the Ax-1 code to the above routine. This was accomplished by inserting at the addresses of formulas 7010 and 9069 a transfer to the tape recall portion of the routine and at the address of formula 9263 a transfer to the tape dump portion of the routine.

Listing of Ax-1 Tape Dump and Recall Routine

		00140	ORG 96	
00140	0	0	REW 5	
00141	-0	00000	PDX 0, 1	(IRCNBR IS IN DEC.
00142	0	00225	RTB 5	OF ACCUMULATOR)
00143	2	00142	TIX 98, 1, 1	
00144	0	00147	TRA 103	
00145	0	00000	TZE 0, 0, 0	
00146	0	00225	WTB 5	
00147	-0	00145	LXD 101, 1	
00150	-0	00000	PXD 0, 0	
00151	-0	00000	CAD 0, 1	
00152	2	00151	TIX	
00153	0	00165	SLW	
00154	0	00165	CLA	
00155	0	00165	CPY	
00156	0	00165	SUB	
00157	0	4	TZE	
00160	0	0	HPR	
00161	0	00205	BST	
00162	0	0	HPR	
00163	0	0	RTB	
00164	0	00147	TRA	
		00000	END	

APPENDIX F. 2

Ax-1 DUMP-TAPE CONSOLIDATION ROUTINE

If many Ax-1 dump tapes are saved in anticipation of restarts, the accumulation of tapes can present problems. In order to have the dumps available and yet avoid keeping a large number of tapes, a routine to combine several tapes into one was written. This routine copies the dumps from individual problems onto one master dump tape, checking both the tape reading and writing processes. Cards for this routine are not included in the Ax-1 deck.

A. Operating Instructions:

Reader: 72 × 72 board.

Punch: Not used.

Printer: Not used.

Tapes: #5-dump tape which is to be added to the consolidated tape.
#3-consolidated tape.

Sense Switches: Not used.

Running Procedure:

1. Ready UA CSB1 Binary Card Loader (3 cards) followed by the Consolidation Routine Deck (4 cards) in the card reader.
2. Mount and ready tapes #5 and #3.
3. Clear and load cards.
4. At stop 2668:
 - a. Enter into the decrement of the MQ the total number (in octal) of records (dumps) on tape #5 to be saved.
 - b. Enter into the address of the MQ the total number (in octal) of records (dumps) already on tape #3.
 - c. Press start.
5. At stop 270_8 , tape #5 has been completely copied onto tape #3. If another tape is to be copied onto tape #3, mount and set it at #5 and follow instructions under 4, omitting step B.

Error Stops:

2458	CKS error in reading tape #5. Press start to try again.
250_8	CKS error in writing or reading tape #3. Press start to try reading tape #3 again. If stop
261_8	CKS error in writing tape #3. Press start to try again.

B. Comments on Dump Numbering:

For a new problem, the dumps are numbered consecutively starting at one. The number of dumps on tape #5 at the time the problem is terminated is equal to the last dump number printed in the on-line output.

For a problem restarted from dump number M , (but not from the consolidated tape), additional dumps are made on tape #5 following dump M and numbered consecutively starting at $M + 1$. Therefore, the total number of dumps on tape #5 at the time the problem is terminated is still equal to the last dump number printed in the on-line output.

For a problem restarted from the consolidated tape the dump number (IRCNBR) specified must be the number of the desired record on the consolidated tape, which is usually not the dump number of the specific problem. Therefore great care must be taken in keeping track of the location and the number of records on the consolidated tape.

Reading in the dump replaces IRCNBR with the dump number of the specified problem. After the dump is completely read in from the consolidated tape, another blank tape should be set at 5 and the consolidated tape removed to avoid destroying dumps from other problems when getting new dumps from the problem being run. Also, it would be wise to manually set IRCNBR = 0 at this time so that the dump numbers from the restarted problem will equal the record numbers on the new tape #5. Depressing S.S. #1 at the start of the problem will cause pause 111 which will enable these changes to be made.
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C. Listing of Ax-1 Dump-Tape Consolidation Routine

	00200	ORG 128	
00200	076300000043	LLS 35	
00201	073400100000	PAX 0, 1	No. of Records on Tape 3
00202	-200000100205	TNX 133, 1, 0	goes to A-Reg.
00203	076200000223	RTB 3	
00204	200001100203	TIX 131, 1, 1	
00205	-073400100000	PDX 0, 1	No. of Records on Tape 5
00206	076200000225	RTB 5	goes to A-Reg.
00207	-053400200265	LXD 181, 2	
00210	-075400000000	PXD 0	
00211	-070000200000	CAD 0, 2	
00212	200001200211	TIX 137, 2, 1	
00213	060200000244	SLW 164	
00214	050000000244	CLA 164	
00215	070000000244	CPY 164	
00216	040200000244	SUB 164	
00217	-010000000245	TNZ 165	
00220	076600000223	WTB 3	
00221	-053400200265	LXD 181, 2	
00222	-075400000000	PXD 0, 0	
00223	-070000200000	CAD 0, 2	
00224	200001200223	TIX 147, 2, 1	
00225	060200000244	SLW 164	
00226	070000000244	CPY 164	
00227	076400000203	BST 3	
00230	076200000223	RTB 3	Read Tape 3 again
00231	-053400200265	LXD 181, 2	to check copying.
00232	-075400000000	PXD 0, 0	
00233	-070000200000	CAD 0, 2	
00234	200001200233	TIX 155, 2, 1	
00235	060200000244	SLW 164	
00236	050000000244	CLA 164	
00237	070000000244	CPY 164	
00240	040200000244	SUB 164	
00241	-010000000250	TNZ 168	
00242	200001100206	TIX 134, 1, 1	
00243	002000000270	TRA 184	
00244	000000000000	HTR 0	
00245	042000000000	HPR 0	Tape 5 read fail -
00246	076400000205	BST 5	try again
00247	002000000206	TRA 134	
00250	042000000000	HPR 0	Tape 3 read or write
00251	-076000000141	SLT 1	fail - try again
00252	002000000254	TRA 172	
00253	002000000256	TRA 174 ₁₀₆	
00254	076000000141	SLN 1	
00255	002000000227	TRA 151	
00256	076000000141	SLN 1	
00257	-076000000142	SLT 2	
00260	002000000262	TRA 178	
00261	042000000000	HPR 0	2nd Tape 3 write fail
00262	076000000142	SLN 2	
00263	076000000222	BST 2	