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A Simplified Scaling Model for the θ-Pinch

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LA-9074-MS

UC-20f
Issued: February 1982

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A SIMPLIFIED SCALING MODEL FOR THE θ-PINCH

by

K. J. Ewing and D. B. Thomson

ABSTRACT

A simple 1D scaling model for the fast θ-pinch was developed and written as a code that would be flexible, inexpensive in computer time, and readily available for use with the Los Alamos explosive-driven high-magnetic-field program. The simplified model uses three successive separate stages: (1) a snowplow-like radial implosion, (2) an idealized resistive annihilation of reverse bias field, and (3) an adiabatic compression stage of a $\beta = 1$ plasma for which ideal pressure balance is assumed to hold. The code uses one adjustable fitting constant whose value was first determined by comparison with results from the Los Alamos Scylla III, Scyllacita, and Scylla IA θ-pinches. The code was first written in 1968 and compared with results from the 1967 shot series at Los Alamos using explosive-driven spiral-generator-powered θ-pinches. The code was primarily applied to short-coil (~25 cm) θ-pinches, so output neutron and x-ray yields were cut off at 2 μs to reduce error from end-loss. More recently, the code has been applied to and compared with results obtained from the Scyllar θ-pinch used for radiation and opacity studies in the mid-1970s. Comparisons of plasma temperature, density, and radius are made at times before the observed onset of instabilities. In general, the code has been able to fit a wide range of the more accurately measured experimental data rather well, predicting measured temperatures to within a factor of 1.6 or better for the applicable laboratory data in the filling density range of 150 to 5000 mtorr. Finally, the code has been used to predict plasma properties that might be achieved with a high-field (~900-kG) θ-pinch that could be driven by plate generators currently in use at Los Alamos.

I. INTRODUCTION

This report summarizes work that was done primarily from 1967 through 1978 to develop and use a simplified one-dimensional model for the fast θ-pinch. In 1967-68, there was an experimental program in Group GMX-6 (now Group M-6) at Los Alamos involving explosive-generator-driven θ-pinch experiments. At that time there was no easily usable theoretical model or code to permit parameter studies and scaling-law calculations that could be compared with experimental results and used in planning. The model described here was designed (in 1967-68) to fill that need. The resulting code, discussed in this report, is basically algebraic in nature and is not a finite difference, differential equation mathematical treatment. It runs in seconds on a computer rather than hundreds or thousands of seconds. It permits parameter studies using one adjustable scaling constant that is determined from experimental data. We have applied the code to capacitor-bank-driven θ-pinches as well as to explosive-generator-driven experiments. Although the adjustable constant was different for the two cases, the scaling was successful to first approximation. The code was calibrated with experimental results from standard short-coil laboratory θ-pinches[1-4] used in the mid-1960s (that is, Scylla III, Scyllacita, and Scylla IA) by the Los Alamos magnetic fusion program. It was then compared with experimental results[5-7] from the 1967 explosive-generator-driven θ-pinch shot series at Los Alamos, which used Sandia National Laboratory (SNL) Model 106 and 169 generators, and was used to give expectations for θ-pinches driven by the higher current generators then being planned.

Later the code was used for prediction and comparison of plasma conditions obtained with the Scyllar[8] θ-pinch used in 1971-77 for radiation and opacity experiments in P-Division. Finally, the code has been used to predict conditions that might be achieved with a very high field (0.9-MG) θ-pinch driven by plate generators currently used by Group M-6.

In recent years, a 1D magnetohydrodynamic (MHD) code, RAVEN,[9] has been developed that treats not only θ-pinches, but also other MHD-driven plasmas (that is, Z-pinches, etc.), much more completely and rigorously. RAVEN solves the basic differential equations involved, allows the various heating mechanisms to overlap, and allows for the proper inclusion of such basic parameters as finite resistivity. The RAVEN code is now expected to predict a θ-pinch much more correctly. However, our code provided a very useful, flexible, and easy-to-use way to predict and compare a very wide variety of experimental θ-pinch results over a number of years; it is being reported on here to summarize these results, comparisons, and predictions. It should provide a useful basis for comparison with the more sophisticated MHD codes. The report also illustrates plasma conditions that could be obtained with short-coil θ-pinches driven by the higher current energy sources now available using plate generator technology.

II. DESCRIPTION OF THE MODEL AND RESULTING CODE

The simplified scaling code was developed in 1967-68. Fitting the code to available experimental data enabled calculation of neutron and x-ray yields that could be expected from scaled-up, higher field, explosive-generator-driven θ-pinch experiments. In particular, the code was geared for easy variation of the input parameters that are thought to be of greatest importance in the plasma compression process, namely, the applied magnetic field, the initial coil voltage, the reverse field, the filling pressure, and the initial radius. Detailed theoretical calculations involving these parameters were not otherwise readily available in the range of values most pertinent to a high-field program.

The code itself was written and operated by K. J. Ewing (Los Alamos Group WX-11). All operations involve straightforward algebraic equations. The code is quite simple and versatile, which facilitates more detailed parameter studies. It has recently been added to the Los Alamos Group WX-11 Code Library (K. J. Ewing, "θ-Pinch Code," WX-11, 1981) and is available for general use.

A. General Description

The model used involves the following considerations.

(1) We assume the heating of the plasma takes place in three separate and independent stages:

(a) a rapid radial motion ($\dot{R}$) snowplow[10]-type stage in which the inward radial motion is converted into kinetic temperature at a time when a dynamic pressure balance is reached.

(b) a reverse field cancellation stage in which conversion of all the reverse field energy into plasma kinetic energy takes place.

(c) a final adiabatic compression stage, during which the plasma is assumed to be a good conductor, β is assumed to be unity, and static pressure balance $B^2/8\pi = (n_i + n_e)kT$ is assumed to hold. A number of calculations were run that deliberately introduced neon (or another appropriate impurity) to augment the x-ray yield. This was done by enhancing the pure bremsstrahlung radiation rate by an arbitrary factor. The temperature was reduced appropriately.

(2) Based on the results of the 1967 explosive-generator-driven θ-pinch shot series,[5-7] the calculations of plasma properties are usually cut off after 2 μs of B-field rise. It is assumed that end-losses can be neglected up to this time and therefore that only the plasma radius need be considered as a space variable. We thus assume that end-loss and instability will destroy the validity of our model after 2 μs. This is obviously an approximation.

(3) We assume collisional equilibrium during the adiabatic compression so that $T_i = T_e$ throughout. We also assume the plasma is homogeneous within the volume defined by the radius R. All results of calculations presented here have been run for, or normalized

to, a θ-coil length of 25 cm.

(4) The principal variable parameters applied to the problem are the initial coil voltage V_θ, the applied magnetic field B (t), the initial ion density n_0, the initial plasma radius R_0, and the initial reverse field($-B_0$). We assume cylindrical symmetry throughout.

(5) During the final adiabatic heating stage, the code prints out the following quantities as a function of time: ion density, plasma radius, plasma temperature, integrated neutron yield, and integrated soft x-ray yield.

The neutron yield is obtained simply by integrating $n_i^2 <\sigma v>$, over time and plasma volume, at the ion temperature T_i, using the currently available D-D cross sections. We assume the soft x-ray yield is purely bremsstrahlung, $\sim n_i^2 \sqrt{T_e}$. When running the problem with a higher Z seed gas (that is, 2% neon, etc.), the pure bremsstrahlung term is multiplied by an arbitrary factor (50, for example).

B. The Ṙ Heating Stage

In describing the initial Ṙ heating stage, we assume an initial condition that includes a fully ionized deuterium (or helium) plasma at a specified starting density at a temperature of about 2 eV, or any other value considered appropriate.

The following general quantities are defined:

t = time,
R = plasma radius,
B = applied axial magnetic field, as a function of time,
T = plasma temperature (assuming $T_i = T_e = T$), and
n = ion density at any time t.

In the Ṙ heating stage, we assume that an initial applied θ-coil voltage V_θ induces an inward radial motion of the plasma with a constant velocity Ṙ. From basic pinch theory,[10] the sheath velocity is proportional to $\sqrt{E}/\rho^{1/4}$, so we write

$$\dot{R}^2 = K_1 V_\theta \left(\frac{100}{P_0}\right)^{1/2} , \qquad (1)$$

where K_1 is a scaling factor to be determined by experiment and P_0 is the fill density in mtorr. In this case K_1 includes the term $1/2\pi R_0$ (because $V_\theta = 2\pi R_0 E_\theta$).

The quantities with the subscript s, namely, R_s, B_s, t_s, T_s, and n_s, are the values of these quantities at the end of the Ṙ heating stage, at which time we set $\dot{R} = 0$.

Next we assume that the end of the Ṙ heating stage is brought about by a dynamic pressure balance of the form

$$2n_s k T_s = \frac{B_s^2}{8\pi} + \frac{\rho \dot{R}^2}{2} , \qquad (2)$$

where ρ is the mass density of the inward moving sheath [assumed to be $n_s x$ (mass/ion)]. The quantity n_s is equated to $n_0 (R_0/R_s)^2$, which expresses conservation of the total number of particles. We included a dynamic pressure term $\rho\dot{R}/2$ to fit the experimental data during preliminary calculations with the code, from which it had been omitted.

The third basic equation of the Ṙ heating stage assumes that the radial directed energy is converted into collisional thermal energy at the time t_s when dynamic pressure balance is achieved; therefore, we write

$$T_s = K_2 \dot{R}^2 \left[1 - \left(\frac{R_s}{R_0}\right)^2\right] . \qquad (3)$$

In Eq. (3) we assume that only those particles actually swept in will have the directed energy, whereas all of the particles must share in the kinetic energy term $n_s T_s$. The constant K_2 is expressed in terms of known quantities (ion mass, etc.) but could, if we desired, include an additional dimensionless fitting factor. In these calculations, all of the fitting is done with the constant K_1. Other straightforward relations between the quantities include

$$\dot{R} = \frac{R_0 - R_s}{T_s} \qquad (4)$$

and

$$\frac{V_\theta}{\pi R_0^2} = \frac{B_s}{t_s} . \qquad (5)$$

Equation (5) assumes that

$$\frac{B_s}{t_s} \cong \left(\frac{dB}{dt}\right)_{t=0}$$

over the small time interval t_s.

We now have five equations with five unknowns: Ṙ, t_s, R_s, B_s, and T_s. These equations are solved simultaneously for each chosen value of K_1 for any given set of parameters.

Note that the code makes no attempt to define the temperature T for $0 < t < t_s$.

C. The Reverse Field Cancellation Stage

The reverse field ($-B_0$) has been ignored during the $\dot{R}$ heating stage, but we assume that all of the initial reverse field is trapped within the plasma area πR^2, and that at the time t_s, all this energy of density

$$\frac{1}{8\pi}\left[B_0\left(\frac{R_0}{R_s}\right)^2\right]^2$$

is converted into particle kinetic energy and added to $2n_sT_s$ to give $2n_sT_s^b$. If the reverse field pressure is greater than $2n_sT_s$, it is set equal to $2n_sT_s$. Otherwise, it is treated as it was above. The value $2n_sT_s^b$ requires a new magnetic field for static pressure balance, and the code lets time run from $t = t_{s'}$ to $t = t_{s'}$ to let this pressure balance occur. During this time, we let the plasma radius expand at the rate $|\dot{R}|$, B increase as the given B(t), n decrease as $(R_s/R)^2$, and T_s^b decrease adiabatically as $V^{-2/3}$ until $B_{s'}^2/8\pi = 2n_{s'}\, kT_{s'}$. The idealized $\beta = 1$ assumption used in the code was suggested by results[2] from Scylla III experiments that showed $\beta = 0.85$ for higher filling pressures (~100 mtorr) with reverse bias field. The $\beta = 1$ assumption represents an upper limit that one may achieve for a variety of θ-pinch parameters during the magnetic confinement stages.

D. Adiabatic Heating Stage

The quantities $B_{s'}$, $T_{s'}$, $n_{s'}$, and $R_{s'}$ now form the initial condition for adiabatic heating caused by further build-up of the applied magnetic field pressure. The adiabatic heating formulas are well known ($\gamma = 5/3$ for a monatomic gas) and may be stated simply as

$$\frac{T}{T_{s'}} = \left(\frac{B}{B_{s'}}\right)^{4/5} \quad \text{to get } T(t), \tag{6}$$

$$\frac{n}{n_{s'}} = \left(\frac{B}{B_{s'}}\right)^{6/5} \quad \text{to get } n(t), \text{ and} \tag{7}$$

$$\frac{R}{R_{s'}} = \left(\frac{B_{s'}}{B}\right)^{3/5} \quad \text{to get } R(t) \text{ and the volume.} \tag{8}$$

The code now calculates and prints out T, n, and R as a function of time and gives the integrated neutron yield and soft x-ray yield as discussed above. The code calculates the adiabatic heating in small time increments (Δt), typically 0.03 μs per increment. At the end of each Δt, the soft x-ray emission rate per cubic centimeter is multiplied by Δt, and this incremental energy loss is subtracted from $(n_e + n_i)\,kT$ by reducing kT. Then the adiabatic heating is applied for the next time increment and the process is repeated. The result is that when the radiation emission rate is substantial, the temperature drops to lower values and the density increases to higher values than those obtained from pure adiabatic compression alone. The high radiation rates also have the effect of reducing the plasma radius to provide the higher densities required to maintain $\beta = 1$ pressure balance.

The code is written in mks and these formulas are written in cgs. The basic difference is that cgs formulas use terminology involving $1/8\pi$ and mks formulas use $2\mu_0$. Those who read the code in the Appendix will notice this. Figure 1 shows the equations and illustrates the model.

The equation for pressure balance for deuterium as discussed previously in Sec. II. A is $B^2/8\pi = 2n_ekT_e$ in cgs units, because $n_e = n_i$ and $T_e = T_i$ (assumed). If we use fully ionized helium, $B^2/8\pi = (2n_i + n_i)kT_i = 3n_ikT_e$. If we use helium with 2% neon, $B^2/8\pi = (2.14\, n_i + n_i)kT_i$ as discussed in Sec. III. C. Figure 2 plots the pressure balance equation for deuterium and shows magnetic field versus electron density with temperature as a parameter. If the deuterium graph is used for pure helium, it will give the correct answer for an electron density $2/3 = 0.667$ times the correct helium electron density. For helium with 2% neon, the factor is $2/3.14 = 0.637$. In using the code as written, one must specify either the "deuterium deck" or the "helium deck" to assure that the correct ion masses are used for the input parameters. The code can be modified easily for any other desired ion mass.

All our work with Scyllar, discussed in Sec. III. C, would appear, if plotted, in the lower left-hand region of Fig. 2. We discuss some work in Sec. IV called "New Regimes"; this data if plotted would appear in the middle of Fig. 2. The upper right-hand corner has not been studied experimentally with θ-pinches.

III. COMPARISON WITH EXPERIMENTAL DATA

A. Early Laboratory θ-Pinches Used to Determine the Fitting Constant

For purposes of testing the applicability of our scaling model, as represented by Eqs. (1)-(8), we used the

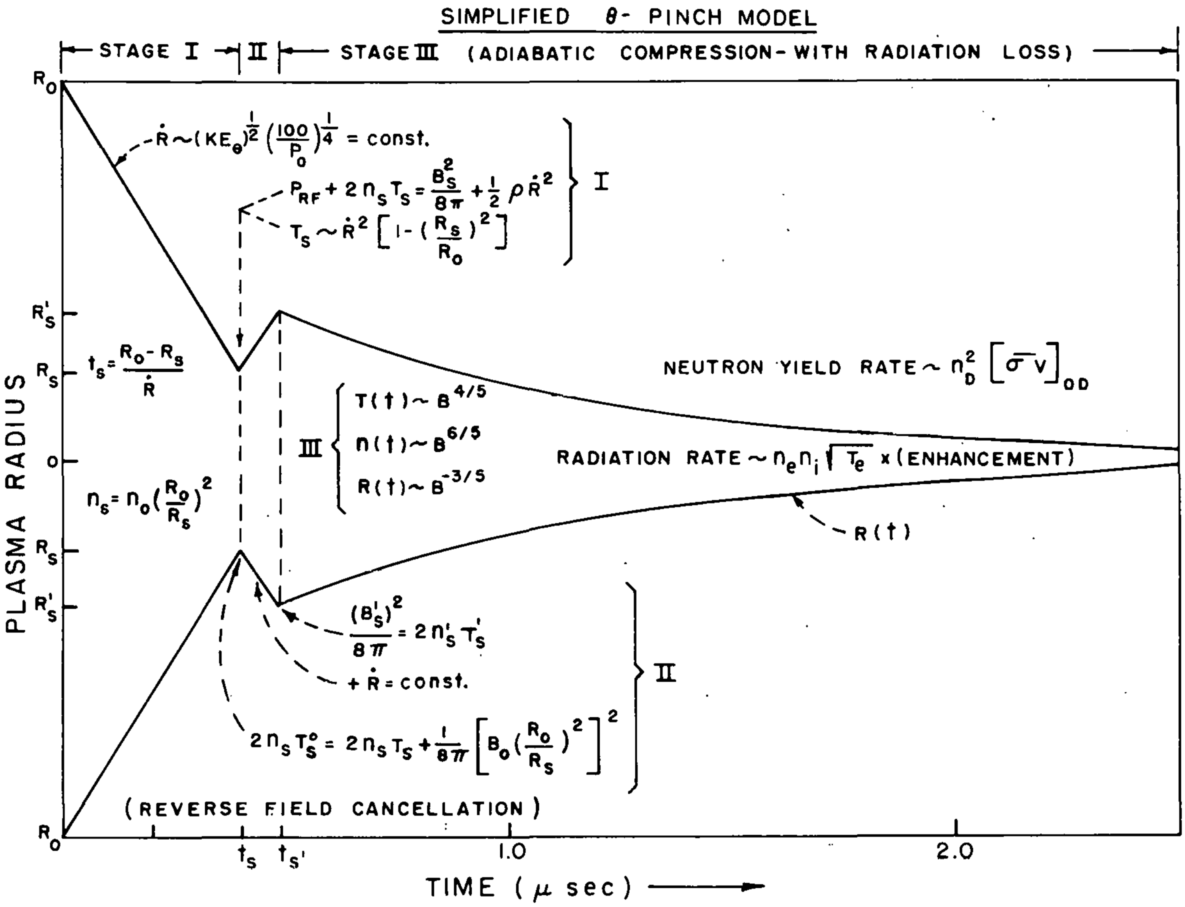

Fig. 1. Schematic diagram of simplified θ-pinch scaling model.

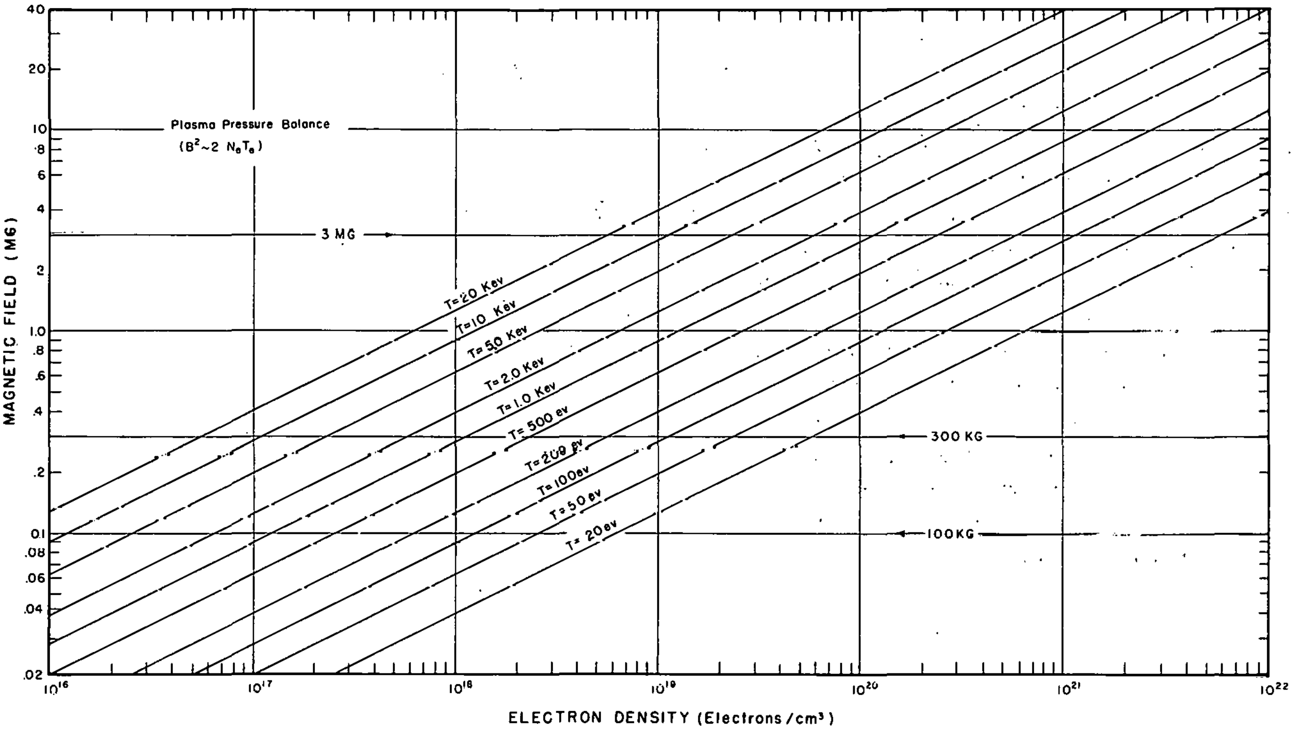

Fig. 2. Family of pressure balance curves for $\beta = 1$ deuterium plasma.

experimental results from Scylla III,[1,2] Scyllacita,[3] and Scylla IA.[4] These three θ-pinch experiments involved similar coil dimensions (length ~19-25 cm, i.d. ~7-8 cm), similar ceramic discharge tubes, and similar $\dot{B}_z$ preionization. The compression field risetimes were short in all three cases (1.75 to 3.0 μs). The maximum values of V_θ ranged from ~18 to 55 kV and peak fields ranged from 50 kG to ~125 kG. For all three machines, first-half-cycle data are available. Laboratory data has shown that the containment times in these experiments ranged from 2.0 to 3.0 μs and that the neutron yield rate half-widths do not exceed 2.0 μs.

These experiments can thus be compared with each other for purposes of comparing results of calculations of our code as a function of the principal scaling parameters V_θ, B(t), n_0, and ($-B_0$).

In using the code, we looked for a value of the fitting constant K_1 [Eq. (1)] that resulted in a best fit of the observed neutron yields over the range of values of B and V_θ.

After making a number of runs with the code, we concluded that the laboratory data[1-4] were best fit (as illustrated in Fig. 3) for a fitting constant, $K = 8 \times 10^5$, in the units used in the code. As explained previously, these units are mks rather than cgs. The calculated cases 1, 2, and 3 use the value of $K_1 = 8 \times 10^5$. The experimental yields for these cases represent the optimum (warmed-up tube) yield for each θ-pinch device. Figure 3 shows that our code tends to slightly underestimate the neutron yield for each case. This may occur because the code keeps $T_i = T_e$, although in practice $T_i > T_e$ for the same pressure balance. In general, we believe the scaling shown by the calculated cases 1, 2, and 3 in Fig. 3 fits the data rather well. Not shown in Fig. 3 are the cases for the Los Alamos Group GMX-6 Bank B θ-pinch[11] for which the first half-cycle measured T_e was ~285 eV, and the code-predicted value was ~240 eV at 60 μm. In addition, the observed T_e was ~60 eV, and the code-predicted value was 90 eV at 400 μm. These calculations also used the same value of $K_1 = 8 \times 10^5$ and predicted negligible (or zero) neutron yields, as observed, on first half-cycle. Also not shown are the rather good comparisons of the code-predicted variation of the normalized neutron yields with the observed variations as a function of reverse field and main bank voltage for Scyllacita data.[3]

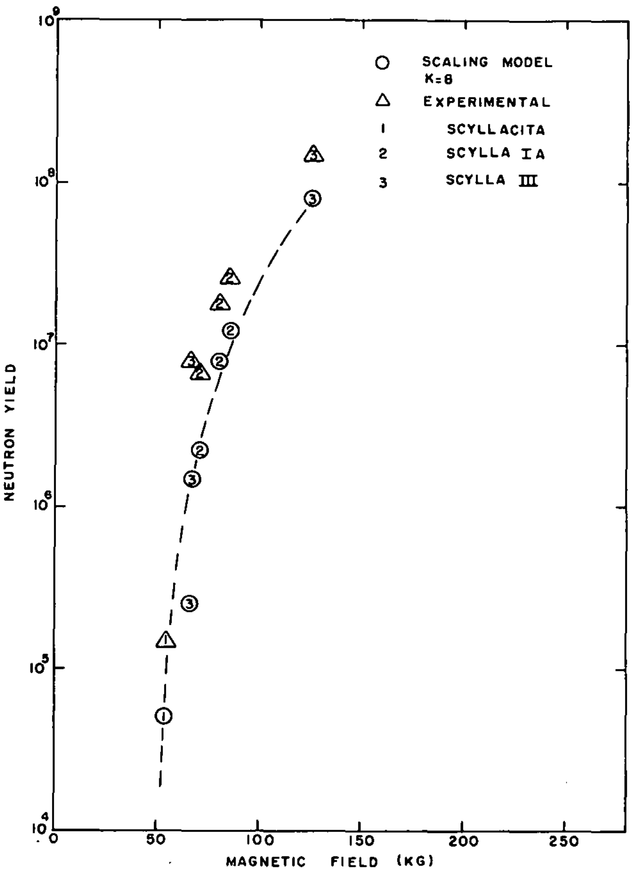

Fig. 3. Plot of neutron yield vs magnetic field by scaling model calculation compared with experimental results for Scyllacita, Scylla III, and Scylla IA. The fitting constant is $K_1 = 8 \times 10^5$.

B. Explosive Generator θ-Pinch

Figure 4 shows how K_1 was determined from the firing-point data from the 1967 explosive-generator-driven θ-pinch shot series.[5-7] The best yielding shots, involving the standard 25-cm coil length, are included. A value of $K_1 = 5 \times 10^5$ fits the high-yield case for Model 169 (shot 9) and is bracketed by the two good Model 106 yields (shots 2 and 5). Thus a value of $K_1 = 5 \times 10^5$ is chosen to fit the firing-point data.

The fact that a somewhat lower value of K_1 appears to fit the firing-point data than that which fits the laboratory data is not unreasonable because the discharge tubes used for explosive shots were never thoroughly conditioned. There is ample available evidence that warm-up

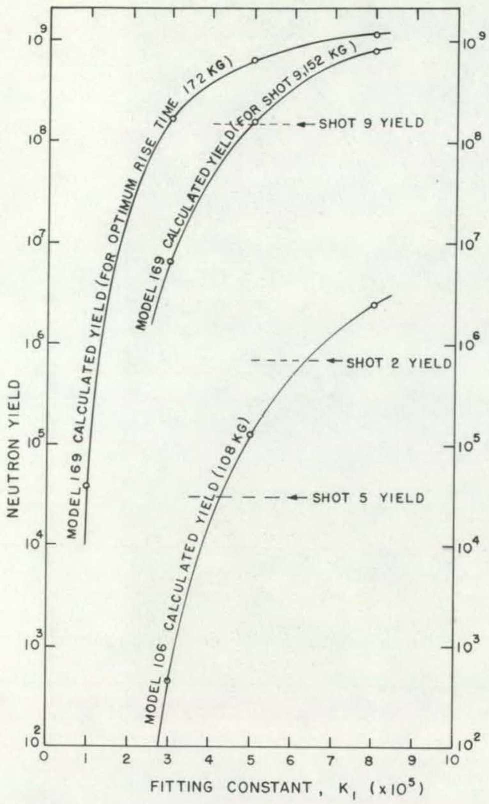

Fig. 4. Plot of neutron yield vs fitting constant for θ-pinch driven by Model 106 and 169 generators.

and tube conditioning play a vital role in observed neutron production. The available evidence indicates that tube-wall conditioning affects the formation of the initial $\dot{R}$ sheath, whose behavior, according to Eq. (1), is described in part by K_1.

Figure 4 also shows the calculations of yield vs K_1 for a case in which the Model 169 optimum current risetime, achieved on shot 7 in a 35-cm coil, is assumed to give 172 kG in 2 μs with a 25-cm coil. No experimental data point to compare with this particular case was fired during the 1967 series, but the curve plotted in Fig. 4 shows dramatically how yield varies with K_1. Because by Eq. (1), $\dot{R}^2 = K_1 V_\theta$, if one lets K_1 stay fixed, then yield vs V_θ would have the same shape as the curves in Fig. 4; one can see the importance of V_θ at the lower values. One can also see that as V_θ increases for a given B-field and coil diameter, the increase in yield begins to saturate and eventually peak B-field becomes the limiting factor.

C. Scyllar θ-Pinch

Scyllar was a θ-pinch used for a variety of experiments including radiation studies, opacities, and atomic processes in high-temperature plasmas. It is described in detail in Refs. 8 and 12. Scyllar results are given in Refs. 8 and 12-18. As described in Ref. 8, the θ-pinch was driven by an axial field of ~90 kG, with a risetime (quarter period) of 3.0 μs in a 25-cm-long, 8.2-cm-i.d. θ-coil. The energy for the θ-pinch was a low-inductance, high-energy (~180 kJ) capacitor bank consisting of 54 capacitors (60 kV, 1.8 μF), each switched with a low-inductance four-electrode spark gap. In the feasibility experiments,[8] the θ-pinch typically was operated with gas fills of 1-2 torr of deuterium or helium and seeded with a few percent neon or other high-Z element. The emission spectra were observed with vacuum ultraviolet (VUV) spectrometers as a function of the seed element and pinch conditions. This Scylla-like θ-pinch was called Scyllar to indicate the radiation studies for which it was intended.

In the earlier experiments,[8,12,13] a pulsed linear discharge of ~20 kA was used for preionization and applied ~37 μs before the start of the main axial drive field. Ceramic discharge tubes were used with the linear discharge preionization because the thin-walled (2-mm) quartz tubes we tried first often cracked or broke. In later experiments,[14-18] preionization was obtained with a $\dot{B}_z$ discharge from two capacitors (0.75 μf, 50 kV each) into the main θ-coil about 30 μs ahead of the main drive field. With this preionization and with a crowbar applied to the main bank current at the peak of the first quarter cycle, thick-walled (4-mm) quartz tubes could be used without breakage for hundreds of shots using the full bank. [We used the quartz tubes successfully for thousands of shots in other experiments where operation with only one-third the bank was required at lower fill densities (≤150 mtorr).]

Scyllar was used for a variety of experiments involving radiation studies and atomic processes. When it was operated with 18 capacitors (one-third bank), several thousand shots of plasma data were obtained yearly with a minimum of bank maintenance. For this case, the axial drive field rose to 45 kG with a quarter period of 2.0 μs (crowbarred at peak current) in the standard θ-coil (25 cm long, 8.2 cm i.d.) with the vacuum LOS radial viewing port. Figure 5 shows a photograph of Scyllar

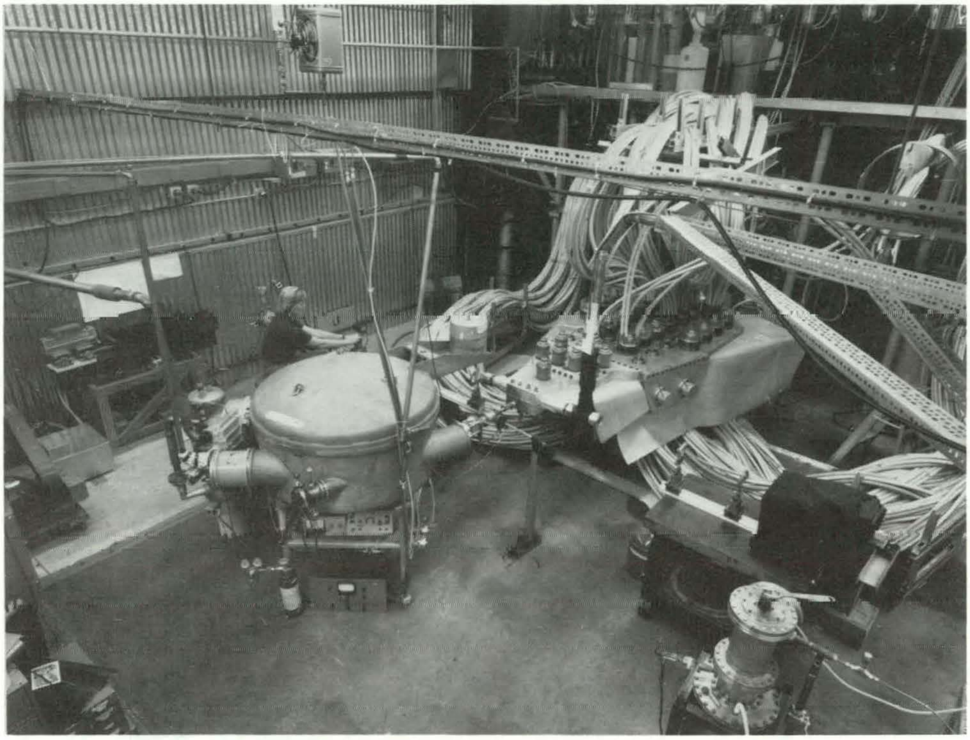

Fig. 5. Photograph of Scyllar θ-pinch.

after it was moved to a dedicated building, SM-316, in 1973.

Because the Scyllar plasma was diagnosed in considerable detail over a wide range of filling pressures and other conditions, we use these results to compare with calculations from our scaling model.

In the first[8] Scyllar experiments, a pure deuterium fill gas was used over a wide range of filling densities to check the general operation of the θ-pinch. Full bank operation (90 kG) and a bias field of −1.5 kG were used. The two-foil soft x-ray technique was used[8] to measure the electron temperature. Figure 6 shows the measured values of T_e vs filling pressure over a range of pure deuterium filling pressures of 100 to ~1700 mtorr. We measured temperature values of ~600 eV to ~40 eV. The smooth curves represent theoretical predictions of T_e vs filling pressure computed with this code. Code calculations are given for the assumption that the radiation loss is bremsstrahlung of pure deuterium ($D_2 \times 1$) and for radiation enhancement of arbitrary amounts, that is, $D_2 \times 50$, $D_2 \times 100$, etc., as is expected with high-Z seeding or with impurities. The case $D_2 \times 50$ means, for example, that the deuterium bremsstrahlung radiation is enhanced by a factor of 50. The scaling model appeared to provide a rough guide to the variation of T_e vs filling pressure for deuterium.

The data for helium-base gas fill from the eight papers[8, 12-18] are summarized in Table I. Experimental initial gas pressures range from 5000 to 16 μm, more than two orders of magnitude. The measured electron temperatures vary from 9.4 to 415 eV. The measured electron densities vary from 30.0×10^{17} cm^{-3} to 0.21×10^{17} cm^{-3}. The low-density plasmas have the high electron temperatures and vice versa. The θ-pinch was a dynamic process with a useful lifetime of about 1-3 μs in these experiments. Instabilities generally terminated the useful plasma lifetime. The time at which the experimental data was recorded varied, and considerable variations in experimental parameters occur as a function of time.

The electron temperature and density were measured in the experiments. The ratios of calculated to experimental values are given in Table I as a measure of the quality of the code. The code assumes that the electron temperature is equal to ion temperature. This is not true, especially for low-density plasmas. The approximation becomes better as the plasma density increases. The comparison of calculation with experiment generally is better above 100 mtorr. Allowing for the simplicity and ideal assumptions of our θ-pinch model, we consider that agreement within a factor of 2 with experiment is reasonable.

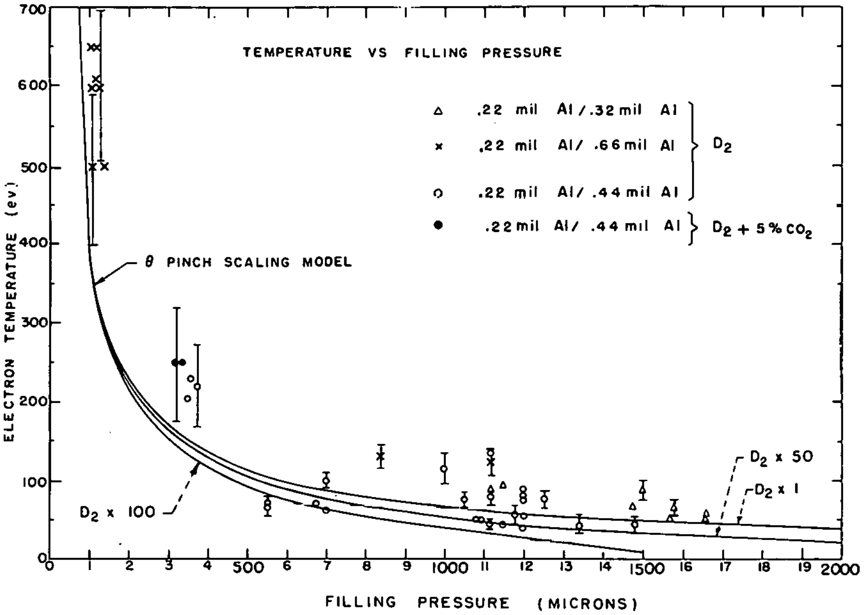

Fig. 6. Plot of electron temperature vs deuterium filling pressure for Scyllar at 90 kG (full bank). The bias field was −1.5 kG. Smooth curves are scaling model calculations, and plotted points are measured temperature at about 1.6 μs using the two-foil soft x-ray technique.

The conservation of mass equation in the calculation uses ion density because ions are so much heavier than electrons. Electron density is a derivative number. Pure fully ionized helium contains two electrons per ion. Using 2% neon adds electrons to the plasma, and we calculated 0.02 times 7 electrons/neon ion equal to 0.14. Thus, the calculations for helium with 2% neon have 2.14 electrons per ion (using Ne VIII as the predominant neon ion stage.)

In the calculations with the helium code used in Table I, we arbitrarily used $K_1 = 10.5 \times 10^5$ for the fitting constant. This value appeared to fit the data as well as or a little better than the value $K_1 = 8 \times 10^5$ used for the deuterium data, but no attempt has been made to optimize the K_1 value (probably $K_1 \sim 9 \times 10^5$) for the Scyllar helium data.

Table II gives numerical counts of the data points as a measure of the comparison between the calculations in Table I and the experiment.

The probability is about two-thirds that a particular calculation will match experiment within a factor of 2 either way over the total range of the experimental data. One can say approximately that the standard deviation is thus a factor of 2. For filling densities ≥150 mtorr, the measured and calculated electron temperatures agree to within a factor of 1.6 or better. A number of calculations are plotted in Figs. 7-11 to give visual comparison with typical experimental data. Table III lists the individual cases that are plotted in Figs. 7-11. We can make several observations or comments.

(1) The experimental temperature data in Fig. 10 probably represent scatter rather than a systematic shape. The code predicts both the radius and approximate temperature rather well considering the expected effects of finite resistivity at $T_e \sim 10$ eV.

(2) The experimental time history of the radius in Fig. 11 varies from the calculation and probably represents a physical reality that is not in the code. The gas pressure initially is 1000 μm. The code assumes that the gas behaves smoothly and uniformly as the plasma compresses, but we expect that the effect of shock waves will produce results not accounted for in our simple model. Also, the code assumes ideal electrical conductivity, whereas in fact we have a resistive plasma with finite sheath thickness, particularly at the lower temperature (≤25 eV).

Considering the ideal assumptions, the code has served as a rather useful guide for expected θ-pinch behavior over a wide range of experiments.

Table I. Comparison of Electron Temperatures. Calculations[a] vs Experimental Measurements (Scyllar)

B_{max} (kG)	T/4 (μs)	Fill Press (mtorr)	Species	t (μs)	$T_{(exp)}$ (eV)	$T_{(code)}$ (eV)	$\frac{T_{code}}{T_{exp}}$	$n_{e(exp)}$ $\times 10^{17}cm^{-3}$	$n_{(code)}$ $\times 10^{17}cm^{-3}$	$\frac{n_{(code)}}{n_{exp}}$	Ref.
45	2	16	He + 2% Ne	1.0	215	606	2.83	0.25	0.28	1.12	18
45	2	16	He + 2% Ne	1.5	370	748	2.03	0.27	0.39	1.45	18
45	2	16	He + 2% Ne	2.0	240	793	3.31	0.45	0.43	0.96	18
45	2	16	He + 2% Ne	2.5	220	745	3.39	0.40	0.40	1.00	18
								1.90		0.24	
45	2	20	He + 2% Ne	1.4	415	621	1.50	1.02	0.45	0.44	15
								1.15		0.30	15
45	2	20	He + 2% Ne	1.04	225	530	2.36	0.70	0.34	0.49	
								0.58		0.36	15
45	2	20	He + 2% Ne	0.66	165	390	2.37	0.35	0.21	0.60	
								0.25		0.44	
45	2	20	He + 2% Ne	0.38	145	260	1.79	0.21	0.11	0.52	15
45	2	150	He + 2% Ne	1.00	130	122	0.94	1.00	1.39	1.39	16
45	2	400	He + 2% Ne	0.55	34	41	1.21	1.46	1.43	0.98	13
90	3	780	He + 2% Ne	0.80	45	50	1.11	6.2(5)	4.32	0.70	12
90	3	1000	He + 2% Ne	0.58	25	34	1.36	9.0	3.50	0.39	17
90	3	1040	Pure He	1.0	33	53	1.61	7.4	6.2	0.84	8
90	3	1040	Pure He	1.8	45	78	1.73	7.4	5.6	0.76	8
90	3	2000	Pure He	1.0	30	34	1.13	7.4	9.6	1.30	8
								22.		0.30	
45	2	3000	Pure He	0.7	9.4	13.5	1.44	15.	6.6	0.44	14
								27.		0.29	
45	2	3000	Pure He	0.8	14.7	14.8	1.01	18.	7.8	0.43	14
								17.		0.52	
45	2	3000	Pure He	0.9	12.1	16.0	1.32	12.	8.8	0.73	14
								30.		0.35	
45	2	5000	Pure He	0.8	16.4	10.8	0.66	26.	10.6	0.41	14
								26.		0.46	
45	2	5000	Pure He	0.9	15.4	11.7	0.76	24.	12.0	0.50	14
								22.		0.61	
45	2	5000	Pure He	1.0	19.9	12.4	0.62	16.	13.4	0.84	14
								18.		0.82	
45	2	5000	Pure He	1.1	18.8	13.2	0.70	12.	14.8	1.23	14

[a] $K = 10.5 \times 10^5$.

TABLE II. Data Comparisons

Number of	that compare within a factor of 2	that compare greater or less than a factor of 2	Totals
Electron Temperatures	16	6	22
Electron Densities	15	8	23
Totals	31	14	45/45

TABLE III. List of Figures Comparing Theory and Experiments for Scyllar θ-Pinch

Figure No.	n_e	Reference
7	high	12
8	low	16
9	medium	13
10	high	14
11	high	17

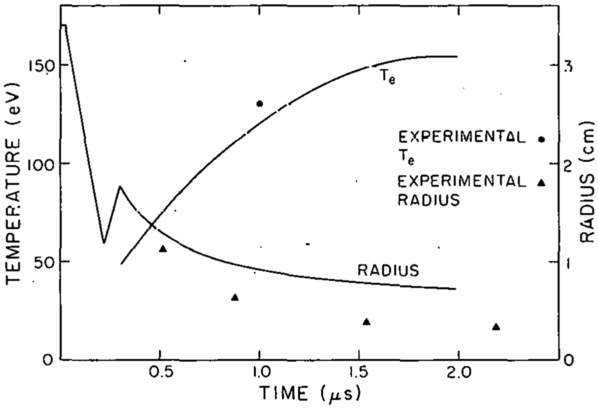

Fig. 8. Plasma temperature and radius vs time for Scyllar operated at 45 kG with a fill of helium + 2% neon at 150 mtorr. The smooth curves are the code calculations. Plotted points are experimental values.

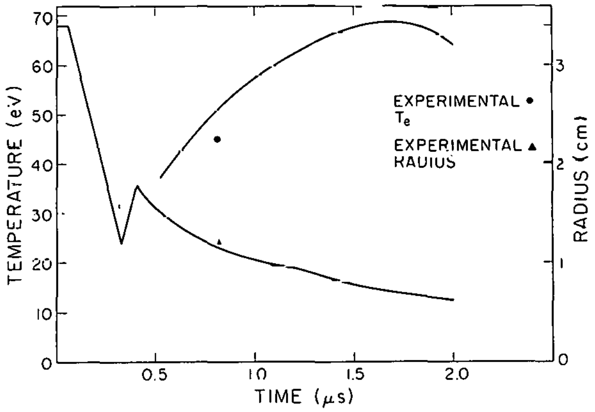

Fig. 7. Plasma temperature and radius vs time for Scyllar operated at 90 kG with a fill of helium + 2% neon at 780 mtorr. The smooth curves are code calculations. Plotted points are experimental values.

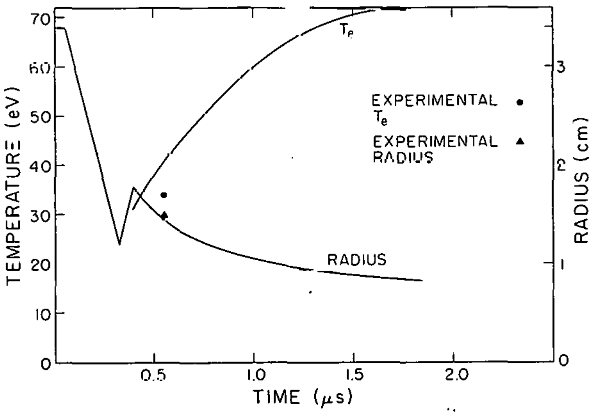

Fig. 9. Plasma temperature and radius vs time for Scyllar operated at 45 kG with a fill of helium + 2% neon at 400 mtorr. The smooth curves are code calculations. Plotted points are experimental values.

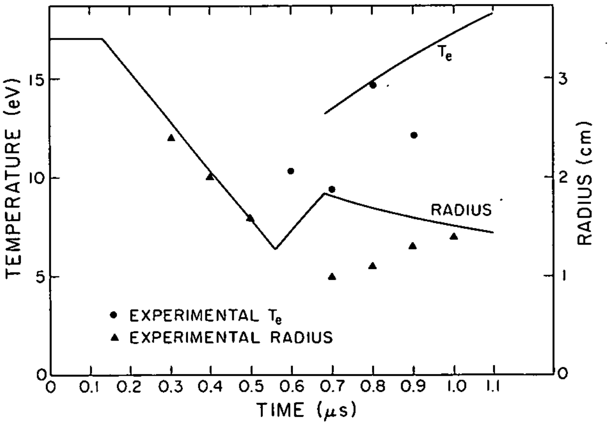

Fig. 10. Plasma temperature and radius vs time for Scyllar operated at 45 kG with a fill of helium at 3 torr. The smooth curves are code calculations. Plotted points are experimental values.

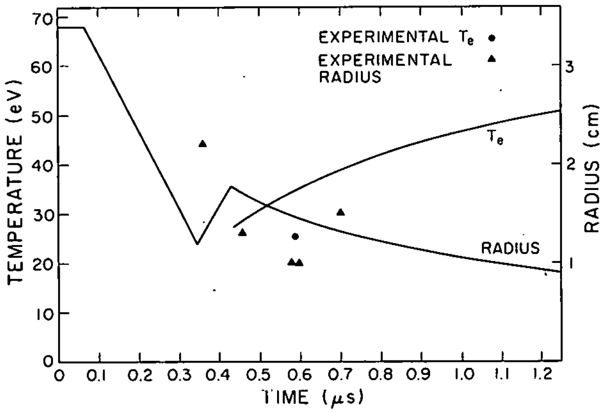

Fig. 11. Plasma temperature and radius vs time for Scyllar operated at 90 kG with a fill of helium + 2% neon at 1.0 torr. The smooth curves are code calculations. Plotted points are experimental values.

IV. NEW REGIMES

A. Drive Field of 550 kG

Calculations were made in 1968-69 for a family of explosive-spiral-generator-driven θ-pinches for which the drive field was assumed to go from 0 to 550 kG in 2 μs. Figure 12 shows plots of plasma temperature and radiation yield as a function of filling pressure for several choices of reverse field and enhanced radiation rates. For the calculations in Fig. 12, V_θ was assumed to be 100 kV, the tube i.d. was 6.5 cm, and the fitting constant (K) was 5×10^5. Figure 12 illustrates that higher fields should make possible emission of a given yield of radiation at higher plasma temperatures. For example, at 3000 μm, with a radiation enhancement factor of 50, the radiation yield is 21 kJ with a plasma temperature of 300 eV. The electron density will be $\sim 10^{19}$ cm^{-3}. There are several cases for which, at a plasma temperature of 50 eV, the radiation yield is as high as 50 kJ. The drive conditions given for Fig. 12 represent a significant extrapolation from experiments previously performed.

We originally expected to develop an explosive-driven generator that would achieve these conditions (B = 550 kG, risetime ≅ 2.0 μs, and $V_\theta = 100$ kV) from experience gained with the SNL Dual Model 169 generator system, which consisted of two single Model 169 generators operated in series. After several tests, this system was abandoned in 1968 because of internal high-voltage breakdown problems.

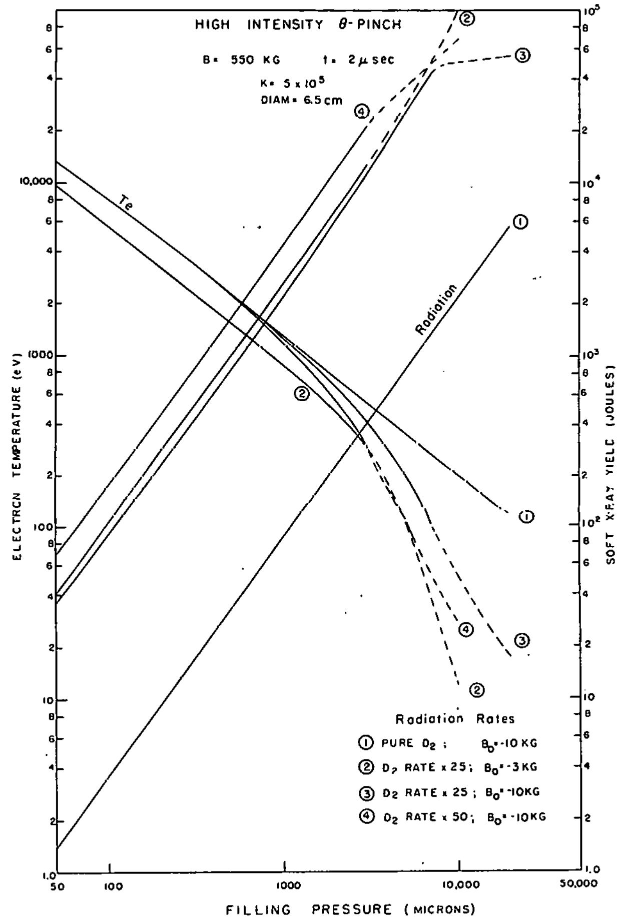

Fig. 12. Plasma temperature and soft x-ray yield calculated as a function of deuterium filling pressure for the case of a θ-pinch driven by an explosive generator expected to create a 550-kG field in a 25-cm-long θ-coil switched with a V_θ of 100 kV.

B. Plate Generator Driven 900 kG θ-Pinch

In the mid-1970s, explosive-driven high-current plate generators were developed[19] extensively at Los Alamos in Group M-6. Such plate generators[19,20] are generally less complex, involve less high explosive, and reach the desired high multimegaampere currents more readily than spiral generators of the type used in the 1967 shot series (Sec. III. B). Using a typical plate generator output, we calculated a field vs time dependence (Ref. 21) for a θ-coil 25.4 cm long and 7.6 cm i.d. This B(t) curve is shown in Fig. 13. The generator output is switched into the θ-coil 2 μs before generator burnout. At switch time, V_θ is about 50 kV, and the B-field rises from 0 to 900 kG in 2 μs.

Figure 14 shows the ion temperature and plasma radius predicted by the θ-pinch scaling model for the case of deuterium fill of 50 mtorr and a bias field of −2 kG, using the drive field system of Fig. 13. A value of $K_1 = 8 \times 10^5$ is used, assuming optimum warm-up. In the case of Fig. 14, the code predicts a temperature of 10 keV at 2.0 μs, a density of $\sim 9. \times 10^{17}$ ion cm^{-3}, and an integrated DD neutron yield of 3×10^{11} neutrons. If the generator plates are widened to make higher currents possible so that the B(t) and V_θ of Fig. 13 would be reached in a 1-m-long coil, plasma containment could be extended to 3 or 4 μs, and a neutron yield of $\sim 3 \times 10^{13}$ (DD) could result. If a deuterium tritium mixture were used, a neutron yield of $\sim 3 \times 10^{15}$ would be predicted. This case would fall short of energy breakeven by a factor of $\lesssim 100$ because of the large ratio of (field volume)/(plasma volume), but it would make possible a study of fusion conditions.

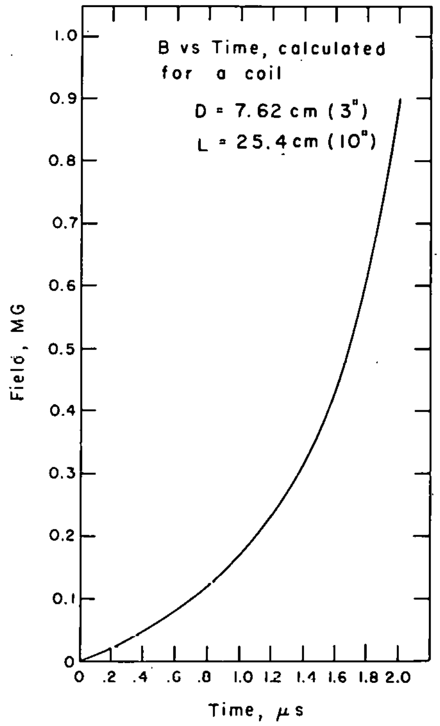

Fig. 13. Magnetic field vs time in a θ-coil (L = 25.4 cm, i.d. = 7.62 cm) calculated from plate generator data. The calculation gives a switch voltage V_θ = 50 kV for this case.

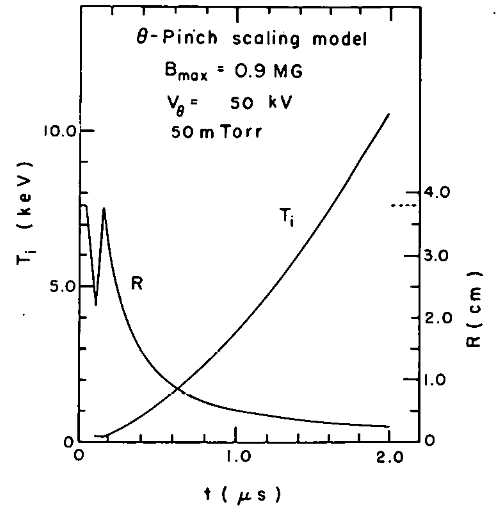

Fig. 14. Plasma temperature and radius vs time calculation for a θ-pinch driven by the magnetic field system of Fig. 13. The curves are calculated with the scaling model code using a fill of deuterium at 50 mtorr.

If the field system of Fig. 13 is used with a high-pressure deuterium fill using a high-Z seed gas, radiation and atomic properties of highly stripped high-Z atoms may be studied, as they were with Scyllar. As an example, Fig. 15 shows the code predictions for the case of a fill gas 1.0 torr deuterium with a small percentage of seed gas in a 25-cm-long θ-coil. In Fig. 15, an electron temperature of 1.0 keV is reached at a density of $\sim 10^{19}$ ions cm^{-3}. The plasma radiates 10-20 kJ of soft x rays.

A principal impediment to achieving the maximum conditions of Fig. 15 might be the effect of instabilities as observed at ~1.0 μs on Scyllar[8,14] at high helium fill pressures. Further study is needed to determine the range of parameters, including fill gas and seed species, for stability for high-density regimes such as those represented by Fig. 15.

If achieved, the plasma of Fig. 15, for example, could be used for opacity[17] studies if sufficient diagnostics are applied. Ionization rates,[15] line broadening,[14] and other[18]

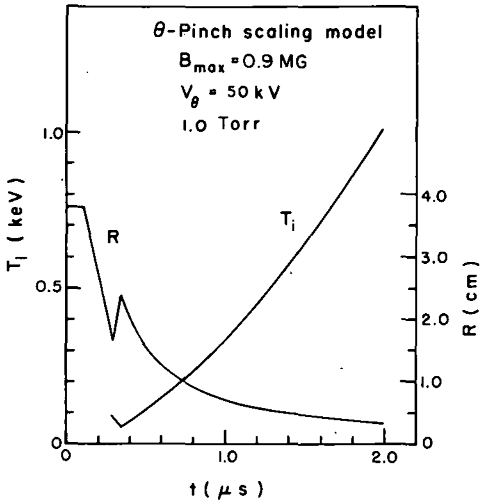

Fig. 15. Plasma temperature and radius vs time calculated for a θ-pinch driven by the magnetic field system of Fig. 13. The curves are calculated with the code using a fill of deuterium at 1.0 torr.

atomic properties might also be studied in a definitive way at unique conditions with such a plasma, taking advantage of the relatively homogeneous temperature and density generally obtainable with θ-pinch plasmas. The plate generator could make achievement of these unique conditions relatively inexpensive per shot.

V. SUMMARY

A simple θ-pinch scaling model has been written into an inexpensive computer code and used to calculate plasma radius, temperature, density, neutron yields, and radiation rates for a large variety of short-coil ($\ell \cong 25$ cm) θ-pinches used at Los Alamos over the past two decades.

The model assumes that the effects of V_θ drive voltage, reverse field cancellation, and adiabatic compression may be separated and treated in a simple way. End-losses are neglected for 2 μs. A $\beta = 1$ plasma and perfect conductivity are assumed.

The one scaling constant in the code was calibrated using results from Scylla III, Scyllacita, and Scylla IA, and compared with results from the explosive-generator-driven θ-pinch shot series conducted in 1967 at Los Alamos using the SNL Model 106 and 169 generators. Code calculations and comparisons are then given with results obtained in 1971-77 with the Scyllar θ-pinch as used for studies of opacities and atomic properties. The Scyllar comparisons are made over a wide range of operating conditions for extensively diagnosed plasmas. The simple scaling model code generally predicted temperatures, densities, and/or neutron yields correctly within a factor of 2 or better within its range of validity for all of these experiments, using one scaling constant value ($K = 8$) for all deuterium laboratory data, $K = 10.5$ for helium data, and a reduced value ($K = 5$) for explosive firing-point data.

Finally, typical conditions are calculated that might be achieved in similar θ-pinches driven to 900 kG in 2 μs by explosive-driven plate generators recently developed within the Los Alamos high-magnetic-field program. These cases represent regimes of plasma temperatures and densities [(10 keV, 10^{18} cm^{-3}) and (1 keV, 10^{19} cm^{-3})] much higher than those studied in any previous θ-pinch experiments.

ACKNOWLEDGMENTS

The support, encouragement, and helpful suggestions of C. M. Fowler throughout the entire course of this work are greatly appreciated. The contributions of L. A. Jones and E. Källne to the Scyllar diagnostics were invaluable. Discussions over the years with G. A. Sawyer, W. E. Quinn, and other members of the Los Alamos CTR program have been most helpful.

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APPENDIX

FORTRAN CODE

Los Alamos Identification
No. LP-1356

Deuterium

```
C     ALGEBRAIC SOLUTION OF THETA PINCH EQUATIONS
C     USING THOMSONS THEORY.  THE INPUT DATA
C     IS THE VOLTAGE PULSE, THE MAXIMUM MAGNETIC
C     FIELD AND ITS TIME TO MAXIMUM ASSUMING
C     SINUSOIDAL.   THE PLASMA IS DEUTERIUM WITH GAMMA=1.667
C     AND THE MOLECULAR WEIGHT=4.003
C     C6 IS THE EXTRA IONIZED PARTICLES ADDED TO THE
C     PURE GAS. C6=1 IS ONE MORE ELECTRON DUE TO
C     IMPURITIES. C6 FRACTIONAL IS PERMISSIBLE.
C     THE NEUTRON AND XRAY YIELD IS CALCULATED PER METER ADIABATIC CALC
C     THE EXPERIMENTAL NEUTRON YIELD IS THE MEASURED YIELD FOR THE
C     LENGTH OF THE TUBE. STATISTICS ARE DONE WITH YIELD$LENGTH CALC.
C                         THE INITIAL PRESSURE,
C     TEMPERATURE(K), RADIUS ARE REQUIRED.  ALL
C     UNITS ARE MKS EXCEPT FOR INITIAL PRESSURE IN MICRONS.
C     100  MICRONS EQUAL 100  MILLITOR OR 100  MT
C     TWO UNDETERMINED
C     CONSTANTS C4=1. INITIALLY AND C5 TO
C     BE DETERMINED FROM EXPERIMENTAL DATA.
C     REVERSE FIELD PUT IN   IF NEGATIVE THEN USES SECOND HALF CYCLE
C        OPERATION AND REVB(J) IS SET EQUAL TO ZERO.
C     READ IN EXXRA INITIALLY NEGATIVE
C     EXXRA IS XRAY AUGMENTED YIELD
C                                  FORMULAS
C      TEST   FORMULA                               CONSTANT
C        1    C5*VTHETA/EMOLES**1.5                 4.0E-07    LOW
C        2    C55*VTHETA**2/EMOLES**3               6.5E-23   ERRATIC
C        3    C555*VTHETA                           5.35E&05    LOW
C        4    C55*RR*VTHETA/EMOLES                  3.33          LOW
C        5    C55*RR*VTHETA/SQRT(EMOLES)            3.33E&01    LOW
C        6    C55*RR*VTHETA*SQRT(EMOLES)            6.0E&12    LOW
C        7    C55*RR*VTHETA*EMOLES                  6.0E&16    LOW
C        8     C555*VTHETA*     (SQRT(100./PO(J)))
C
C        IF TEST1=1 USES BSS=CONST7*T
C        IF TEST1=2 USES BSS=BMAX(J)*SIN(OMEGA*T)
C        FIELD CAUSED BY GENERATOR     SPIRAL
C        IF TEST1=3 USES BSS=BMAX(J)/TAU(J)*SQRT(T*(2.0*TAU(J)-T))
C        FIELD CAUSED BY GENERATOR     PLATE
C     IF TEST1=4 USES BSS=BMAX(J)*(T/TAU(J))**2.0
C
C        IF TEST2=1 GO FROM REVERSE FIELD ABSORPTION DIRECTLY TO
C                   ADIABATIC COMPRESSION.
C        IF TEST2=2 GO FROM REVERSE FIELD ABSORPTION TO AN EXPANSION
C                   PHASE UNTIL PRESSURE BALANCE AND THEN GO TO
C                   ADIABATIC COMPRESSION.
C        IF TEST3=1 REVERSE FIELD PRESSURE IS FORCED TO BE EQUAL TO
C                   PLASMA PRESSURE AT SECOND PRESSURE BALANCE DURING
C                   IMPLOSION
C        IF TEST3=2 TOTAL REVERSE FIELD PRESSURE USED IN ENERGY
C                   CALCULATIONS. NO REDUCTION IN PRESSURE.
C     IF TEST4=1 PRESSURE TEST DURING IMPLOSION DOES NOT INVOLVE
C                REVERSE FIELD, ONLY GAS PRESSURE.
C     IF TEST4=2 RESISTING PRESSURE DURING IMPLOSION IS THE SUM OF
```

```
C                    GAS PRESSURE AND REVERSE FIELD PRESSURE.
C
C           NEGATIVE SIGN ON VTHETA(J) MEANS THE MACHINE USES VTHETT
C        VTHETA(J) READ IN FIXED POINT IN KILOVOLTS.  EL(J) READ IN FIXED
C        POINT IN CENTIMETERS.   RDOT READ IN FIXED POINT AS KILOMETERS
C        PER SECOND.   ELECTRON AND ION TEMPERATURES READ IN FIXED POINT
C        IN VOLTS. RO READ IN FIXED POINT AS TENTHS OF MILLIMETER.
C        QUARTER PERIOD AND CONTAINMENT TIME READ IN SHAKES
C        IN THE DEBUGGING PRINT   TEST=MAGNETIC PRESSURE-GAS PRESSURE
         DIMENSION LABL(7),LABEL(40),RO(40),EL(40),PO(40),TO(40),
        1VTHETA(40),YIELD(40),BMAX(40),TAU(40),YIELDC(40),
        2          YIELDE(40),IRDOTE(40),IRDOTC(40),TCONTA(40),REVB(40)
        3,ITELEC(40),ITION(40),IT7(40),IDUMMY(40),IPOO(40),IREVB(40),
        4TPLOT(200),RPLOT(200),TEMPP(200),LABEL1(8),LABEL2(8),IXRAY(40),
        5IRR(40)                        ,DENS1(40),DENS2(40),ENUT1(40),
        6ENUT2(40),XRAY11(40),XRAY12(40),ITP1(40),ITP2(40),DENS3(40),
        7ENUT3(40),XRAY13(40),ITP3(40),IBMAX(40)
         DATA LABEL1/48H     PLASMA RADIUS (CM)    VS.  TIME (SHAKES )   /
         DATA LABEL2/48H     PLASMA TEMP (KEV)     VS.  TIME (SHAKES )   /
         READ(10,5)N,(LABL(I),I=1,7)
       5 FORMAT(I5,7A10)
         READ(10,4)ITEST,ITEST1,ITEST2,ITEST3,ITEST4,EXXRA
       4 FORMAT(5I5,1P1E10.5)
         DO 13 J=1,N
         READ(10,6)LABEL(J),IRO  ,IEL,IPO,ITO,I ELEC,I ION,IRDOT,IVTH,
        1YIELD(J),BMAX(J),REVB(J),ITAU,ITCNTA,IDUMMY(J)
       6 FORMAT(1A10,I5,I4,I5,     5I4,1P3E7.2,2I4,I7)
         TAU(J)=ITAU
         TAU(J)=TAU(J)*1.0E-08
         TCONTA(J)=ITCNTA
         TCONTA(J)=TCONTA(J)*1.0E-08
         VTHETA(J)=IVTH
         VTHETA(J)=VTHETA(J)*1000.
         EL(J)=IEL
         EL(J)=EL(J)*.01
         RO(J)=IRO
         RO(J)=RO(J)*.0001
         IRDOTE(J)=IRDOT
         ITELEC(J)=IELEC
         ITION(J)=IION
         IPOO(J)=IPO
         PO(J)=IPO
         TO(J)=ITO
         IT7(J)=0
         IREVB(J)=REVB(J)*(-10000.)
         IBMAX(J)=BMAX(J)*10000.
      13 CONTINUE
         T=0.0
       8 READ(10,7)C4,C5,C55,C555
        1,C6
       7 FORMAT(1P5E10.5)
         IF(EOF,10)14,15
      14 STOP
      15 DO 1000 J=1,N
```

```
      REVTRG=&1.0
      IF(EXXRA.GT.0.0)EXXRA=-EXXRA
      VTHTST=-1.0
      ANGIES=0.0
      NTEST=0
      T1=-1.0
      T2=-1.0
      T5=-1.0
      T3=-1.0
      T4=1.0
      CALL       PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
   17 WRITE(9,9)(LABEL(I),I=1,7)
    9 FORMAT(1H1,7A10)
      WRITE(9,2)
    2 FORMAT(1H0,16HGAS IS DEUTERIUM)
      WRITE(9,3)ITEST,ITEST1,ITEST2,ITEST3,ITEST4
    3 FORMAT(1H0,5X,5HTEST=,I5,5X,6HTEST1=,I5,5X,6HTEST2=,I5,5X,6HTEST3=
     1,I5,5X,6HTEST4=,I5)
      WRITE(9,100)
  100 FORMAT(1H0,14X,2HC4,14X,2HC5,13X,3HC55,12X,4HC555,12X,4HTIME,
     1,8X,8HADDITIVE)
      WRITE(9,10)C4,C5,C55,C555,T
     1,C6
   10 FORMAT(1H ,1P6E16.5)
      WRITE(9,101)
  101 FORMAT(1H0,6X,4HEXPT,7X,6HRADIUS,7X,6HLENGTH,
     17X,6HINIT P,7X,6HINIT T,8X,5HVOLTS,5X,8HNEUTRONS,
     28X,5HFIELD,9X,4HTIME)
      WRITE(9,11)LABEL(J),RC(J),EL(J),PO(J),TO(J),VTHETA(J),
     1YIELD(J),BMAX(J),TAU(J)
   11 FORMAT(1H ,1A10,1P8E13.4)
      RR=RO(J)*RO(J)
      RRR=RR*RO(J)
      OMEGA=1.5707963/TAU(J)
      IF(ITEST1.EQ.3)GO TO 137
      VTHETT=OMEGA*BMAX(J)*3.14159*RR
      WRITE(9,16)VTHETT
   16 FORMAT(1H0,69HVOLTAGE SPIKE CALCULATED FROM THE ASSUMED SINUSOIDAL
     1 DRIVING FIELD IS,1P1E16.5)
      IF(VTHETA(J).LT.0.0)VTHETA(J)=VTHETT
  137 P1=PO(J)/7.5
      V1=3.14159*RR
      EMOLES=P1*V1/(8314.*TC(J))
      YIELDE(J)=YIELD(J)
      YIELDC(J)=0.0
      P6=0.0
      CONST=C4*1.5*8314.*EMOLES
C     FULLY IONIZED DEUTERIUM IS 4 PARTICLES
      FOUR=4.0&C6
      CONST1=8314./3.14159*EMCLES*FOUR
      CONST7=VTHETA(J)/(3.14159*RR)
      TEST=0.0
      WRITE(9,102)
  102 FORMAT(1H0,8X,8HPRESSURE,10X,6HVOLUME,11X,5HMOLES,
```

```
     15X,11HNEUTRONS    ,5X,11HCONTAINMENT,7X,9HREV FIELD)
      WRITE(9,12)P1,V1,EMOLES,YIELDE(J),TCONTA(J),REVB(J)
   12 FORMAT(1H ,1P6E16.5)
      WRITE(9,21)
   21 FORMAT(1H0,30X,18HINITIAL CONDITIONS)
      ISTS=0
      RDOT=0.0
      BS=0.0
      PDYNA=0.0
      TS=TO(J)
      TSKEV=TS/11.6E&06
      RS=RO(J)
      IF(REVB(J).GT.0.0)GO TO 22
      EREVB=0.0
      PREVB=0.0
      GO TO 23
   22 PREVB=3.98E&05*REVB(J)*REVB(J)
      EREVB=PREVB*3.14159*RR
      VREVB=0.0
   23 ELEFT=TS*CONST
C     UN-IONIZED CONDITIONS
      PEQST=CONST1*TS/RR*.25
      IP=1
      TPLOT(IP)=ISTS
      RPLOT(IP)=BS*100.
      TEMPP(IP)=TSKEV
      WRITE(9,105)
      FLDP=3.98E&05*BS*BS
      BT=PEQST
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMOLES,BS)
      WRITE(9,120)
  120 FORMAT(1H0,30X,50HCONDITIONS AT PREHEAT AND INITIAL PRESSURE BALAN
     1CE)
C     FULLY IONIZED GAS-DEUTERIUM
      CONST=1.5*8314.*EMOLES*C4*FOUR
      WRITE(9,105)
      DUMMY=IDUMMY(J)
      IF(DUMMY.EQ.0.0)DUMMY=2.0
      TSKEV=DUMMY*.001
      TS=TSKEV*11.6E&06
      PEQST=CONST1*TS/RR
      T=4.0*TAU(J)
      BSS=SQRT(PEQST/3.98E&05)
      BMA1=BMAX(J)
      TA1=TAU(J)
      CALL SHAPE(ITEST1,BSS,CONST7,BMA1,TA1,T,OMEGA)
  123 ISTS=T*1.0E&08
      BS=BSS
      EINIT=TS*CONST
      ELEFT=EINIT
      IP=2
```

```
      TPLCT(IP)=ISTS
      RPLCT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,PLEFT,PEQST
      CALL RATIO(RS,BT,TS,EMOLES,BS)
      IF(ITEST.EQ.1)GO TO 110
      IF(ITEST.EQ.2)GO TO 111
      IF(ITEST.EQ.3)GO TO 113
      IF(ITEST.EQ.4)GO TO 114
      IF(ITEST.EQ.5)GO TO 115
      IF(ITEST.EQ.6)GO TO 116
      IF(ITEST.EQ.7)GO TO 117
      IF(ITEST.EQ.8)GO TO 118
  110 RDOTSQ=C5*VTHETA(J)/(EMOLES*SQRT(EMOLES))
      GO TO 112
  111 RDOTSQ=C55*VTHETA(J)**2/EMOLES**3
      GO TO 112
  113 RDOTSQ=C555*VTHETA(J)
      GO TO 112
  114 RDOTSQ=C55*RR*VTHETA(J)/EMOLES
      GO TO 112
  115 RDOTSQ=C55*VTHETA(J)/SQRT(EMOLES)
      GO TO 112
  116 RDOTSQ=C55*VTHETA(J)*SQRT(EMOLES)*RR
      GO TO 112
  117 RDOTSQ=C55*VTHETA(J)*EMOLES*RR
      GO TO 112
C     THIS EQUATION HAS EXPERIMENTAL VALIDITY
  118 RDOTSQ=C555*VTHETA(J)*     (SQRT(100./PO(J)))
      GO TO 112
  112 RDOT=SQRT(RDOTSQ)
      IRDOTC(J)=RDOT*.001
      WRITE(9,28)RDOT
   28 FORMAT(1H0,39HIMPLOSION AND EXPLOSION VELOCITY EQUALS,1P1E16.3)
C     MOLECULAR WEIGHT OF DEUTERIUM
      CONST2=EMOLES*4.03*RDOTSQ
      RS=RO(J)
      DELTAT=RO(J)*.002/RDOT
      IF(REVB(J).GE.0.0)GO TO 27
      REVTRG=-1.0
      REVB(J)=0.0
   27 T=T&DELTAT
      RS=RS-RDOT*DELTAT
      TA1=TAU(J)
      BMA1=BMAX(J)
      CALL         FIELD(ITEST1,CONST7,T,OMEGA,TA1,BSS,BMA1)
   62 PLEFT=3.98E&05*BSS*BSS
      BSSR=REVB(J)*RR/(RS*RS)
      PREVB=3.98E&05*BSSR*BSSR
      PDYNA=.5*CONST2/(3.14159*RS*RS)
      PLEFT=PLEFT&PDYNA
      IF(ITEST4.EQ.2)PLEFT=PLEFT-PREVB
```

```
      ELEFT=(1.0-RS*RS/RR)*CONST2&EINIT
   18 TS=ELEFT/CONST
      IF(TS.LE.TO(J))TS=TO(J)
      PEQST=CONST1*TS/(RS*RS)
      TEST=PLEFT-PEQST
      IF(RS.LT.0.0)GO TO 8
      IF(VTHTST.GT.0.0)GO TO 109
      IF(TEST.LT.0.0)GO TO 27
      VTHTST=&1.0
      WRITE(9,108)
  108 FORMAT(1H0,30X,53HCONDITIONS AT FIRST PRESSURE BALANCE DURING IMPL
     1OSION)
      WRITE(9,105)
      BS=BSS
      ISTS=T*1.0E&08
      TSKEV=TS/11.6E&06
      BSSR=REVB(J)*RR/(RS*RS)
      VREVB=3.14159*RS*RS
      PREVB=3.98E&05*BSSR*BSSR
      EREVB=PREVB*VREVB
      IP=3
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMOLES,BS)
      GO TO 27
  109 IF(TEST.GT.0.0)GO TO 27
      BS=BSS
      IF(ITEST3.EQ.2)GO TO 93
      IF(PREVB.GT.PEQST)GO TO 94
      GO TO 93
   94 WRITE(9,91)PREVB,PEQST
   91 FORMAT(1H0,30X,38HREVERSE FIELD PRESSURE DECREASED FROM ,
     11P1E16.5,5X,2HTO,1P1E16.5)
      PREVB=PEQST
   93 VREVB=3.14159*RS*RS
      EREVB=PREVB*3.14159*RS*RS
      STS=T
      ISTS=STS*1.0E&08
      TSKEV=TS/11.6E&06
      WRITE(9,104)
  104 FORMAT(1H0,30X,54HCONDITIONS AT SECOND PRESSURE BALANCE DURING IMP
     1LOSION)
      WRITE(9,105)
  105 FORMAT(1H ,4X,8HMG FLD P,6X,6HRADIUS,2X,4HTIME,3X,9HMAG FIELD,
     11X,11H DYNAMIC P,7X,5HT KEV,2X,10HR FLD ENGY,5X,7HR FLD P,
     22X,10HSHOCK ENGY,5X,7HP EQ ST)
      IP=4
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
      TEMPP(IP)=TSKEV
```

```
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMCIES,BS)
   26 FORMAT(1H ,1P2E12.3,I6,1P7E12.3)
      IF(REVTRG.LT.0.0)GO TO 20
      IF(ITEST2.EQ.1)WRITE(9,106)
      IF(ITEST2.EQ.2)WRITE(9,98)
  106 FORMAT(1H0,30X,51HCONDITIONS AFTER ABSORPTION OF REVERSE FIELD ENE
     1RGY)
   98 FORMAT(1H0,30X,63HCONDITIONS IMMEDIATELY AFTER ABSORPTION OF REVER
     1SE FIELD ENERGY)
      ESAVE=ELEFT
   71 ELEFT=ESAVE&EREVB
      TS=ELEFT/CONST
      PDYNA=0.0
      RDOT=0.0
      PEQST=CONST1*TS/(RS*RS)
      BST=SQRT(PEQST/3.98E&05)
      IF(ITEST2.EQ.2)GO TO 126
      IF(BST.GT.BSS)BSS=BST
      T=2.0*TAU(J)
      BMA1=BMAX(J)
      TA1=TAU(J)
      CALL SHAPE(ITEST1,BSS,CONST7,BMA1,TA1,T,OMEGA)
  126 PLEFT=PEQST
      BS=BSS
      STS=T
      ISTS=STS*1.0E&08
      TSKEV=TS/11.6E&06
      WRITE(9,105)
      IP=5
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      PREVB=0.0
      EREVB=0.0
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMCIES,BS)
      IF(ITEST2.EQ.2)GO TO 97
      IF(BS.GT.BMAX(J))GO TO 8
      IF(STS.GT.TAU(J))GO TO 8
      GOTO40
   97 WRITE(9,99)
   99 FORMAT(1H0,30X,49HCONDITIONS AT PRESSURE BALANCE AFTER FIRST BOUNC
     1E)
      DELTAT=DELTAT*.10
      RDOT=IRDOTC(J)*1000
      WRITE(9,28)RDOT
   86 VRAT=VREVB/(3.14159*RS*BS)
      PP=PEQST*VRAT**1.667
      PB=3.98E&05*BSS*BSS
```

```
      IF(PP.LT.PB)GO TO 90
      RS=RS&RDOT*DELTAT
      T=T&DELTAT
      TA1=TAU(J)
      BMA1=BMAX(J)
      CALL        FIELD(ITEST1,CONST7,T,OMEGA,TA1,BSS,BMA1)
      GO TO 86
   90 ISTS=T*1.0E&08
      BS=BSS
      PDYNA=0.0
      TS=TS*VRAT**.667
      TSKEV=TS/11.6E&06
      PEQST=PEQST*VRAT**1.667
      ELEPT=TS*CONST
      WRITE(9,105)
      IP=6
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEPT,PEQST
      CALL RATIO(RS,BT,TS,EMOLES,BS)
      GO TO 40
   20 WRITE(9,19)
  .19 FORMAT(1H0,43HSECOND HALF CYCLE CALCULATION DOES NOT WORK)
   40 WRITE(9,41)
   41 FORMAT(1H0,30X,29HADIABATIC COMPRESSION FOLLOWS)
      BMA1=BMAX(J)
      TA1=TAU(J)
      CALL SHAPE(ITEST1,BSS,CONST7,BMA1,TA1,T,OMEGA)
      BT=3.98E&05*BS*BS
      CALL RATIO(RS,BT,TS,EMOLES)
  134 IEXXRA=-EXXRA
      WRITE(9,95)IEXXRA
   95 FORMAT(1H0,30X,37HAUGMENTED XRAY YIELD BY A FACTOR OF  ,I10)
      DELTAT=.01*TAU(J)
   50 TA1=TAU(J)
      BMA1=BMAX(J)
      CALL        FIELD(ITEST1,CONST7,T,OMEGA,TA1,BSS,BMA1)
  136 CALL         PLASM(RS,BSS,TS,EXXRA,DELTAT,T,ENEUTS,XRAY,IR,DENS,
     1FOUR)
      YIELDC(J)=ENEUTS
      IXRAY(J)=XRAY*(-1.)
      IRR(J)=IR
      T=T&DELTAT
      TSKEV=TS/11.6E&06
      ISTS=T*1.0E&08
      IP=IP&1
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      IF(T.GE.TCONTA(J))GO TO 1006
      IF(T2.LT.0.0)GO TO 1220
```

```
      IF(T5.LT.0.0)GO TO 1230
      IF(T3.LT.0.0)GO TO 1222
      GO TO 1225
 1220 IF(T.GT.6.0E-07)GO TO 1221
      GO TO 1225
 1221 CALL         PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
      GO TO 1225
 1230 IF(T.GT.1.00E-06)GO TO 1231
      GO TO 1225
 1231 CALL         PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
      GO TO 1225
 1222 IF(T.GT.1.98E-06)GO TO 1223
      GO TO 1225
 1223 CALL         PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
      GO TO 1225
 1225 IF(T.GE.TCONTA(J))GO TO 1006
      GOTO50
 1006 EEMOL=3.98E+05*BSS*BSS*3.14159*RS*RS/(8314.*TS)
      TOTAL=CONST*TS
      RATIO=EEMOL/EMOLES
      IT7(J)=TS/11.6E+03
      WRITE(9,53)EEMOL,RATIO,TOTAL
   53 FORMAT(1H0,6HMOLES=,1P1E16.5,5X,6HRATIO=,1P1E16.5,5X,
     122HTOTAL INTERNAL ENERGY=,1P1E16.5)
      CALL SPLOT(1,IP,TPLOT,RPLOT,42,1)
      CALL LINCNT(1)
      WRITE(12,25)IPO,IRO,IVTH,BMAX(J),ITAU,REVB(J),IEXXRA
     1,ITEST,ITEST1,ITEST2,ITEST3,ITEST4
      WRITE(12,24)C555,LABEL(J)
      CALL WLCH(244,25,48,IABEL1,1)
      CALL WLCV(40,722,25,IABEL1,1)
      CALL WLCH(440,1002,15,IABEL1(4),1)
      CALL ADV(1)
   25 FORMAT(1H , 1X,9HPRESSURE=,I6,1X,7HRADIUS=,I5,1X,7HVTHETA=,I5,1X,
     15HBMAX=,1P1E11.3,1X,11HQTR PERIOD=,I5,1X,10HREV FIELD=,1P1E11.3,
     21X,6HEXXRA=,I3,1X,5I1)
   24 FORMAT(1H ,1X,2HC=,1P1E10.2,1A10)
      CALL SPLOT(1,IP,TPLOT,TEMPP,42,1)
      CALL LINCNT(1)
      WRITE(12,25)IPO,IRO,IVTH,BMAX(J),ITAU,REVB(J),IEXXRA
     1,ITEST,ITEST1,ITEST2,ITEST3,ITEST4
      WRITE(12,24)C555,LABEL(J)
      CALL WLCH(244,25,48,IABEL2,1)
      CALL WLCV(40,722,25,IABEL2,1)
      CALL WLCH(440,1002,15,IABEL2(4),1)
      CALL ADV(1)
      GO TO 1000
 1000 CONTINUE
```

```
      WRITE(9,9)(LABL(I),I=1,7)
      WRITE(9,95)IEXXRA
      WRITE(9,3)ITEST,ITEST1,ITEST2,ITEST3,ITEST4
      WRITE(9,101)
      WRITE(9,11)LABEL(1),RC(1),EL(1),PO(1),TO(1),VTHETA(1),YIELD(1),
     1BMAX(1),TAU(1)
      WRITE(9,100)
      WRITE(9,10)C4,C5,C55,C555,T
      T1=1.0
      T2=1.0
      T5=1.0
      T3=1.0
      T4=-1.0
      CALL        PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
      SUM=0.0
      SUMSQ=0.0
      WRITE(9,1002)
 1002 FORMAT(1H0,7X,5HEXPER,2X,10HCALCULATED,2X,10HDIFFERENCE,7X,5HRATIO
     1,11X,4HEXPT,1X,5HEXP V,1X,5HCAL V,1X,5HP MIC,1X,5HREV B,2X,4HXRAY,
     21X,5HRATIO,2X,4HT EL,1X,5HT ION,2X,4HCALC)
      DO1001J=1,N
      YIELDC(J)=YIELDC(J)*EL(J)
      DELTA   =YIELDE(J)-YIELDC(J)
      DIVIDE   =YIELDC(J)/YIELDE(J)
      WRITE(9,1003)YIELDE(J),YIELDC(J),DELTA    ,DIVIDE    ,LABEL(J),
     1 IRDOTE(J),IRDOTC(J),IPOO(J),IREVB(J),IXRAY(J),IRR(J),ITELEC(J),
     2ITION(J),IT7(J)
 1003 FORMAT(1H ,1P4E12.3,5X,1A10,9I6)
      SUM=SUM&DIVIDE
      SUMSQ=SUMSQ&DIVIDE   *DIVIDE
 1001 CONTINUE
      EN=N
      SUMSQ=SQRT(SUMSQ/EN)
      SUM=SUM/EN
      WRITE(9,1004)
 1004 FORMAT(1H0,9X,7HAVERAGE,9X,7HSTD DEV)
      WRITE(9,1005)SUM,SUMSQ
 1005 FORMAT(1H ,1P2E16.5)
      GO TO 8
      END
      SUBROUTINE PLASM(RPLAS,BSS,TPLAS,EXXRA,DELTAT,T,ENEUTS,XRAY,IR,
     1DENS,FOUR)
C         P3= NUMBER OF MOLES
C         GAS CONST=8314. IN MKS
C         HEAT CAPACITY=3/2R PER MOLE
C         FULLY IONIZED DEUTERIUM IS FOUR PARTICLES PER MOLE OF
C         UN-IONIZED GAS. ONLY TWO PARTICLES HAVE MASS, ELECTRONS NEGLIG
C         DENS IS ION DENSITY
C         THERE ARE 11.6E&06 KELVIN IN ONE KEV
C         DEUTERIUM CROSS SECTIONS
C         PRINT FIELD IN KILOGAUSS
      IF(EXXRA.GT.0.0)GO TO 10
```

```
      EXXRA=ABS(EXXRA)
      VOL=3.14159*RPLAS*RPLAS
      VOL1=VOL
      TPLAS2=TPLAS
      PPLAS=3.98E&05*BSS*BSS
      P3=PPLAS*VOL/(8314.*TPLAS)
      CONST=1.5*8314.*P3
      CONST3=1.3E-20*.50*1.35
      CONST4=P3*6.023E&26*2.0/FOUR
      CONST5=5.35E-31*1.0E-12*1.0E&06
      PDV1=0.0
      XRAY=0.0
      ENEUTS=0.0
      WRITE(9,51)
   51 FORMAT(1H0,1X,4HTIME,2X,3HFLD,4X,8HION DENS,6X,6HRADIUS,2X,3HV/V,7
     1X,5HT KEV,2X,3HT/T,4X,8HNEUTRONS,7X,5HXRAYS,2X,3HX/E,5X,7HENGY CK,
     26X,5HTOTAL,5X,4HPDV1)
      ELL=1.0
   10 VOL=3.14159*RPLAS*RPLAS
      PPLAS=3.98E&05*BSS*BSS
      DENS=CONST4/VOL
      DENSQ=DENS*DENS
      TPLAS4=TPLAS
      TPLAS=(PPLAS*VOL/(8314.*P3)&TPLAS)/2.0
      TPLAS1=TPLAS/11.6E&06
      TPLAS3=TPLAS1**.33333
      ENEUTS=ENEUTS&CONST3*DENSQ*EXP(-18.76/TPLAS3)
     1*DELTAT*VOL/(TPLAS3*TPLAS3)*ELL
      XRAY1=EXXRA*CONST5*DENSQ*SQRT(TPLAS1)
     1*DELTAT*VOL*ELL
      TOTAL=CONST*TPLAS
      XRAY=XRAY-XRAY1
      PDV=-XRAY1-CONST*(TPLAS-TPLAS4)
      PDV1=PDV1&PDV
      RPLAS=RPLAS&PDV/(6.284*TPLAS*RPLAS)
      IT=T*1.0E&08
      IF(RPLAS.LT.0.0)GO TO 53
      IBSS=BSS*10.
      IV=VOL/VOL1*100.
      IS=TPLAS/TPLAS2*100.
      IR=-XRAY*100./TOTAL
      ECK=TOTAL-XRAY&PDV1
      WRITE(9,52)IT,IBSS,DENS,RPLAS,IV,TPLAS1,IS,ENEUTS,
     1XRAY,IR,ECK,TOTAL,PDV1
   52 FORMAT(1H ,2I5,1P2E12.3,I5,1P1E12.3,I5,1P2E12.3,
     1I5,1P1E14.5,1P2E9.1)
      GO TO 55
   53 WRITE(9,54)RPLAS
   54 FORMAT(1H0,30X,31HPLASMA RADIUS HAS GONE NEGATIVE,1P1E16.5)
      T=T*1.0E&10
   55 RETURN
      END
      SUBROUTINE RATIO(RS,BT,TS,EMOLES,BS)
C         BETA SHOULD BE ONE. FOR DEUTERIUM MOLES RATIO SHOULD BE 4.
```

```
C        IF THE GAS IS FULLY IONIZED
  134 P1=3.14159*RS*RS
      P2=BT
      P3=P1*P2/(8314.*TS)
      RATIO=P3/EMOLES
      IF(BT*BS.EQ.0.0)GO TO 108
      BETA=P2/(3.98E&05*BS*BS)
      GO TO 109
  108 BETA=0.0
  109 WRITE(9,107)
  107 FORMAT(1H0,8X,8HPRESSURE,10X,6HVOLUME,11X,5HMOLES,11X,5HRATIO,12X,
     14HBETA)
      WRITE(9,42)P2,P1,P3,RATIO,BETA
   42 FORMAT(1H ,1P5E16.5)
      WRITE(9,106)
  106 FORMAT(1H ,46HP EQ ST MUST EQUAL MG FLD P FOR BETA TO BE 1.0)
      RETURN
      END
      SUBROUTINE SHAPE(ITEST1,BSS,CONST7,BMA1,TA1,T,OMEGA)
      ANGLES=BSS/BMA1
      IF(ANGLES.GE.1.0)GO TO 70
      IF(ITEST1.EQ.1)GO TO 124
      IF(ITEST1.EQ.2)GO TO 125
      IF(ITEST1.EQ.3)GO TO 126
      IF(ITEST1.EQ.4)GO TO 127
  124 T=BSS/CONST7
      GO TO 73
  125 ANGLEC=SQRT(1.0-ANGLES*ANGLES)
      ANGLE=ATAN(ANGLES/ANGLEC)
      T=ANGLE/OMEGA
      GO TO 73
  126 T=TA1*(1.0-SQRT(1.0-ANGLES*ANGLES))
      GO TO 73
  127 T=TA1*SQRT(ANGLES)
      GO TO 73
   70 WRITE(9,72)
   72 FORMAT(1H0,30X,20HERROR IN CALCULATION)
   30 WRITE(9,31)
   31 FORMAT(1H0,28HNO FURTHER SOLUTION POSSIBLE)
      T=TA1*1.01
   73 RETURN
      END
      SUBROUTINE FIELD(ITEST1,CONST7,T,OMEGA,TA1,BSS,BMA1)
C     CROWBAR MUST OCCUR INSIDE ADIABATIC COMPRESSION
C     FOR OPTIONS 3 AND 4.
C        FIELD IS ETHETA*TIME
      IF(ITEST1.EQ.1)GO TO 89
C        FIELD CAUSED BY CAPACITOR BANK
      IF(ITEST1.EQ.2)GO TO 88
C        FIELD CAUSED BY GENERATOR     SPIRAL
      IF(ITEST1.EQ.3)GO TO 87
C        FIELD CAUSED BY GENERATOR     PLATE
      IF(ITEST1.EQ.4)GO TO 90
   89 BSS=CONST7*T
```

```
      GO TO 86
   88 BSS=BMA1*SIN(OMEGA*T)
      GO TO 86
   87 IF(T.GE.TA1)GO TO 91
      BSS=BMA1/TA1*SQRT(T*(2.0*TA1-T))
      GO TO 86
   90 IF(T.GE.TA1)GO TO 91
      BSS=BMA1*(T/TA1)**2.0
   86 RETURN
   91 BSS=BMA1
      GO TO 86
      END
      SUBROUTINE PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
      DIMENSION IREVB(40),IPOC(40),DENS1(40),DENS2(40),ENUT1(40),
     1ENUT2(40),XRAY11(40),XRAY12(40),ITP1(40),ITP2(40),DENS3(40),ENUT3
     2(40),XRAY13(40),ITP3(40),IBMAX(40)
C     T1 CONTROLS INITIALIZING
C     T2 STORES FIRST SET OF DATA AT 0.6 MICROSECOND
C     T5 STORES THIRD SET OF DATA AT 1.00 MICROSECONDS
C     T3 STORES SECOND SET OF DATA AT 2.0 MICROSECONDS
C     T4 CONTROLS OUTPUT PRINTING
      IF(T1.LT.0.0)GO TO 1200
      IF(T2.LT.0.0)GO TO 1201
      IF(T5.LT.0.0)GO TO 1210
      IF(T3.LT.0.0)GO TO 1202
      IF(T4.LT.0.0)GO TO 1203
      GO TO 1205
 1200 T1=1.0
      DENS1(J)=0.0
      DENS2(J)=0.0
      DENS3(J)=0.0
      ENUT1(J)=0.0
      ENUT2(J)=0.0
      ENUT3(J)=0.0
      XRAY11(J)=0.0
      XRAY12(J)=0.0
      XRAY13(J)=0.0
      ITP1(J)=0.0
      ITP2(J)=0.0
      ITP3(J)=0.0
      GO TO 1205
 1201 T2=1.0
      DENS1(J)=DENS
      ENUT1(J)=ENEUTS
      XRAY11(J)=XRAY
      ITP1(J)=TS/11.6E&03
      GO TO 1205
 1210 T5=1.0
      DENS3(J)=DENS
      ENUT3(J)=ENEUTS
      XRAY13(J)=XRAY
      ITP3(J)=TS/11.6E&03
```

```
      GO TO 1205
 1202 T3=1.0
      DENS2(J)=DENS
      ENUT2(J)=ENEUTS
      XRAY12(J)=XRAY
      ITP2(J)=TS/11.6E&03
      GO TO 1205
 1203 T4=1.0
      WRITE(9,1204)
 1204 FORMAT (1H0,5X,33HSUMMARY TABLE AT 0.6 MICROSECCNDS)
      WRITE(9,1206)
 1206 FORMAT (1H0,4X,8HPRESSURE,1X,11HREVERSE FLD,1X,11HION DENSITY,
     14X,8HNEUTRONS,7X,5HXRAYS,5X,7HTEMP EV,3X,9HDRIVE FLD)
      WRITE(9,1207) (IPOO(J),IREVB(J),DENS1(J),ENUT1(J),XRAY11(J),
     1ITP1(J),IBMAX(J),J=1,N)
 1207 FORMAT(1H ,2I12,1P3E12.4,2I12)
      WRITE(9,1211)
 1211 FORMAT(1H0,5X,34HSUMMARY TABLE AT 1.00 MICROSECONDS)
      WRITE(9,1206)
      WRITE(9,1207) (IPOO(J),IREVB(J),DENS3(J),ENUT3(J),XRAY13(J),
     1ITP3(J),IBMAX(J),J=1,N)
      WRITE(9,1208)
 1208 FORMAT (1H0,5X,33HSUMMARY TABLE AT 2.0 MICROSECCNDS)
      WRITE(9,1206)
      WRITE(9,1207) (IPOO(J),IREVB(J),DENS2(J),ENUT2(J),XRAY12(J),
     1ITP2(J),IBMAX(J),J=1,N)
 1205 RETURN
      END
```

Helium

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C      ALGEBRAIC SOLUTION OF THETA PINCH EQUATIONS
C      USING THOMSONS THEORY.  THE INPUT DATA
C      IS THE VOLTAGE PULSE, THE MAXIMUM MAGNETIC
C      FIELD AND ITS TIME TO MAXIMUM ASSUMING
C      SINUSOIDAL.   THE PLASMA IS HELIUM WITH GAMMA=1.667
C      AND THE MOLECULAR WEIGHT=4.0026
C      C6 IS THE EXTRA IONIZED PARTICLES ADDED TO THE
C      PURE GAS. C6=1 IS ONE MORE ELECTRON DUE TO
C      IMPURITIES. C6 FRACTIONAL IS PERMISSIBLE.
C      THE XRAY YIELD IS CALCULATED PER METER.
C                        THE INITIAL PRESSURE,
C      TEMPERATURE(K), RADIUS ARE REQUIRED.  ALL
C      UNITS ARE MKS EXCEPT FOR INITIAL PRESSURE IN MICRONS.
C      100  MICRONS EQUAL 100  MILLITOR OR 100  MT
C      TWO UNDETERMINED
C      CONSTANTS C4=1. INITIALLY AND C5 TO
C      BE DETERMINED FROM EXPERIMENTAL DATA.
C      REVERSE FIELD PUT IN   IF NEGATIVE THEN USES SECOND HALF CYCLE
C         OPERATION AND REVB(J) IS SET EQUAL TO ZERO.
C      READ IN EXXRA INITIALLY NEGATIVE
C      EXXRA IS XRAY AUGMENTED YIELD
C                                  FORMULAS
C       TEST   FORMULA                                CONSTANT
C         1     C5*VTHETA/EMOLES**1.5                 4.0E-07     LOW
C         2     C55*VTHETA**2/EMOLES**3               6.5E-23   ERRATIC
C         3     C555*VTHETA                           5.35E&05     LOW
C         4     C55*RR*VTHETA/EMOLES                  3.33          LOW
C         5     C55*RR*VTHETA/SQRT(EMOLES)            3.33E&01     LOW
C         6     C55*RR*VTHETA*SQRT(EMOLES)            6.0E&12     LOW
C         7     C55*RR*VTHETA*EMOLES                  6.0E&16     LOW
C         8      C555*VTHETA*     (SQRT(100./PO(J)))
C
C         IF TEST1=1 USES BSS=CONST7*T
C         IF TEST1=2 USES BSS=BMAX(J)*SIN(OMEGA*T)
C         FIELD CAUSED BY GENERATOR      SPIRAL
C         IF TEST1=3 USES BSS=BMAX(J)/TAU(J)*SQRT(T*(2.0*TAU(J)-T))
C         FIELD CAUSED BY GENERATOR      PLATE
C      IF TEST1=4 USES BSS=BMAX(J)*(T/TAU(J))**2.0
C
C         IF TEST2=1 GO FROM REVERSE FIELD ABSORPTION DIRECTLY TO
C                    ADIABATIC COMPRESSION.
C         IF TEST2=2 GO FROM REVERSE FIELD ABSORPTION TO AN EXPANSION
C                    PHASE UNTIL PRESSURE BALANCE AND THEN GO TO
C                    ADIABATIC COMPRESSION.
C         IF TEST3=1 REVERSE FIELD PRESSURE IS FORCED TO BE EQUAL TO
C                    PLASMA PRESSURE AT SECOND PRESSURE BALANCE DURING
C                    IMPLOSION
C         IF TEST3=2 TOTAL REVERSE FIELD PRESSURE USED IN ENERGY
C                    CALCULATIONS. NO REDUCTION IN PRESSURE.
C      IF TEST4=1 PRESSURE TEST DURING IMPLOSION DOES NOT INVOLVE
C                 REVERSE FIELD, ONLY GAS PRESSURE.
C      IF TEST4=2 RESISTING PRESSURE DURING IMPLOSION IS THE SUM OF
C                 GAS PRESSURE AND REVERSE FIELD PRESSURE.
C
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C        NEGATIVE SIGN ON VTHETA(J) MEANS THE MACHINE USES VTHETT
C     VTHETA(J) READ IN FIXED POINT IN KILOVOLTS.  EL(J) READ IN FIXED
C     POINT IN CENTIMETERS.   RDOT READ IN FIXED POINT AS KILOMETERS
C     PER SECOND.   ELECTRON AND ION TEMPERATURES READ IN FIXED POINT
C     IN VOLTS. RO READ IN FIXED POINT AS TENTHS OF MILLIMETER.
C     QUARTER PERIOD AND CONTAINMENT TIME READ IN SHAKES
C     IN THE DEBUGGING PRINT   TEST=MAGNETIC PRESSURE-GAS PRESSURE
      DIMENSION LABL(7),LABEL(40),RO(40),EL(40),PO(40),TO(40),
     1VTHETA(40),YIELD(40),BMAX(40),TAU(40),YIELDC(40),
     2           YIELDE(40),IRDOTE(40),IRDOTC(40),TCONTA(40),REVB(40)
     3,ITELEC(40),ITION(40),IT7(40),IDUMMY(40),IPOO(40),IREVB(40),
     4TPLOT(200),RPLOT(200),TEMPP(200),LABEL1(8),LABEL2(8),IXRAY(40),
     5IRR(40)                    ,DENS1(40),DENS2(40),ENUT1(40),
     6ENUT2(40),XRAY11(40),XRAY12(40),ITP1(40),ITP2(40),DENS3(40),
     7ENUT3(40),XRAY13(40),ITP3(40),IBMAX(40)
      DATA LABEL1/48H     PLASMA RADIUS (CM)    VS.  TIME (SHAKES )    /
      DATA LABEL2/48H     PLASMA TEMP (KEV)     VS.  TIME (SHAKES )    /
      READ(10,5)N,(LABL(I),I=1,7)
    5 FORMAT(I5,7A10)
      READ(10,4)ITEST,ITEST1,ITEST2,ITEST3,ITEST4,EXXRA
    4 FORMAT(5I5,1P1E10.5)
      DO 13 J=1,N
      READ(10,6)LABEL(J),IRO  ,IEL,IPO,ITO,I ELEC,I ION,IRDOT,IVTH,
     1YIELD(J),BMAX(J),REVB(J),ITAU,ITCNTA,IDUMMY(J)
    6 FORMAT(1A10,I5,I4,I5,     5I4,1P3E7.2,2I4,I7)
      TAU(J)=ITAU
      TAU(J)=TAU(J)*1.0E-08
      TCONTA(J)=ITCNTA
      TCONTA(J)=TCONTA(J)*1.0E-08
      VTHETA(J)=IVTH
      VTHETA(J)=VTHETA(J)*1000.
      EL(J)=IEL
      EL(J)=EL(J)*.01
      RO(J)=IRO
      RO(J)=RO(J)*.0001
      IRDOTE(J)=IRDOT
      ITELEC(J)=IELEC
      ITION(J)=IION
      IPOO(J)=IPO
      PO(J)=IPO
      TO(J)=ITO
      IT7(J)=0
      IREVB(J)=REVB(J)*(-10000.)
      IBMAX(J)=BMAX(J)*10000.
   13 CONTINUE
      T=0.0
    8 READ(10,7)C4,C5,C55,C555
     1,C6
    7 FORMAT(1P5E10.5)
      IF(EOF,10)14,15
   14 STOP
   15 DO 1000 J=1,N
      REVTRG=81.0
      IF(EXXRA.GT.0.0)EXXRA=-EXXRA
```

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      VTHIST=-1.0
      ANGLES=0.0
      NTEST=0
      T1=-1.0
      T2=-1.0
      T5=-1.0
      T3=-1.0
      T4=1.0
      CALL        PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
   17 WRITE(9,9)(LABL(I),I=1,7)
    9 FORMAT(1H1,7A10)
      WRITE(9,2)
    2 FORMAT(1H0,16HGAS IS HELIUM   )
      WRITE(9,3)ITEST,ITEST1,ITEST2,ITEST3,ITEST4
    3 FORMAT(1H0,5X,5HTEST=,I5,5X,6HTEST1=,I5,5X,6HTEST2=,I5,5X,6HTEST3=
     1,I5,5X,6HTEST4=,I5)
      WRITE(9,100)
  100 FORMAT(1H0,14X,2HC4,14X,2HC5,13X,3HC55,12X,4HC555,12X,4HTIME,
     1,8X,8HADDITIVE)
      WRITE(9,10)C4,C5,C55,C555,T
     1,C6
   10 FORMAT(1H ,1P6E16.5)
      WRITE(9,101)
  101 FORMAT(1H0,6X,4HEXPT,7X,6HRADIUS,7X,6HLENGTH,
     17X,6HINIT P,7X,6HINIT T,8X,5HVOLTS,5X,8HNEUTRONS,
     28X,5HFIELD,9X,4HTIME)
      WRITE(9,11)LABEL(J),RO(J),EL(J),PO(J),TO(J),VTHETA(J),
     1YIELD(J),BMAX(J),TAU(J)
   11 FORMAT(1H ,1A10,1P8E13.4)
      RR=RO(J)*RO(J)
      RRR=RR*RO(J)
      OMEGA=1.5707963/TAU(J)
      IF(ITEST1.EQ.3)GO TO 137
      VTHETT=OMEGA*BMAX(J)*3.14159*RR
      WRITE(9,16)VTHETT
   16 FORMAT(1H0,69HVOLTAGE SPIKE CALCULATED FROM THE ASSUMED SINUSOIDAL
     1 DRIVING FIELD IS,1P1E16.5)
      IF(VTHETA(J).LT.0.0)VTHETA(J)=VTHETT
  137 P1=PO(J)/7.5
      V1=3.14159*RR
      EMOLES=P1*V1/(8314.*TO(J))
      YIELDE(J)=YIELD(J)
      YIELDC(J)=0.0
      P6=0.0
      CONST=C4*1.5*8314.*EMOLES
C     FULLY IONIZED HELIUM    IS 3 PARTICLES
      THREE=3.0E06
      CONST1=8314./3.14159*EMOLES*THREE
      CONST7=VTHETA(J)/(3.14159*RR)
      TEST=0.0
      WRITE(9,102)
  102 FORMAT(1H0,8X,8HPRESSURE,10X,6HVOLUME,11X,5HMOLES,
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     15X,11HNEUTRONS    ,5X,11HCONTAINMENT,7X,9HREV FIELD)
      WRITE(9,12) P1,V1,EMOLES,YIELDE(J),TCONTA(J),REVB(J)
   12 FORMAT(1H ,1P6E16.5)
      WRITE(9,21)
   21 FORMAT(1H0,30X,18HINITIAL CONDITIONS)
      ISTS=0
      RDOT=0.0
      BS=0.0
      PDYNA=0.0
      TS=TO(J)
      TSKEV=TS/11.6E&06
      RS=RO(J)
      IF(REVB(J).GT.0.0)GO TO 22
      EREVB=0.0
      PREVB=0.0
      GO TO 23
   22 PREVB=3.98E&05*REVB(J)*REVB(J)
      EREVB=PREVB*3.14159*RR
      VREVB=0.0
   23 ELEFT=TS*CONST
C     UN-IONIZED CONDITIONS
      PEQST=CONST1*TS/RR*.333333
      IP=1
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      WRITE(9,105)
      FLDP=3.98E&05*BS*BS
      BT=PEQST
      WRITE(9,26) FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMOLES,BS)
      WRITE(9,120)
  120 FORMAT(1H0,30X,50HCONDITIONS AT PREHEAT AND INITIAL PRESSURE BALAN
     1CE)
C     FULLY IONIZED GAS-HELIUM
      CONST=1.5*8314.*EMOLES*C4*THREE
      WRITE(9,105)
      DUMMY=IDUMMY(J)
      IF(DUMMY.EQ.0.0) DUMMY=2.0
      TSKEV=DUMMY*.001
      TS=TSKEV*11.6E&06
      PEQST=CONST1*TS/RR
      T=4.0*TAU(J)
      BSS=SQRT(PEQST/3.98E&05)
      BMA1=BMAX(J)
      TA1=TAU(J)
      CALL SHAPE(ITEST1,BSS,CONST7,BMA1,TA1,T,OMEGA)
  123 ISTS=T*1.0E&08
      BS=BSS
      EINIT=TS*CONST
      ELEFT=EINIT
      IP=2
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
```

```
      TEMPP(IP)=TSKEV
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMOLES,BS)
      IF(ITEST.EQ.1)GO TO 110
      IF(ITEST.EQ.2)GO TO 111
      IF(ITEST.EQ.3)GO TO 113
      IF(ITEST.EQ.4)GO TO 114
      IF(ITEST.EQ.5)GO TO 115
      IF(ITEST.EQ.6)GO TO 116
      IF(ITEST.EQ.7)GO TO 117
      IF(ITEST.EQ.8)GO TO 118
  110 RDOTSQ=C5*VTHETA(J)/(EMOLES*SQRT(EMOLES))
      GO TO 112
  111 RDOTSQ=C55*VTHETA(J)**2/EMOLES**3
      GO TO 112
  113 RDOTSQ=C555*VTHETA(J)
      GO TO 112
  114 RDOTSQ=C55*RR*VTHETA(J)/EMOLES
      GO TO 112
  115 RDOTSQ=C55*VTHETA(J)/SQRT(EMOLES)
      GO TO 112
  116 RDOTSQ=C55*VTHETA(J)*SQRT(EMOLES)*RR
      GO TO 112
  117 RDOTSQ=C55*VTHETA(J)*EMOLES*RR
      GO TO 112
C     THIS EQUATION HAS EXPERIMENTAL VALIDITY
  118 RDOTSQ=C555*VTHETA(J)*     (SQRT(100./PO(J)))
      GO TO 112
  112 RDOT=SQRT(RDOTSQ)
      IRDOTC(J)=RDOT*.001
      WRITE(9,28)RDOT
   28 FORMAT(1H0,39HIMPLOSION AND EXPLOSION VELOCITY EQUALS,1P1E16.3)
C     MOLECULAR WEIGHT OF HELIUM
      CONST2=EMOLES*4.0026*RDOTSQ
      RS=RO(J)
      DELTAT=RO(J)*.002/RDOT
      IF(REVB(J).GE.0.0)GO TO 27
      REVTRG=-1.0
      REVB(J)=0.0
   27 T=T&DELTAT
      RS=RS-RDOT*DELTAT
      TA1=TAU(J)
      BMA1=BMAX(J)
      CALL       FIELD(ITEST1,CONST7,T,OMEGA,TA1,BSS,BMA1)
   62 PLEFT=3.98E&05*BSS*BSS
      BSSR=REVB(J)*RR/(RS*RS)
      PREVB=3.98E&05*BSSR*BSSR
      PDYNA=.5*CONST2/(3.14159*RS*RS)
      PLEFT=PLEFT&PDYNA
      IF(ITEST4.EQ.2)PLEFT=PLEFT-PREVB
      ELEFT=(1.0-RS*RS/RR)*CONST2&EINIT
   18 TS=PLEFT/CONST
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```
      IF(TS.LE.TO(J))TS=TO(J)
      PEQST=CONST1*TS/(RS*RS)
      TEST=PLEFT-PEQST
      IF(RS.LT.0.0)GO TO 8
      IF(VTHTST.GT.0.0)GO TC 109
      IF(TEST.LT.0.0)GO TO 27
      VTHTST=&1.0
      WRITE(9,108)
  108 FORMAT(1H0,30X,53HCONDITIONS AT FIRST PRESSURE BALANCE DURING IMPL
     1OSICN)
      WRITE(9,105)
      BS=BSS
      ISTS=T*1.0E&08
      TSKEV=TS/11.6E&06
      BSSR=REVB(J)*RF/(RS*RS)
      VREVB=3.14159*RS*RS
      PREVB=3.98E&05*BSSR*BSSR
      EREVB=PREVB*VREVB
      IP=3
      TPLCT(IP)=ISTS
      RPLCT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMCIES,BS)
      GO TO 27
  109 IF(TEST.GT.0.0)GO TO 27
      BS=BSS
      IF(ITEST3.EQ.2)GO TO 93
      IF(PREVB.GT.PEQST)GO TC 94
      GO TO 93
   94 WRITE(9,91)PREVB,PEQST
   91 FORMAT(1H0,30X,38HREVERSE FIELD PRESSURE DECREASED FROM ,
     11P1E16.5,5X,2HTO,1P1E16.5)
      PREVB=PEQST
   93 VREVB=3.14159*RS*RS
      EREVB=PREVB*3.14159*RS*RS
      STS=T
      ISTS=STS*1.0E&08
      TSKEV=TS/11.6E&06
      WRITE(9,104)
  104 FORMAT(1H0,30X,54HCONDITIONS AT SECOND PRESSURE BALANCE DURING IMP
     1LOSICN)
      WRITE(9,105)
  105 FORMAT(1H ,4X,8HMG FLD P,6X,6HRADIUS,2X,4HTIME,3X,9HMAG FIELD,
     11X,11H  DYNAMIC P,7X,5HT KEV,2X,10HR FLD ENGY,5X,7HR FLD P,
     22X,10HSHOCK ENGY,5X,7HP EQ ST)
      IP=4
      TPLOT(IP)=ISTS
      RPLCT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      BT=PEQST
      FLDP=3.98E&05*BS*BS
```

```
      WRITE(9,26) FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMCIES,BS)
   26 FORMAT(1H ,1P2E12.3,I6,1P7E12.3)
      IF(REVTRG.LT.0.0) GO TO 20
      IF(ITEST2.EQ.1) WRITE(9,106)
      IF(ITEST2.EQ.2) WRITE(9,98)
  106 FORMAT(1H0,30X,51HCONDITIONS AFTER ABSORPTION OF REVERSE FIELD ENE
     1RGY)
   98 FORMAT(1H0,30X,63HCONDITIONS IMMEDIATELY AFTER ABSORPTION OF REVER
     1SE FIELD ENERGY)
      ESAVE=ELEFT
   71 ELEFT=ESAVE&EREVB
      TS=ELEFT/CONST
      PDYNA=0.0
      RDOT=0.0
      PEQST=CONST1*TS/(RS*RS)
      BST=SQRT(PEQST/3.98E&05)
      IF(ITEST2.EQ.2)GO TO 126
      IF(BST.GT.BSS) BSS=BST
      T=2.0*TAU(J)
      BMA1=BMAX(J)
      TA1=TAU(J)
      CALL SHAPE(ITEST1,BSS,CONST7,BMA1,TA1,T,OMEGA)
  126 PLEFT=PEQST
      BS=BSS
      STS=T
      ISTS=STS*1.0E&08
      TSKEV=TS/11.6E&06
      WRITE(9,105)
      IP=5
      TPLOT(IP)=ISTS
      RPLOT(IP)=BS*100.
      TEMPP(IP)=TSKEV
      PREVB=0.0
      EREVB=0.0
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26) FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMCIES,BS)
      IF(ITEST2.EQ.2)GO TO 97
      IF(BS.GT.BMAX(J)) GO TO 8
      IF(STS.GT.TAU(J)) GO TO 8
      GOTO40
   97 WRITE(9,99)
   99 FORMAT(1H0,30X,49HCONDITIONS AT PRESSURE BALANCE AFTER FIRST BOUNC
     1E)
      DELTAT=DELTAT*.10
      RDOT=IRDOTC(J)*1000
      WRITE(9,28) RDOT
   86 VRAT=VREVB/(3.14159*RS*RS)
      PP=PEQST*VRAT**1.667
      PB=3.98E&05*BSS*BSS
      IF(PP.LT.PB) GO TO 90
      RS=RS&RDOT*DELTAT
```

```
      T=T&DELTAT
      TA1=TAU(J)
      BMA1=BMAX(J)
      CALL       FIELD(ITEST1,CONST7,T,OMEGA,TA1,BSS,BMA1)
      GO TO 86
   90 ISTS=T*1.0E&08
      BS=BSS
      PDYNA=0.0
      TS=TS*VRAT**.667
      TSKEV=TS/11.6E&06
      PEQST=PEQST*VRAT**1.667
      ELEFT=TS*CONST
      WRITE(9,105)
      IP=6
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      BT=PEQST
      FLDP=3.98E&05*BS*BS
      WRITE(9,26)FLDP,RS,ISTS,BS,PDYNA,TSKEV,EREVB,PREVB,ELEFT,PEQST
      CALL RATIO(RS,BT,TS,EMOLES,BS)
      GO TO 40
   20 WRITE(9,19)
   19 FORMAT(1H0,43HSECOND HALF CYCLE CALCULATION DOES NOT WORK)
   40 WRITE(9,41)
   41 FORMAT(1H0,30X,29HADIABATIC COMPRESSION FOLLOWS)
      BMA1=BMAX(J)
      TA1=TAU(J)
      CALL SHAPE(ITEST1,BSS,CONST7,BMA1,TA1,T,OMEGA)
      BT=3.98E&05*BS*BS
      CALL RATIO(RS,BT,TS,EMOLES)
  134 IEXXRA=-EXXRA
      WRITE(9,95)IEXXRA
   95 FORMAT(1H0,30X,37HAUGMENTED XRAY YIELD BY A FACTOR OF   ,I10)
      DELTAT=.01*TAU(J)
   50 TA1=TAU(J)
      BMA1=BMAX(J)
      CALL       FIELD(ITEST1,CONST7,T,OMEGA,TA1,BSS,BMA1)
  136 CALL        PLASM(RS,BSS,TS,EXXRA,DELTAT,T,ENEUTS,XRAY,IR,DENS,
     1THREE)
      YIELDC(J)=ENEUTS
      IXRAY(J)=XRAY*(-1.)
      IRR(J)=IR
      T=T&DELTAT
      TSKEV=TS/11.6E&06
      ISTS=T*1.0E&08
      IP=IP&1
      TPLOT(IP)=ISTS
      RPLOT(IP)=RS*100.
      TEMPP(IP)=TSKEV
      IF(T.GE.TCONTA(J))GO TO 1006
      IF(T2.LT.0.0)GO TO 1220
      IF(T5.LT.0.0)GO TO 1230
      IF(T3.LT.0.0)GO TO 1222
```

```
      GO TO 1225
1220 IF(T.GT.6.0E-07) GO TO 1221
      GO TO 1225
1221 CALL        PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
    1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
    2XRAY13,ITP3,T5,IBMAX)
      GO TO 1225
1230 IF(T.GT.1.00E-06) GO TO 1231
      GO TO 1225
1231 CALL        PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
    1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
    2XRAY13,ITP3,T5,IBMAX)
      GO TO 1225
1222 IF(T.GT.1.98E-06) GO TO 1223
      GO TO 1225
1223 CALL        PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
    1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
    2XRAY13,ITP3,T5,IBMAX)
      GO TO 1225
1225 IF(T.GE.TCONTA(J))GO TO 1006
      GOTO50
1006 EEMOL=3.98E&05*BSS*BSS*3.14159*RS*RS/(8314.*TS)
      TOTAL=CONST*TS
      RATIO=EEMOL/EMOLES
      IT7(J)=TS/11.6E&03
      WRITE(9,53) EEMOL,RATIO,TOTAL
   53 FORMAT(1H0,6HMOLES=,1P1E16.5,5X,6HRATIO=,1P1E16.5,5X,
    122HTOTAL INTERNAL ENERGY=,1P1E16.5)
      CALL SPLOT(1,IP,TPLOT,RPLOT,42,1)
      CALL LINCNT(1)
      WRITE(12,25) IPO,IRO,IVTH,BMAX(J),ITAU,REVB(J),IEXXRA
    1,ITEST,ITEST1,ITEST2,ITEST3,ITEST4
      WRITE(12,24)C555,LABEL(J)
      CALL WLCH(244,25,48,LABEL1,1)
      CALL WLCV(40,722,25,LABEL1,1)
      CALL WLCH(440,1002,15,LABEL1(4),1)
      CALL ADV(1)
   25 FORMAT(1H , 1X,9HPRESSURE=,I6,1X,7HRADIUS=,I5,1X,7HVTHETA=,I5,1X,
    15HBMAX=,1P1E11.3,1X,11HQTR PERIOD=,I5,1X,10HREV FIELD=,1P1E11.3,
    21X,6HEXXRA=,I3,1X,5I1)
   24 FORMAT(1H ,1X,2HC=,1P1E10.2,1A10)
      CALL SPLOT(1,IP,TPLOT,TEMPP,42,1)
      CALL LINCNT(1)
      WRITE(12,25) IPO,IRO,IVTH,BMAX(J),ITAU,REVB(J),IEXXRA
    1,ITEST,ITEST1,ITEST2,ITEST3,ITEST4
      WRITE(12,24)C555,LABEL(J)
      CALL WLCH(244,25,48,LABEL2,1)
      CALL WLCV(40,722,25,LABEL2,1)
      CALL WLCH(440,1002,15,LABEL2(4),1)
      CALL ADV(1)
      GO TO 1000
1000 CONTINUE
      WRITE(9,9)(LABL(I),I=1,7)
      WRITE(9,95)IEXXRA
```

```
      WRITE(9,3)ITEST,ITEST1,ITEST2,ITEST3,ITEST4
      WRITE(9,101)
      WRITE(9,11)LABEL(1),RO(1),EL(1),PO(1),TO(1),VTHETA(1),YIELD(1),
     1BMAX(1),TAU(1)
      WRITE(9,100)
      WRITE(9,10)C4,C5,C55,C555,T
      T1=1.0
      T2=1.0
      T5=1.0
      T3=1.0
      T4=-1.0
      CALL        PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
      SUM=0.0
      SUMSQ=0.0
      WRITE(9,1002)
 1002 FORMAT(1H0,7X,5HEXPER,2X,10HCALCULATED,2X,10HDIFFERENCE,7X,5HRATIO
     1,11X,4HEXPT,1X,5HEXP V,1X,5HCAL V,1X,5HP MIC,1X,5HREV B,2X,4HXRAY,
     21X,5HRATIO,2X,4HT EL,1X,5HT ION,2X,4HCALC)
      DO1001J=1,N
      YIELDC(J)=YIELDC(J)*EL(J)
      DELTA    =YIELDE(J)-YIELDC(J)
      DIVIDE    =YIELDC(J)/YIELDE(J)
      WRITE(9,1003)YIELDE(J),YIELDC(J),DELTA    ,DIVIDE    ,LABEL(J),
     1 IRDOTE(J),IRDOTC(J),IPOO(J),IREVB(J),IXRAY(J),IRR(J),ITELEC(J),
     2ITION(J),IT7(J)
 1003 FORMAT(1H ,1P4E12.3,5X,1A10,9I6)
      SUM=SUM&DIVIDE
      SUMSQ=SUMSQ&DIVIDE    *DIVIDE
 1001 CONTINUE
      EN=N
      SUMSQ=SQRT(SUMSQ/EN)
      SUM=SUM/EN
      WRITE(9,1004)
 1004 FORMAT(1H0,9X,7HAVERAGE,9X,7HSTD DEV)
      WRITE(9,1005)SUM,SUMSQ
 1005 FORMAT(1H ,1P2E16.5)
      GO TO 8
      END
      SUBROUTINE PLASM(RPLAS,BSS,TPLAS,EXXRA,DELTAT,T,ENEUTS,XRAY,IR,
     1DENS,THREE)
C         P3= NUMBER OF MOLES
C         GAS CONST=8314. IN MKS
C         HEAT CAPACITY=3/2R PER MOLE
C     FULLY IONIZED HELIUM IS 3 PARTICLES PER MOLE OF UN-IONIZED GAS.
C     ONLY ONE PARTICLE HAS MASS,ELECTRONS NEGLIGABLE.
C         DENS IS ION DENSITY
C         THERE ARE 11.6E&06 KELVIN IN ONE KEV
C         HELIUM    CROSS SECTIONS
C         PRINT FIELD IN KILOGAUSS
      IF(EXXRA.GT.0.0)GO TO 10
      EXXRA=ABS(EXXRA)
      VOL=3.14159*RPLAS*RPLAS
```

```
      VOL1=VOL
      TPLAS2=TPLAS
      PPLAS=3.98E&05*BSS*BSS
      P3=PPLAS*VOL/(8314.*TPLAS)
      CONST=1.5*8314.*P3
      CONST4=P3*6.023E&26*1.0/THREE
      CONST5=5.35E-31*2.0*4.0*1.0E-12*1.0E&06
      PDV1=0.0
      XRAY=0.0
      ENEUTS=0.0
      WRITE(9,51)
   51 FORMAT(1H0,1X,4HTIME,2X,3HFLD,4X,8HION DENS,6X,6HRADIUS,2X,3HV/V,7
     1X,5HT KEV,2X,3HT/T,4X,8HNEUTRONS,7X,5HXRAYS,2X,3HX/E,5X,7HENGY CK,
     26X,5HTOTAL,5X,4HPDV1)
      ELL=1.0
   10 VOL=3.14159*RPLAS*RPLAS
      PPLAS=3.98E&05*BSS*BSS
      DENS=CONST4/VOL
      DENSQ=DENS*DENS
      TPLAS4=TPLAS
      TPLAS=(PPLAS*VOL/(8314.*P3)&TPLAS)/2.0
      TPLAS1=TPLAS/11.6E&06
      TPLAS3=TPLAS1**.33333
      XRAY1=EXXRA*CONST5*DENSQ*SQRT(TPLAS1)
     1*DELTAT*VOL*ELL
      TOTAL=CONST*TPLAS
      XRAY=XRAY-XRAY1
      PDV=-XRAY1-CONST*(TPLAS-TPLAS4)
      PDV1=PDV1&PDV
      RPLAS=RPLAS&PDV/(6.284*PPLAS*RPLAS)
      IT=T*1.0E&08
      IF(RPLAS.LT.0.0)GO TO 53
      IBSS=BSS*10.
      IV=VOL/VOL1*100.
      IS=TPLAS/TPLAS2*100.
      IR=-XRAY*100./TOTAL
      ECK=TOTAL-XRAY&PDV1
      WRITE(9,52)IT,IBSS,DENS,RPLAS,IV,TPLAS1,IS,ENEUTS,
     1XRAY,IR,ECK,TOTAL,PDV1
   52 FORMAT(1H ,2I5,1P2E12.3,I5,1P1E12.3,I5,1P2E12.3,
     1I5,1P1E14.5,1P2E9.1)
      GO TO 55
   53 WRITE(9,54)RPLAS
   54 FORMAT(1H0,30X,31HPLASMA RADIUS HAS GONE NEGATIVE,1P1E16.5)
      T=T*1.0E&10
   55 RETURN
      END
      SUBROUTINE RATIO(RS,BT,TS,EMOLES,BS)
C     BETA SHOULD BE ONE. FOR HELIUM MOLES RATIO SHOULD BE 3.
C        IF THE GAS IS FULLY IONIZED
  134 P1=3.14159*RS*RS
      P2=BT
      P3=P1*P2/(8314.*TS)
      RATIO=P3/EMOLES
```

```
      IF(BT*BS.EQ.0.0)GO TO 108
      BETA=P2/(3.98E&05*BS*BS)
      GO TO 109
  108 BETA=0.0
  109 WRITE(9,107)
  107 FORMAT(1H0,8X,8HPRESSURE,10X,6HVOLUME,11X,5HMOLES,11X,5HRATIO,12X,
     14HBETA)
      WRITE(9,42)P2,P1,P3,RATIO,BETA
   42 FORMAT(1H ,1P5E16.5)
      WRITE(9,106)
  106 FORMAT(1H ,46HP EQ ST MUST EQUAL MG FLD P FOR BETA TO BE 1.0)
      RETURN
      END
      SUBROUTINE SHAPE(ITEST1,BSS,CONST7,BMA1,TA1,T,OMEGA)
      ANGLES=BSS/BMA1
      IF(ANGLES.GE.1.0)GO TO 70
      IF(ITEST1.EQ.1)GO TO 124
      IF(ITEST1.EQ.2)GO TO 125
      IF(ITEST1.EQ.3)GO TO 126
      IF(ITEST1.EQ.4)GO TO 127
  124 T=BSS/CONST7
      GO TO 73
  125 ANGLEC=SQRT(1.0-ANGLES*ANGLES)
      ANGLE=ATAN(ANGLES/ANGLEC)
      T=ANGLE/OMEGA
      GO TO 73
  126 T=TA1*(1.0-SQRT(1.0-ANGLES*ANGLES))
      GO TO 73
  127 T=TA1*SQRT(ANGLES)
      GO TO 73
   70 WRITE(9,72)
   72 FORMAT(1H0,30X,20HERROR IN CALCULATION)
   30 WRITE(9,31)
   31 FORMAT(1H0,28HNO FURTHER SOLUTION POSSIBLE)
      T=TA1*1.01
   73 RETURN
      END
      SUBROUTINE FIELD(ITEST1,CONST7,T,OMEGA,TA1,BSS,BMA1)
C     CROWBAR MUST OCCUR INSIDE ADIABATIC COMPRESSION
C     FOR OPTIONS 3 AND 4.
C        FIELD IS ETHETA*TIME
      IF(ITEST1.EQ.1)GO TO 89
C        FIELD CAUSED BY CAPACITOR BANK
      IF(ITEST1.EQ.2)GO TO 88
C        FIELD CAUSED BY GENERATOR     SPIRAL
      IF(ITEST1.EQ.3)GO TO 87
C        FIELD CAUSED BY GENERATOR     PLATE
      IF(ITEST1.EQ.4)GO TO 90
   89 BSS=CONST7*T
      GO TO 86
   88 BSS=BMA1*SIN(OMEGA*T)
      GO TO 86
   87 IF(T.GE.TA1)GO TO 91
      BSS=BMA1/TA1*SQRT(T*(2.0*TA1-T))
```

```
      GO TO 86
   90 IF(T.GE.TA1)GO TO 91
      BSS=BMA1*(T/TA1)**2.0
   86 RETURN
   91 BSS=BMA1
      GO TO 86
      END
      SUBROUTINE PRINT1(T1,T2,T3,T4,IREVB,IPOO,DENS1,DENS2,ENUT1,ENUT2,
     1XRAY11,XRAY12,ITP1,ITP2,DENS,XRAY,TS,ENEUTS,J,N,DENS3,ENUT3,
     2XRAY13,ITP3,T5,IBMAX)
      DIMENSION IREVB(40),IPOO(40),DENS1(40),DENS2(40),ENUT1(40),
     1ENUT2(40),XRAY11(40),XRAY12(40),ITP1(40),ITP2(40),DENS3(40),ENUT3
     2(40),XRAY13(40),ITP3(40),IBMAX(40)
C     T1 CONTROLS INITIALIZING
C     T2 STORES FIRST SET OF DATA AT 0.6 MICROSECOND
C     T5 STORES THIRD SET OF DATA AT 1.00 MICROSECONDS
C     T3 STORES SECOND SET OF DATA AT 2.0 MICROSECONDS
C     T4 CONTROLS OUTPUT PRINTING
      IF(T1.LT.0.0)GO TO 1200
      IF(T2.LT.0.0)GO TO 1201
      IF(T5.LT.0.0)GO TO 1210
      IF(T3.LT.0.0)GO TO 1202
      IF(T4.LT.0.0)GO TO 1203
      GO TO 1205
 1200 T1=1.0
      DENS1(J)=0.0
      DENS2(J)=0.0
      DENS3(J)=0.0
      ENUT1(J)=0.0
      ENUT2(J)=0.0
      ENUT3(J)=0.0
      XRAY11(J)=0.0
      XRAY12(J)=0.0
      XRAY13(J)=0.0
      ITP1(J)=0.0
      ITP2(J)=0.0
      ITP3(J)=0.0
      GO TO 1205
 1201 T2=1.0
      DENS1(J)=DENS
      ENUT1(J)=ENEUTS
      XRAY11(J)=XRAY
      ITP1(J)=TS/11.6E&03
      GO TO 1205
 1210 T5=1.0
      DENS3(J)=DENS
      ENUT3(J)=ENEUTS
      XRAY13(J)=XRAY
      ITP3(J)=TS/11.6E&03
      GO TO 1205
 1202 T3=1.0
      DENS2(J)=DENS
      ENUT2(J)=ENEUTS
      XRAY12(J)=XRAY
```

```
      ITP2(J)=TS/11.6E&03
      GO TO 1205
 1203 T4=1.0
      WRITE(9,1204)
 1204 FORMAT (1H0,5X,33HSUMMARY TABLE AT 0.6 MICROSECONDS)
      WRITE(9,1206)
 1206 FORMAT (1H0,4X,8HPRESSURE,1X,11HREVERSE FLD,1X,11HION DENSITY,
     14X,8HNEUTRONS,7X,5HXRAYS,5X,7HTEMP EV,3X,9HDRIVE FLD)
      WRITE(9,1207) (IPOO(J),IREVB(J),DENS1(J),ENUT1(J),XRAY11(J),
     1ITP1(J),IBMAX(J),J=1,N)
 1207 FORMAT(1H ,2I12,1P3E12.4,2I12)
      WRITE(9,1211)
 1211 FORMAT(1H0,5X,34HSUMMARY TABLE AT 1.00 MICROSECCNDS)
      WRITE(9,1206)
      WRITE(9,1207) (IPOO(J),IREVB(J),DENS3(J),ENUT3(J),XRAY13(J),
     1ITP3(J),IBMAX(J),J=1,N)
      WRITE(9,1208)
 1208 FORMAT (1H0,5X,33HSUMMARY TABLE AT 2.0 MICROSECONDS)
      WRITE(9,1206)
      WRITE(9,1207) (IPOO(J),IREVB(J),DENS2(J),ENUT2(J),XRAY12(J),
     1ITP2(J),IBMAX(J),J=1,N)
 1205 RETURN
      END
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☆ U.S. GOVERNMENT PRINTING OFFICE: 1982-0-576-020/30

Printed in the United States of America
Available from
National Technical Information Service
US Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Microfiche $3.50 (A01)

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