Thermonuclear Burn Characteristics of Compressed DT Pellets

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Abstract

Thermonuclear yield, gain on core, fuel fractional burnup, and representative charged particle and X-ray spectra are computed for "micro core ignited", bare, deuterium-tritium pellet cores as functions of pellet core mass, density-radius product and microcore density radius product using a plasma hydrodynamic-thermonuclear burn-radiative transfer computer code. Numerical results are fitted by simple analytic expressions and the optimum core conditions for producing 100 MJ of energy yield, a range of interest for reactor applications, are identified as 1 mg of DT and a density-radius product of 3 g/cm^2. The gain of this pellet is 120 assuming a 5% implosion efficiency and this would be acceptable for a power plant if an 8% efficient laser is used. The yield sensitively depends on the density-radius product of the micro core where this value must be at least 0.4 g/cm^2 to achieve significant yield, however, any value greater than this will result in approximately the same yield. The X-ray spectrum at the surface of the bare pellet constitutes 1% of the energy release and is peaked at 7 keV. Thirty-three percent of the charged particle reaction products escape with 19% of their total initial energy, and spectra of these are also given.

1. Introduction

The two most fundamental parameters characterizing laser fusion pellet performance in the context of reactor applications are thermonuclear yield (Y) and pellet gain (G_p). The thermonuclear yield is energy in the form of neutrons, charged particles, and X-rays and the pellet gain is the ratio of thermonuclear yield energy to incident laser light energy (E_L). From purely engineering feasibility arguments, the yield and gain necessary for a practical laser fusion reactor can be specified. The yield and micro-explosion repetition rate will determine the thermal output of a reactor. For instance, 3000 MW thermal output might be achieved with a repetition rate of 30 Hz and a yield of 100 MJ/shot. The necessary pellet gain is determined by the fraction of electrical energy that must be recirculated to drive the power plant itself. Assuming the laser requires the greatest fraction of energy, the relation between the relevant plant efficiencies and the pellet gain can be expressed as[1]

$$G_p = \left[\frac{1}{\eta_L(\eta_{th} - \eta_p)}\right] - 1 \qquad (1.1)$$

where

η_L = laser efficiency

η_{th} = gross plant thermal efficiency

η_p = net plant thermal efficiency

For $\eta_L = .10$, $\eta_p = .30$, and $\eta_{th} = .40$, the pellet gain must be 100. Should the laser efficiency be only 1%, then the necessary gain is increased to 1000.

To relate the pellet gain to laser-plasma dynamics, G_p is most conveniently expressed as the product of gain on core (G_c) and hydrodynamic efficiency (η_H).

$$G_p = G_c \, \eta_H \tag{1.2}$$

This relation assumes that the implosion process ultimately results in a pellet core composed of fusion fuel that is highly compressed and heated to thermonuclear ignition conditions. This core may be surrounded with a tamper material that aids the implosion process. The remainder of the pellet is assumed to not play a significant role in the thermonuclear burn dynamics. It has presumably been ablated away in order to compress and/or heat the pellet core. The gain on core is then the ratio of thermonuclear yield to the internal energy of the pellet core (E_c) at the instant of ignition, and the hydrodynamic efficiency is the ratio of internal energy in the pellet core to the incident laser energy.

$$\begin{aligned} G_c &= Y/E_c \\ \eta_H &= E_c/E_L \end{aligned} \tag{1.3}$$

Under the above assumptions, the gain on core will be determined by the thermonuclear burn process and the conditions in the core at the time of ignition. The details of the implosion process; including the complexities of laser light absorption in the plasma, energy transfer via thermal conduction, nonthermal particles and X-rays, and two-dimensional effects such as fluid instabilities and self-generated magnetic fields will determine the hydrodynamic efficiency. This decoupling of the implosion and thermonuclear burn phases of the pellet dynamics suggests that yield and gain on core can be studied without specifying the details of the implosion process. Such an analysis can define the most attractive core configuration while leaving to more sophisticated computer modelling the problem of how to achieve such a configuration.

One pellet core initial condition of interest is shown in Fig. 1. The core is a constant density, adiabatically compressed, deuterium-tritium (DT) sphere with a central hot microcore. Only the microcore is heated to ignition conditions while the surrounding plasma is kept as cold as possible.[2] The spherical core is characterized by its mass (m), density-radius product (ρR), temperature (T), and the microcore density-radius product (ρR_μ) and temperature (T_μ).

In this report we compute the thermonuclear yield, gain on core, fuel fractional burnup, and representative charged particle and X-ray spectra for the core shown in Fig. 1 and for the above parameters taken within a range of interest for laser fusion reactor applications. In Section 2, the computer code used to model the thermonuclear burn is briefly described and in Section 3, the results are presented.

2. Description of the Model

The thermonuclear burn dynamics is modelled using the PHD-IV plasma hydrodynamics-thermonuclear burn-radiative transfer computer code.[3] PHD-IV solves the one-dimensional, one fluid, two temperature (electron and ion) plasma hydrodynamics equations in Lagrangian form. It also computes DT and DD reaction rates, accounting for the depletion of these species, and transports the charged particle thermonuclear reaction products using a time dependent particle tracking algorithm[4] that redeposits the energy and momentum of the reaction products back into the thermal plasma using a collisional slowing down model. Bremsstrahlung X-radiation is transported using a time dependent, multi-frequency group, variable Eddington technique.

3. Results

Pellet core masses of 0.1 mg to 1.0 mg were chosen to bound the estimated necessary mass required to give a yield of interest for reactor applications. Approximately 0.3 mg of DT totally burned will provide 100 MJ of energy with 17.6 MeV per reaction.[5] The ranges of all parameters studied are summarized as follows:

$$
\begin{aligned}
1 &\leq \rho R\ (g/cm^2) \leq 7 \\
0.3 &\leq \rho R_{\mu} (g/cm^2) \leq 0.7 \\
10^{-4} &\leq m(g) \leq 10^{-3} \\
T &= 1\ (ev)\ (\rho/\rho_{solid})^{2/3} \\
T_{\mu} &= 10\ keV.
\end{aligned}
\tag{1.3}
$$

The temperature of the microcore was fixed at 10 keV while the surrounding core temperature was computed for the adiabatic compression of a 1 eV plasma. This must be done in a consistent manner because it will strongly effect the gain on core. Most of the internal energy of the core is in the cold compressed part because the microcore is such a small fraction of the total mass.

For the pellet core of Fig. 1, the burn progresses in two steps. First, the hot microcore must have a density-radius product great enough to recapture a significant amount of charged particle reaction product energy in order for it to "bootstrap" heat itself to greater than 20 keV. Then, once the center is heated, a burn wave propagates outward, driven by the charged particle reaction products from the central hot spot. This burn wave heats the surrounding plasma to thermonuclear conditions as it propagates out from the center of the core. In this way, the entire pellet core is ultimately heated while initially only a central hot microcore is necessary, Fig. 2.

Such a process can greatly increase the gain on core because E_c is much less than if the entire pellet core was heated to 10 keV.[6]

In Fig. 3, the yield is plotted as a function of the density-radius product of the microcore and it is seen that the dependence is of a threshold nature. Below $\rho R_\mu = 0.38$ g/cm^2, the yield is negligible while above this value the yield is almost constant. The dramatic drop in yield below $\rho R_\mu = 0.38$ g/cm^2 can be attributed to the failure of the first step in the burn process. Without self-heating of the microcore, the second step (where most of the yield energy originates) does not occur at all, and the gain of the microcore alone is only about 10. Taking the microcore size to the maximum limit, that is a uniformly heated 10 keV core, results in a yield identical to the $\rho R_\mu = 0.5$ g/cm^2 case. Fig. 4 plots the integrated 14 MeV neutron yield as a function of time from ignition. It is seen that the uniform temperature case burns to the same high yield more quickly than the microcore case, however the microcore case has a gain on core 55.4 times higher than the uniform temperature case. The 25 psec time lag between the two cases is equal to the time that the burn wave takes to propagate from the microcore to the outer edge of the core. Since this occurs before the pellet can disassemble, the microcore case subsequently burns the same as the uniform temperature case with no degradation in yield.

The yield plotted as a function of total core "ρR" is shown in Fig. 5. The yield increases rapidly up to 3 g/cm^2 and then does not increase much more. The same behavior is seen for all these masses and the yield is linearly proportional to the mass. These results can be fitted with simple functions to provide more convenient analytic estimates of yield and gain on core as functions of the pellet core parameters. The yield is expressed to within a few percent by the expression

$$Y = 10^3 \; m \; H(\rho R_\mu - 0.38) \begin{Bmatrix} [16 + 60(\rho R - 1)^{.585}] & 1 < \rho R < 3 \\ [71 + 11 \; \rho R \qquad] & 3 \leq \rho R < 7 \end{Bmatrix} \tag{3.2}$$

and the internal energy invested in the core is

$$E_c = (.32) \; (\tfrac{4\pi}{3})^{1/3} \; m^{2/3} \; \rho R + (38.3) \; (\tfrac{4\pi}{3})^{1/2} \; \frac{(\rho R_\mu)^{3/2}}{m_\mu^{1/2}} \; T_\mu \tag{3.3}$$

where Y is the yield in MJ, m is the core mass in grams, H is a step function, ρR is the density-radius product in grams/cm^2, E_c is the core internal energy in MJ, ρR_μ is the density-radius product of the microcore in grams/cm^2, m_μ is the microcore mass in grams and T_μ is the microcore temperature in keV. The ratio of Eq. (3.2) and Eq. (3.3) will give an expression for the gain on core. In most cases of interest, the second term in Eq. (3.3), the energy invested in heating the microcore, will be considerably smaller than the first term and the ρR of interest will be between 3 g/cm^2 and 7 g/cm^2, so the gain on core can be given as

$$G_c = 2.1 \times 10^4 \; m^{1/3} \; [1 + 6.45/\rho R] \; , \tag{3.4}$$

assuming that the microcore conditions are met. Using these analytic fits to the computed results, a 100MJ iso-yield contour is plotted for the ρR and mass parameters in Fig. 6. The gain on core (computed as the ratio of Eq. (3.2) and (3.3)) for the locus of points on this line is plotted in Fig. 7 and we see that it reaches a maximum at about ρR = 3 g/cm^2. This indicates that 3 g/cm^2 and 1 mg are the optimum parameters for producing 100 MJ of energy.

Using 5% as the hydrodynamic efficiency and also assuming that the implosion process results in twice as much energy in the pellet core as our adiabatic estimate, the maximum gain on core of 4800 from Fig. 7 translates into an overall pellet gain of 120. As discussed in Section 1, this pellet gain would be adequate for a 3000 MW thermal laser fusion reactor provided the laser efficiency is 10%. Since the yield is linearly dependent on core mass, the fractional burn up takes the same functional form as the yield.

$$f_B = \left\{ \begin{array}{ll} [0.05 + 0.1875\ (\rho R - 1)^{.585}] & 1 < \rho R < 3 \\ [0.21 + 0.033\ \rho R] & 3 \leq \rho R < 7 \end{array} \right\} . \qquad (3.5)$$

The fractional burnup of the optimum (100 MJ) core is 31% while the fractional burnup at $\rho R = 7\ g/cm^2$ is only 42%. In a reactor application, the fractional burnup will be important to the design of the tritium recovery system where a high value is desired; however, we see from this analysis that the highest possible fractional burnup is not the most optimum for pellet gain. Since adequate pellet gain is only marginal for a 1 mg core and an implosion efficiency of 5%, optimum gain on core must be considered most important.

In addition to the total energy yield, the fraction of energy in neutrons, charged particles, and X-rays along with their spectra are important to the design of the reactor first wall. In this analysis, the neutrons are assumed to escape the pellet but the charged particle and X-ray spectra are computed. For the 100 MJ, $\rho R = 3\ g/cm^2$ pellet core, 80% of the energy escapes as neutrons, 19% as charged particles and 1% as X-rays. The charged particle spectrum consists of two components: (1) the non-thermal fusion reaction products ($_2He^4$, $_1T^3$, $_1H^1$, $_2He^3$) that escape from the surface of the pellet core and (2) the thermal core itself consisting of D, T and thermalized $_2He^2$, $_1H^1$, and $_2He^3$ which explodes with a very high directed velocity. The non-thermal time integrated alpha particle spectrum emerging from the pellet core surface is plotted in Fig. 8. Since PHD-IV does a "Monte-Carlo like" charged particle transport calculation, particles emerge from the surface at many different energies. These particles are then accumulated into energy groups, which explains the histogram nature of the spectrum. Most of the spectrum is fairly flat with an average alpha particle energy of 1.8 MeV in the laboratory frame of reference. Alpha particles with energy greater than 3.5 MeV are seen in the laboratory frame of reference because the outside of the pellet has a large directed motion. Thirty-three percent of the 3.6×10^{19} alpha particles created during the thermonuclear burn escape from the pellet core and carry 3.8 MJ or 19% of their initial energy. The other 81% of the energy is deposited into the thermal electrons and ions. Only 1.29 x 10^{17} DD fusion events occurred, providing less than 1% of the total yield. The spectra of the DD reaction products are plotted in Fig. 9. The disassembling thermal plasma has almost all of its energy in radial fluid motion with ion energies ranging from 100-2500 keV and an average energy of about 400 keV/ion. The velocity decreases monotonically toward the center of the pellet core.

The ten frequency group, time integrated X-ray spectrum at the pellet core surface is plotted in Fig. 10. For this 100 MJ pellet core, the total X-ray energy is about 1 MJ and the spectrum peaks at 7 keV. The absence of low energy photons is due to the increased absorption of the bremsstrahlung at low frequencies by the pellet core.

To test the sensitivity of the thermonuclear burn results to uncertainties in the charged particle collisional slowing down mechanism, the slowing down coefficients in PHD IV were enhanced by a factor of ten and calculations were rerun for "ρR" values between 1 g/cm^2 and 3 g/cm^2. Such an enhancement might be due to collisionless slowing down mechanisms. These results are plotted in Fig. 11. As expected, at higher "ρR" there is no difference between the enhanced and unenhanced cases, but at low "ρR" values the difference between the two cases is not very dramatic either. At 1 g/cm^2, the yield is increased by only about 50%. Furthermore, variations in computer code parameters such as the number of finite difference zones, the number of angular directions used in the charged particle transport calculation, and the number and length of time steps made little difference in the total thermonuclear yield results, however the non-thermal charged particle spectra were affected somewhat. For the results presented here, the PHD-IV code was run using parameters in a range where results were insensitive to them.

4. Conclusions

The purpose of these results has been to draw a complete and consistent picture of the thermonuclear burn process for a "microcore ignited", bare, DT pellet core for a range of fuel masses that provide an energy yield and gain of interest for laser fusion reactor applications (100 MJ). It is found that the yield depends linearly on the DT fuel mass (for this range of masses) and the "ρR" and mass values that optimize the gain on core are 3 g/cm^2 and 1 mg for a 100 MJ yield. This corresponds to a fractional fuel burnup of 31%. The "ρR" value of the microcore that is necessary to promote "bootstrap heating" is 0.38 g/cm^2 and the total yield depends very sensitively on this parameter. For $\rho R_\mu < 0.38$ g/cm^2 the yield is negligible while for $\rho R_\mu > 0.38$ g/cm^2 the yield is almost constant, for the same total "ρR" value. In fact, a uniformly heated pellet core of 3 g/cm^2 burns to the same yield as a 3 g/cm^2 core with a 0.5 g/cm^2 microcore. The gain on core in the microcore case is, however, 55.4 times as large as the uniform temperature case due to the reduced amount of energy initially invested in the core. The increased gain on core for the microcore case is crucial to the performance of such pellet cores for reactor applications. Under the rather ideal conditions of compressing the core to a state with only twice as much energy as the adiabatic lower limit, the optimum gain on core produces an overall pellet gain of 120. This is adequate only if the laser efficiency is at least 8%.

The spectrum of non-thermal alpha particles escaping from the pellet surface is rather flat with an average energy of 1.8 MeV, however, 81% of the charged particle energy is in the thermal exploding plasma core. The energy of directed motion of this plasma is about 400-500 keV/ion. The time integrated X-ray spectrum contains 1% of the thermonuclear yield, 1 MJ, and peaks at 7 keV with the low frequency radiation absorbed by the pellet.

Acknowledgement

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References

1. R. W. Conn, et al., UWFDM-190, "Studies of the Technological Problems of Laser Driven Fusion Reactors," p. II-A-10.

2. G. S. Fraley, E. J. Linnebur, R. J. Mason, and R. L. Morse, Phys, Fluids 17, 474 (1974).

3. G. A. Moses and G. Magelssen, UWFDM-194, "PHD-IV, A Plasma Hydrodynamics-Thernonculear Burn-Radiative Transfer Computer Code".

4. G. A. Moses, UWFDM-195, "Charged Particle Transport by Time Dependent Particle Tracking".

5. Ref. 1, p. II-A-14.

6. R. E. Kidder, Nucl. Fus. 16, 3 (1976).

Figure Captions

FIG. 1 - Schematic of compressed pellet core with density, ρ, and hot central microcore at temperature, T_μ.

FIG. 2 - Thermonuclear burn wave propagating away from a central, hot microcore.

FIG. 3 - Thermonuclear yield, with Q_{DT} = 17.6 MeV, plotted as a function of microcore density-radius product.

FIG. 4 - Integrated 14 MeV neutron yield plotted as a function of time from the initiation of burn for a microcore ignited core and a uniformly heated core.

FIG. 5 - Thermonuclear yield plotted as a function of total core density-radius product.

FIG. 6 - A 100 MJ iso-yield contour. Any combination of ρR and mass falling on this contour will yield 100 MJ of energy.

FIG. 7 - Gain on core for the ρR-mass points that fall on the 100 MJ iso-yield contour.

FIG. 8 - Non-thermal, time integrated alpha particle spectrum emerging from the surface of a 3 g/cm^2 DT pellet core.

FIG. 9 - Non-thermal, time integrated spectra of the DD charged particle reaction products emerging from the surface of a 3 g/cm^2 DT pellet core.

FIG. 10 - Ten frequency group, time integrated X-ray spectrum emerging from the surface of a 3 g/cm^2 DT pellet core.

FIG. 11 - Thermonuclear yield plotted as a function of core ρR for normal collisional charged particle slowing down and collisional slowing down enhanced by a factor of ten.

COMPRESSED PELLET CORE

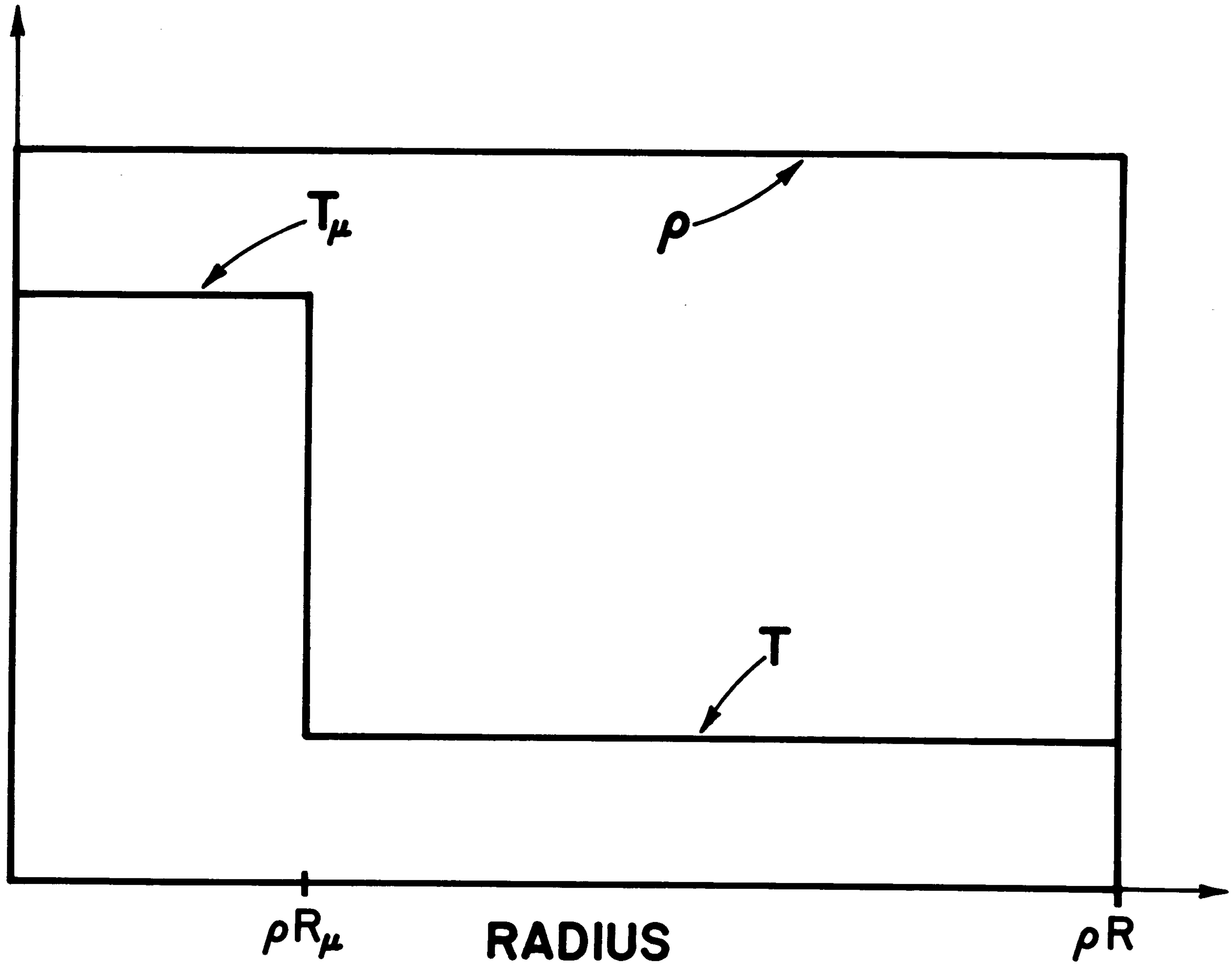
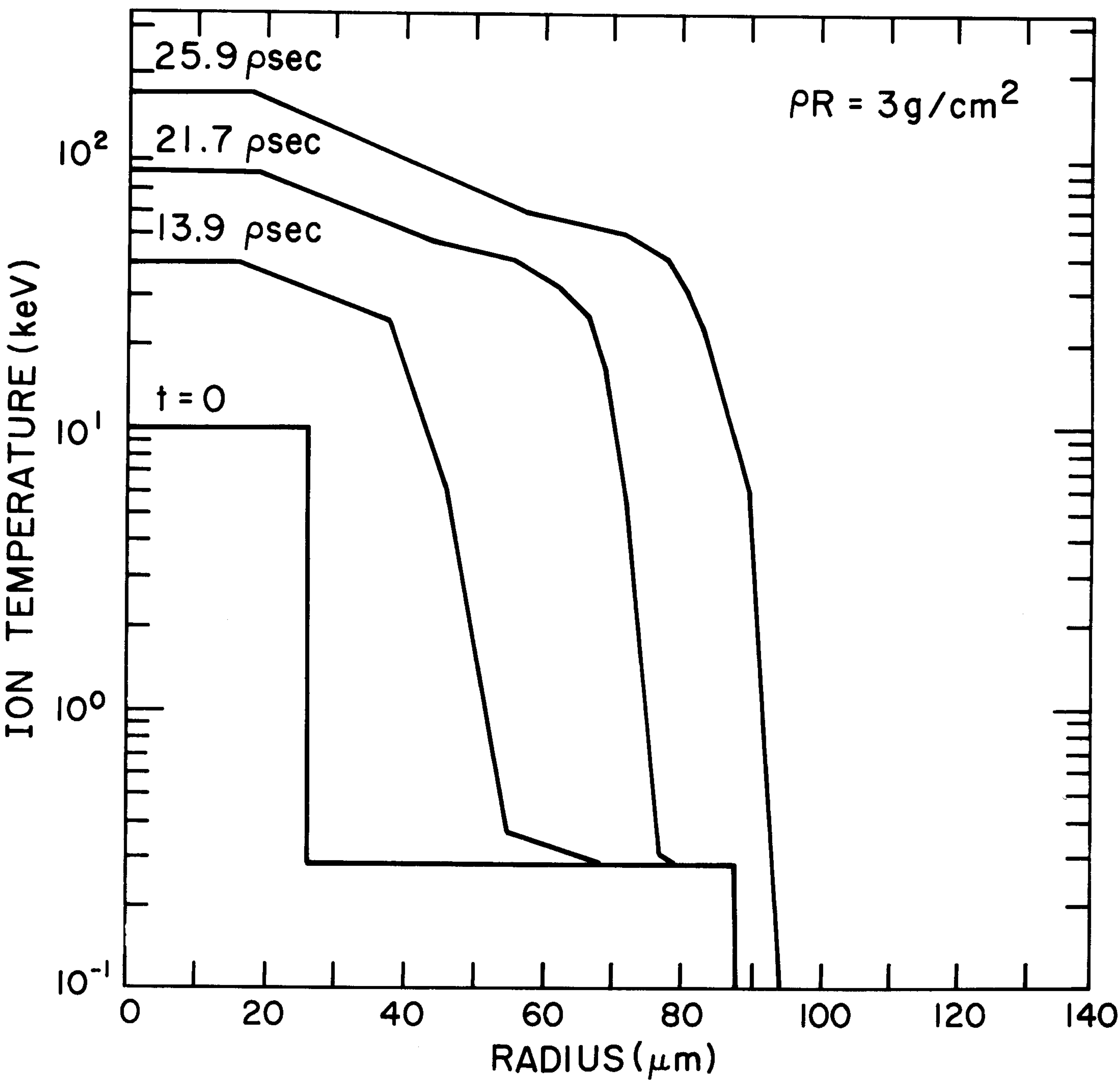
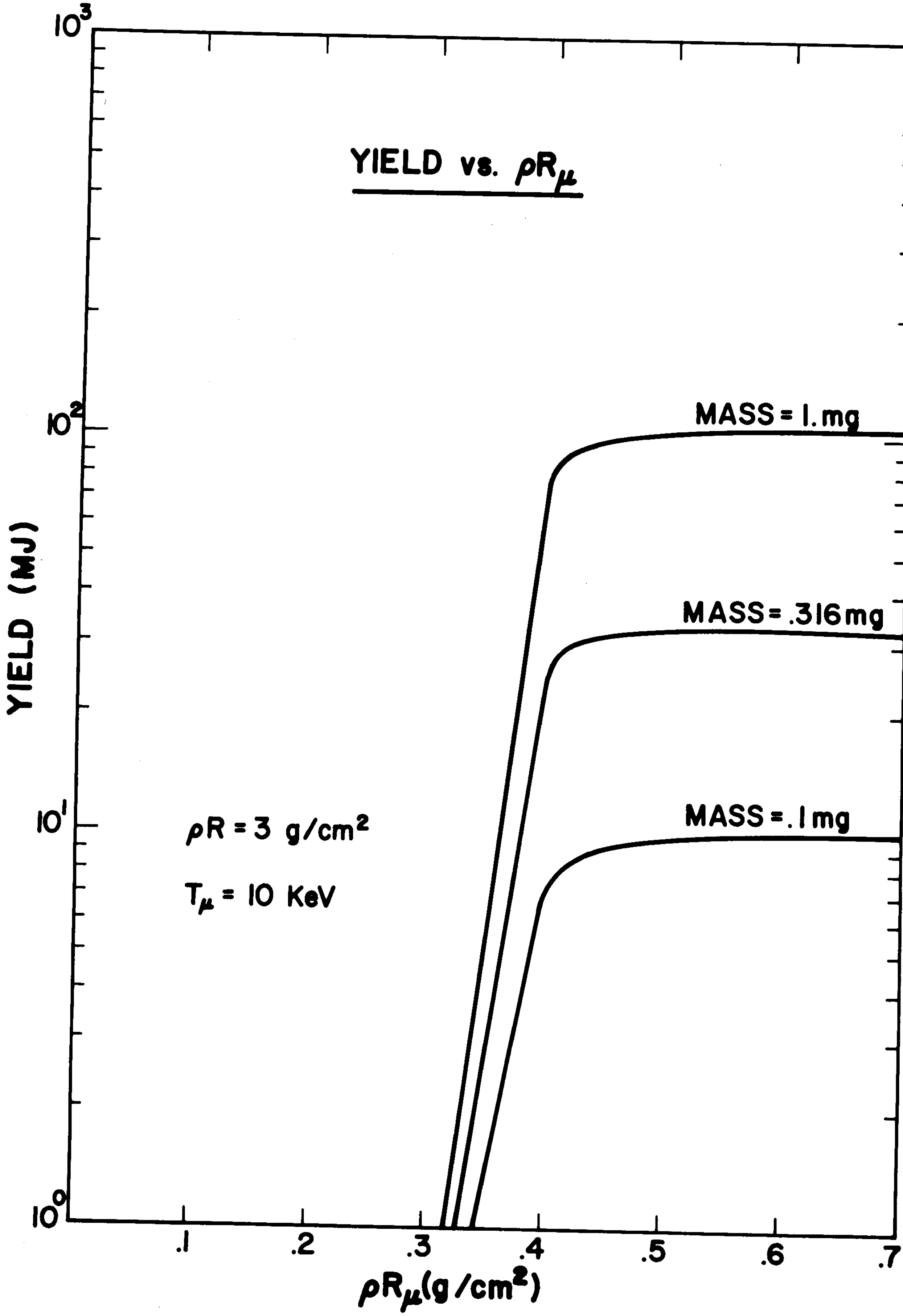


Figure 1

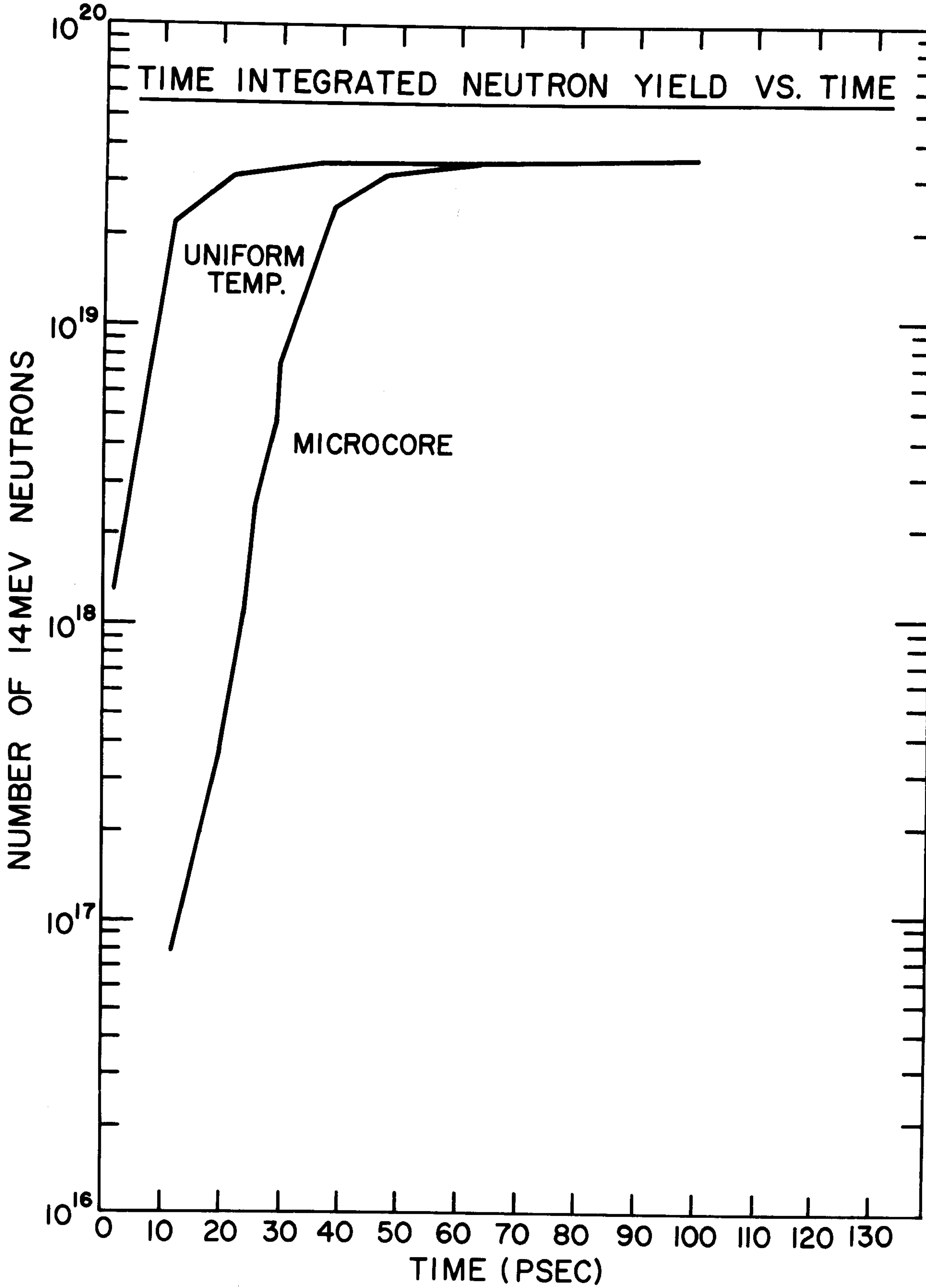
FIG. 2 PROPAGATING BURN FROM 10keV MICROCORE





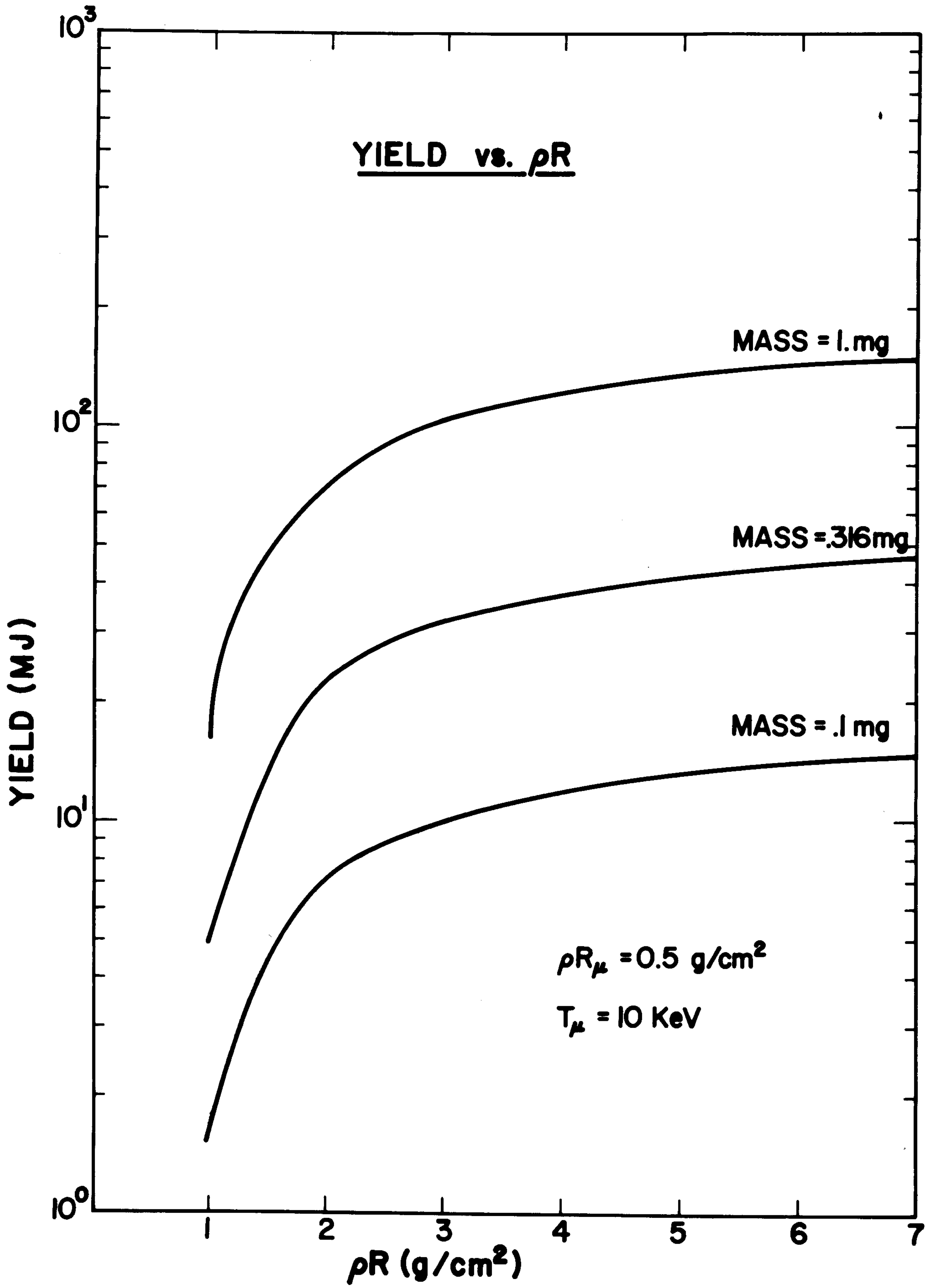
YIELD vs. ρR_μ
YIELD (MJ)
10^3
10^2
10^1
10^0
MASS = 1. mg
MASS = .316 mg
MASS = .1 mg
$\rho R = 3$ g/cm²
T_μ = 10 KeV
.1
.2
.3
.4
.5
.6
.7
ρR_μ(g/cm²)

Figure 3



TIME INTEGRATED NEUTRON YIELD VS. TIME
UNIFORM TEMP.
MICROCORE
NUMBER OF 14MEV NEUTRONS
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
0 10 20 30 40 50 60 70 80 90 100 110 120 130
TIME (PSEC)

Figure 4



YIELD vs. ρR
MASS = 1.mg
MASS = .316mg
MASS = .1 mg
ρRμ = 0.5 g/cm2
Tμ = 10 KeV
YIELD (MJ)
ρR (g/cm2)
10^3
10^2
10^1
10^0
1
2
3
4
5
6
7

Figure 5

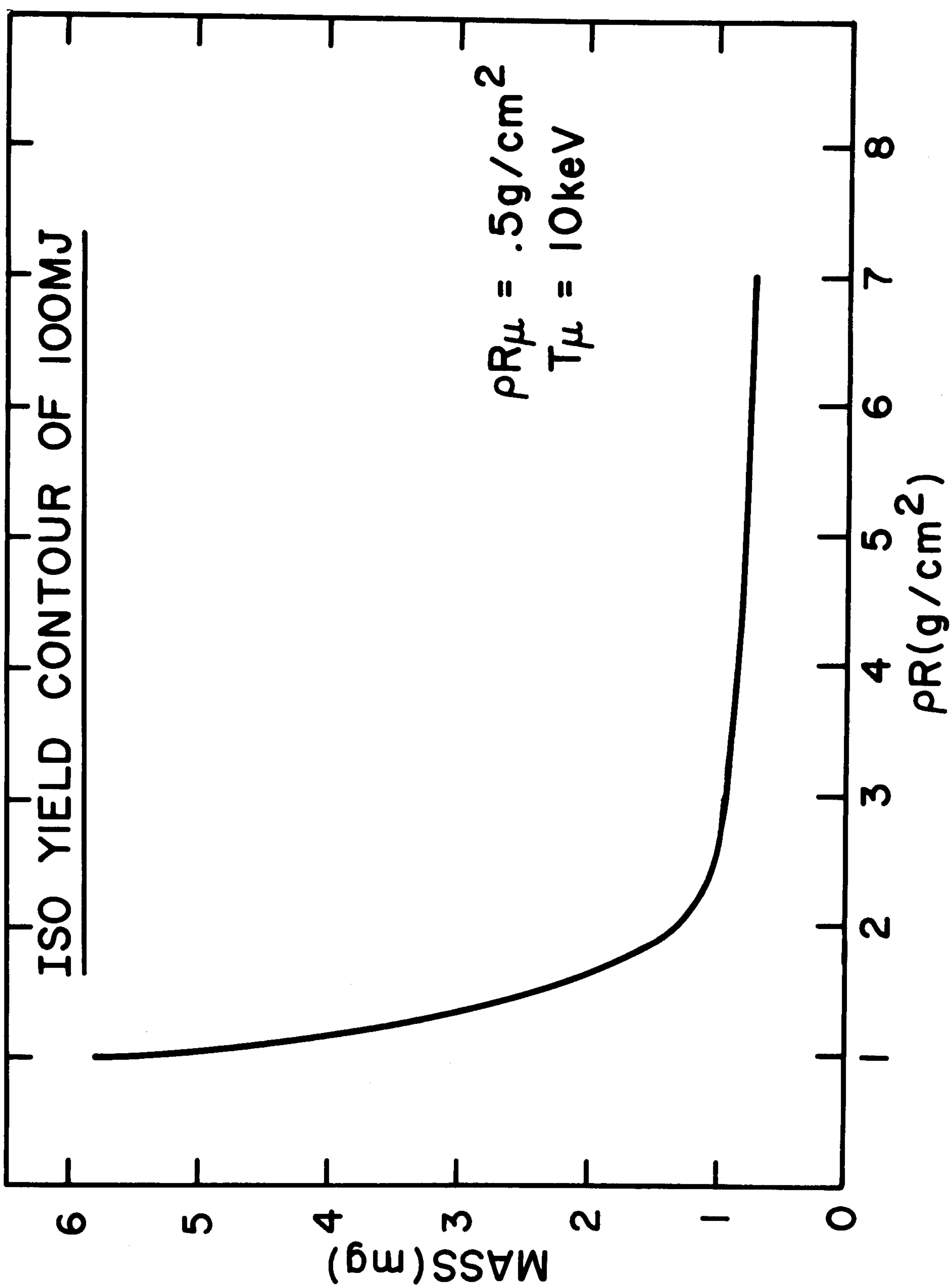

ISO YIELD CONTOUR OF 100MJ
ρRμ = .5g/cm2
Tμ = 10keV
ρR(g/cm2)
MASS(mg)
1 2 3 4 5 6 7 8
0 1 2 3 4 5 6

Figure 6

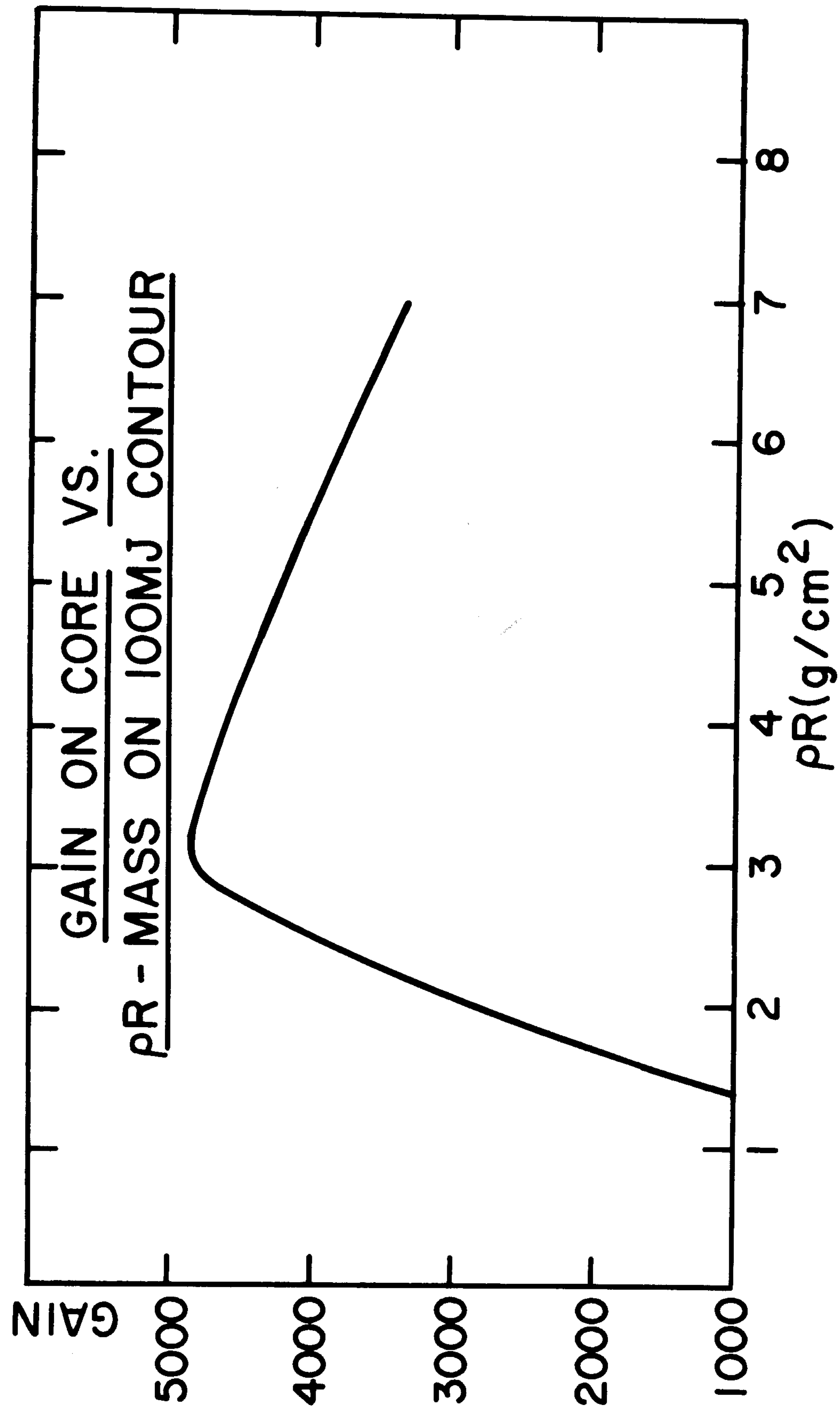
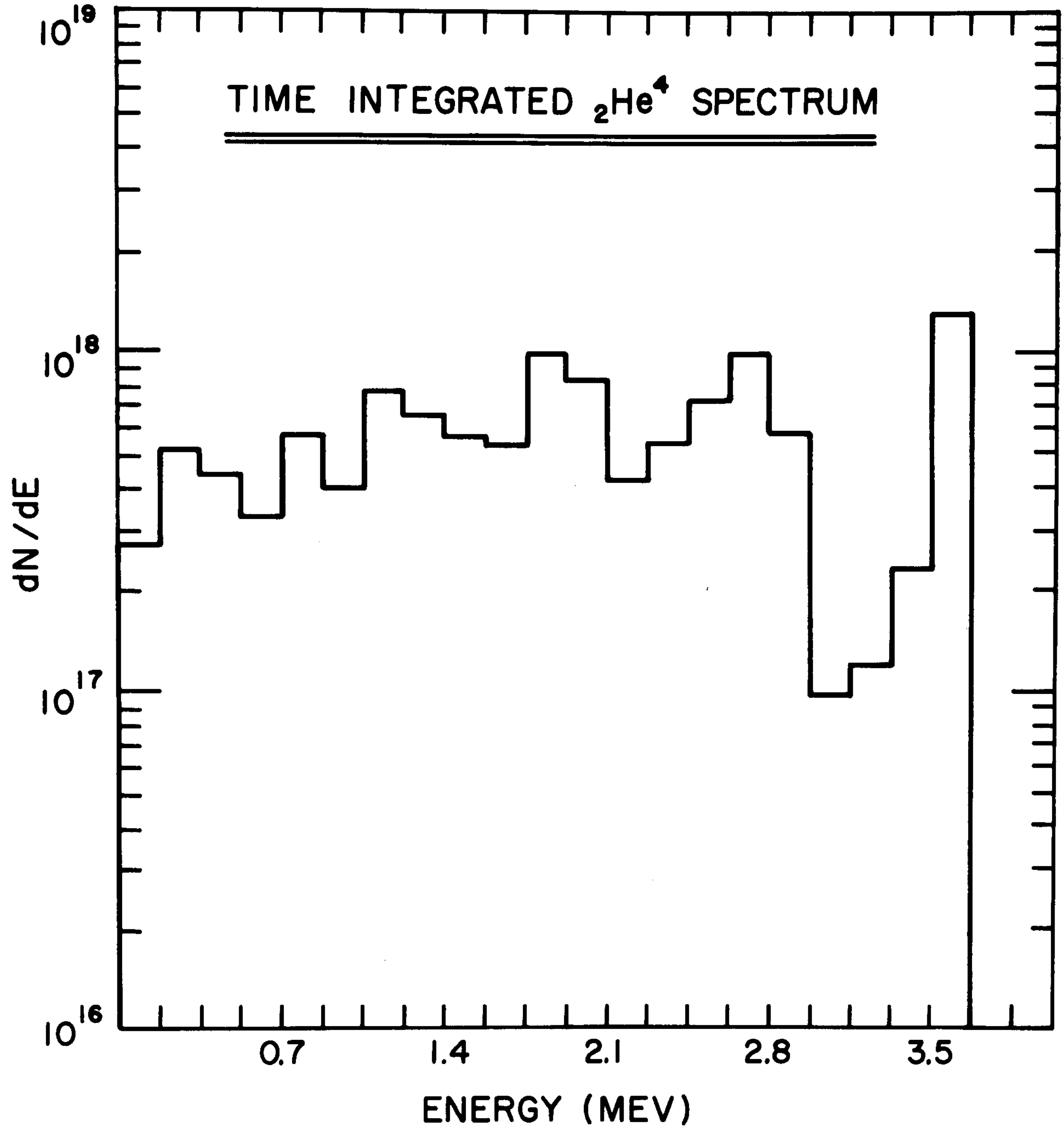
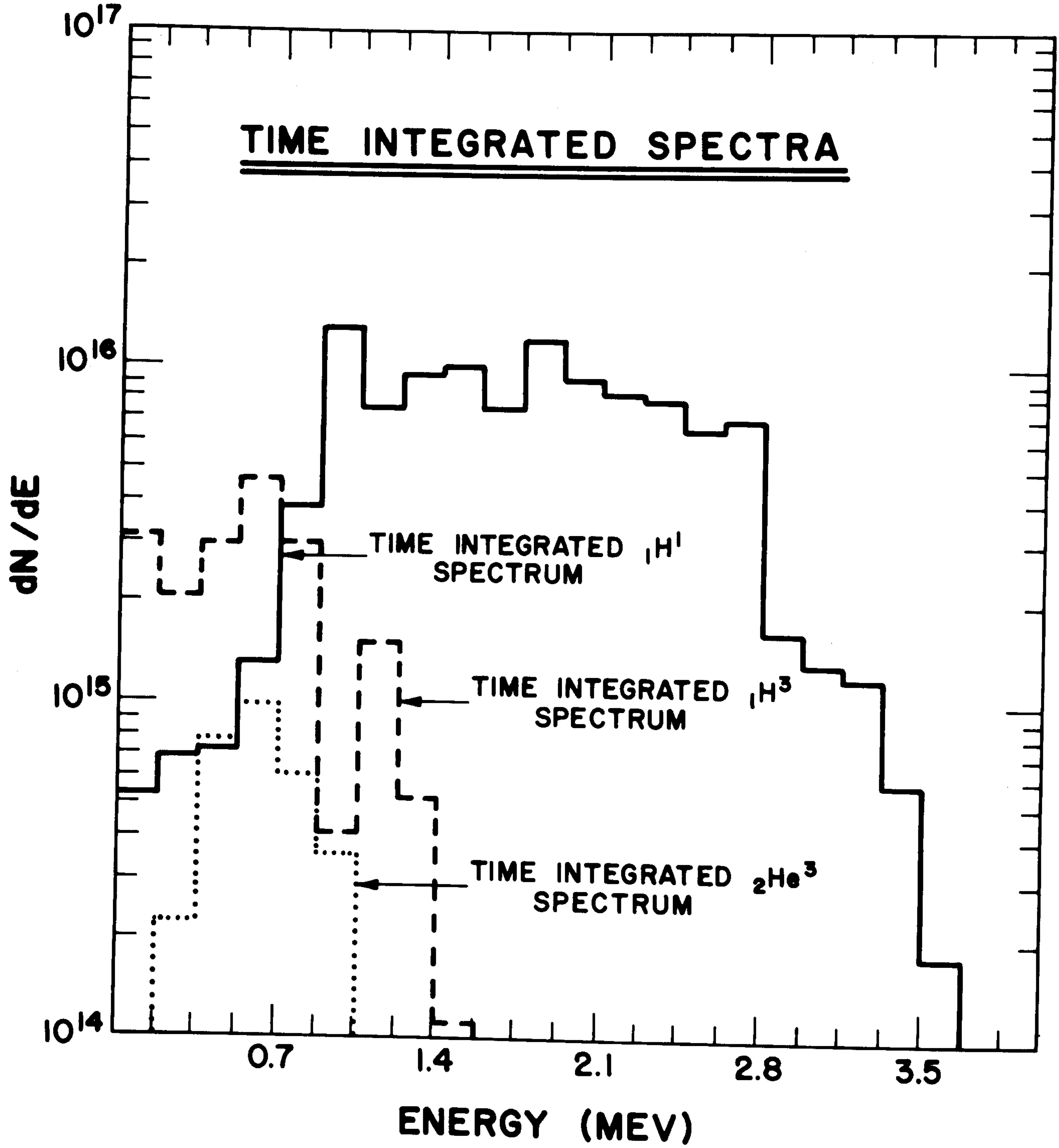

GAIN ON CORE VS.
ρR - MASS ON 100MJ CONTOUR
GAIN
5000
4000
3000
2000
1000
1
2
3
4
5
6
7
8
ρR(g/cm²)

Figure 7



TIME INTEGRATED $_2He^4$ SPECTRUM
10^{19}
10^{18}
10^{17}
10^{16}
dN/dE
0.7
1.4
2.1
2.8
3.5
ENERGY (MEV)

Figure 8



TIME INTEGRATED SPECTRA
TIME INTEGRATED $_1H^1$ SPECTRUM
TIME INTEGRATED $_1H^3$ SPECTRUM
TIME INTEGRATED $_2He^3$ SPECTRUM
dN/dE
10^{17}
10^{16}
10^{15}
10^{14}
0.7
1.4
2.1
2.8
3.5
ENERGY (MEV)

Figure 9

X - RAY SPECTRUM OF 100 MEGAJOULE

D - T FUSION MICROEXPLOSION.

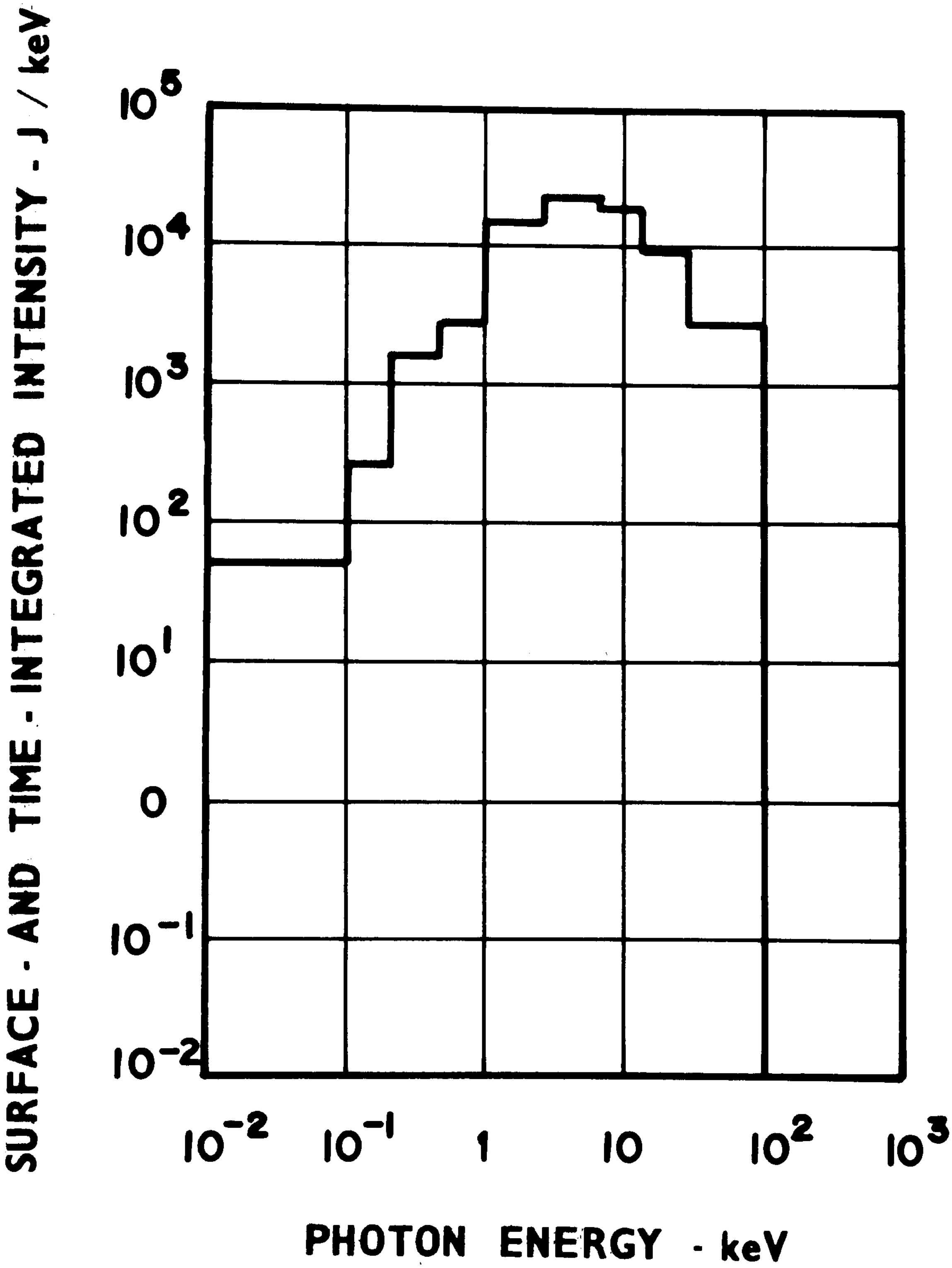


Figure 10

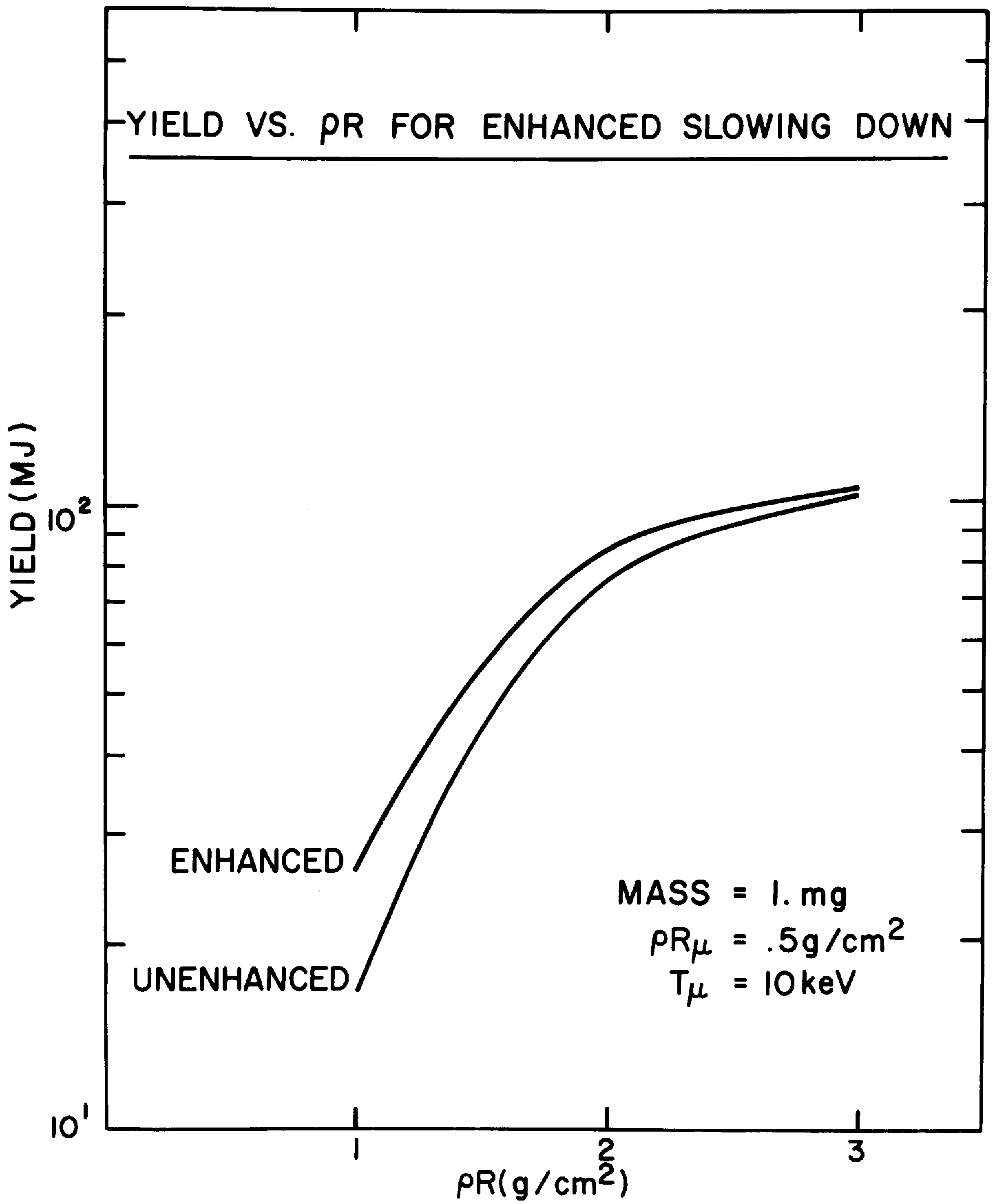

YIELD VS. ρR FOR ENHANCED SLOWING DOWN
YIELD (MJ)
10²
10¹
ENHANCED
UNENHANCED
MASS = 1. mg
ρRμ = .5g/cm²
Tμ = 10keV
1
2
3
ρR(g/cm²)

Figure 11