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THERMODYNAMIC PROPERTIES OF A HIGH PRESSURE SUBCRITICAL UF_6/He GAS VOLUME (IRRADIATED BY AN EXTERNAL SOURCE)

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PREFACE

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ABSTRACT

A computer simulation study concerning a compressed fissioning UF_6 gas is presented. The compression is to be achieved by a ballistic piston compressor. Data on UF_6 obtained with this compressor were incorporated in the simulation study. As a neutron source to create the fission events in the compressed gas, a fast burst reactor was considered. The conclusion is that it takes a neutron flux in excess of 10^{15} n/sec cm^2 to produce measurable increases in pressure and temperature, while a flux in excess of 10^{19} n/cm^2sec would probably damage the compressor.

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I. INTRODUCTION

Advanced reactor concepts like the gaseous core reactor, the nuclear piston engine, and the nuclear pumped laser, employ fissioning UF_6 gas. For this reason, the neutron physics of a gaseous critical assembly and the optical and thermodynamic properties of a fissioning UF_6 gas are of interest.

One way to study fissioning UF_6 in a subcritical configuration is to use a ballistic piston compressor in connection with a pulsed high flux neutron source.

The U.S. Naval Surface Weapons Center pioneered research in this field in the early sixties [1]. Successful numerical analysis of the phenomena observed in ballistic compressors was achieved by Takeo [2] in 1965 with the development of a computer program which calculates gas leakage past the piston and heat losses from the test gas to the walls of the compressor. The University of Florida has developed the Ballistic Compressor Computer Code (BCCC) to aid in the experimental determination of thermodynamic parameters of gases at high temperatures and pressures from measurements of volume, temperature and pressure [3].

The BCCC has been modified to accept a variety of energy (fission) deposition profiles such as those produced by the Godiva reactor. The resultant effects on the equation of state of the gas mixture and compressor are predicted before, during and after such energy deposition.

A ballistic compressor shown schematically in Figure 1 consists of four main parts: the reservoir, the piston release section, the tube, and the high pressure section.

The reservoir was designed for a maximum operating pressure of 136 atm and was statically tested to 200 atm. The reservoir is sufficiently large that the driver gas pressure remains essentially constant during the entire piston stroke. The tube is 3.89 m long and has a 5-cm bore. The 5-cm bore high pressure section is 17.78 cm long, has a wall thickness of 2.57 cm. and contains diametrically opposite windows for absorption and emission measurements.

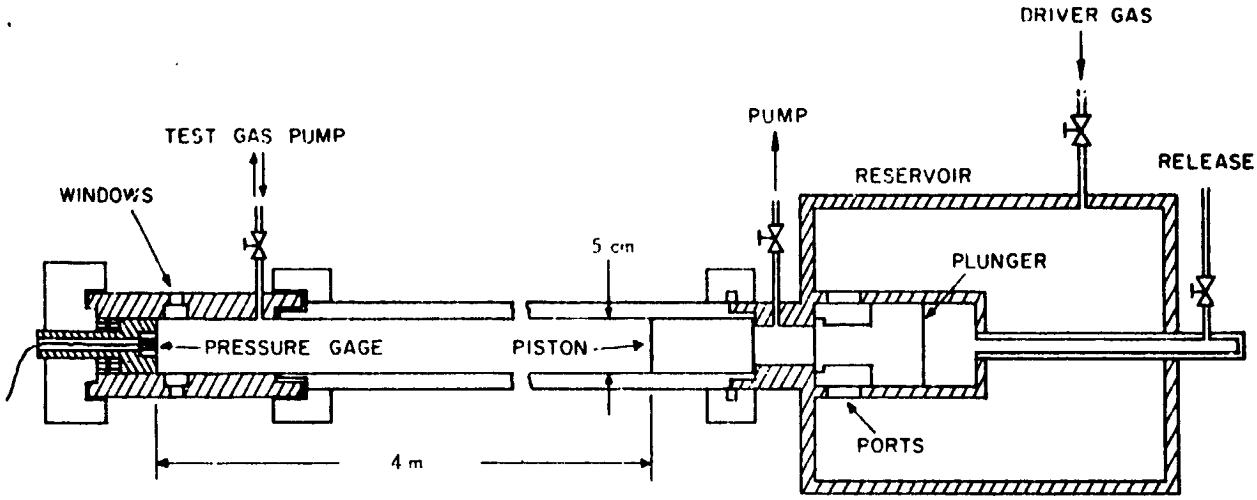


Fig. 1. Schematic diagram of ballistic piston compressor.

The high pressure section is designed for pressures up to 5000 atm. Since the high temperatures generated in the high pressure section cause a slight vaporization of the inner walls, resulting in emission from impurities, the inner bore is plated with chromium. Figure 2 shows the piston and cup seals in detail. To minimize gas leakage around the piston, two cup seals are employed. The gases before and behind the piston expand these seals against the bore thus minimizing gas leakage past the piston. The steel piston body contains two phosphor bronze bearings that provide the surface upon which the piston moves and a molybdenum piston head to prevent ablation by the hot gas. The radial clearance between the bearing surface and the tube bore is 50 µm.

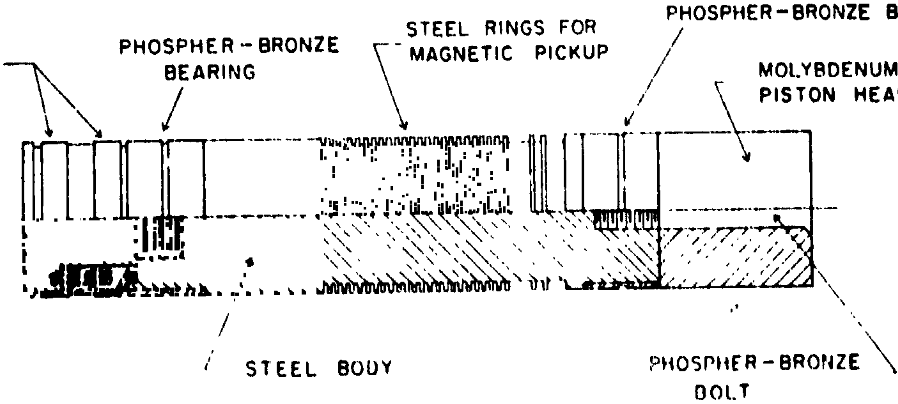


Figure 2. Schematic Diagram of Piston

In operation the chamber behind the plunger of the piston release section is pressurized so that the plunger moves to the forward (left) position and seals the reservoir from the tube. The tube is then filled with the test gas or gas mixture, and its pressure and temperature are adjusted. Next, the reservoir is filled with driver gas to the pressure necessary to produce the desired maximum pressure in the test gas. The compressor is fired by releasing the pressure behind the plunger in the piston release section. The reservoir pressure acting on the front of the plunger moves it to its rear (right) position removing the seal between the reservoir and the tube. Reservoir gas rushes through the ports in the piston release section and impinges on the back of the piston driving it swiftly down the tube. The seals on the rear of the piston prevent all but a very small amount of reservoir gas from leaking into the tube and mixing with the test gas during a shot. Similarly, during the peak pressure part of the compression cycle, some test gas leaks across the piston and mixes with the reservoir gas. After the first compression cycle the piston oscillates back and forth until friction brings it to rest with equal gas pressure on its front and rear sides. The desired measurements are made during the peak pressure of the first compression stroke by the instrumentation located in the high pressure section.

A rough approximation of the variation of test gas density and temperature with test gas pressure can be obtained from the polytropic relations

$$\frac{P}{P_0} = \left(\frac{n}{n_0}\right)^{\gamma} = \left(\frac{T}{T_0}\right)^{\gamma/\gamma-1} , \qquad (1)$$

where γ is the polytropic exponent, the ratio of specific heats. Equating the work done on the piston by the expanding reservoir gas to the work done by the piston on the test gas being compressed, assuming that the reservoir pressure,

P_r, is constant, and substituting Eq. (1) gives the following equation:

$$\frac{P_r}{P_0}(\gamma - 1) = \frac{\left(\frac{P_{max}}{P_0}\right) - \left(\frac{P_{max}}{P_0}\right)^{1/\gamma}}{\left(\frac{P_{max}}{P_0}\right)^{1/\gamma} - 1} , \qquad (2)$$

which shows that P_{max} does not depend on the length of the tube or piston diameter, but is a function of only P_o, P_r, and γ. For $(P_{max}/P_o) \gg 1$, Eq. (2) simplifies to

$$\frac{P_{max}}{P_0} = \left[1 + (\gamma - 1)\frac{P_r}{P_0}\right]^{\gamma/\gamma - 1} , \qquad (3)$$

which illustrates that the peak pressure generated in the test gas has a power law increase with reservoir pressure; i.e., a relatively low reservoir pressure generates a high test gas pressure, and that low γ gases produce the highest peak test gas pressure for a given reservoir pressure. Typically, a reservoir pressure of 30 atm will generate a test gas pressure of 1000 atm in a monatomic gas. The ballistic piston compressor was used before to measure the ratio of specific heats [4] (γ) for UF_6.

In this report--based on the previous experience--a numerical simulation of such a ballistic piston compressor, being subjected to an intense neutron pulse during the time of maximum compression of the UF_6-gas, is presented. As a neutron source, the use of a bare fast burst reactor, such as Godiva IV was assumed. The expectation is that fission will occur in the UF_6, and a fissioning UF_6 gas will be formed. It is intended to study this UF_6 gas experimentally. For safety reasons, the numerical simulation was necessary before the actual experiment is undertaken.

II. CONDITIONS FOR THE SIMULATION

A. Experimental Constraints

The reactor burst (~100 μsec) is much shorter than the 0.1 seconds it takes the compressor to reach maximum pressure and temperature. The objective is to initiate the reactor burst at the ~1/2 millisecond of high temperature and pressure.

After the compressor is readied for operation, the reactor is placed in in its supercritical operating condition awaiting a random neutron chain or an initiating burst from a neutron gun. The compressor is then fired and as the piston enters the high pressure test section a signal is produced in a magnetic pickup. This signal is used after suitable delay to initiate the neutron gun which initiates the reactor burst.

Timing becomes critical here, since the compressor must be fired as soon as possible after the Godiva reactor awaits the burst of the neutron gun, least a random neutron chain result in an early burst from the Godiva reactor.

Special consideration must be given to two aspects of this experiment. First, the increased reactivity from the rapidly compressed UF_6 must be isolated from the Godiva reactor. This can be effectively done by placing a thermal absorber between the moderating material for the compressor and the Godiva reactor.

B. Treatment of the Test Gas as a Real Gas

Nonideal processes to be considered in the simulation include gas leakage past the piston and heat loss from the test gas to the walls of the compressor.

The Van der Waals' equation of state is:

$$(p + a/V^2)(V-b) = RT$$

where a and b are the Van der Waals' constants.

The leakage of test gas past the piston is approximated by:

$$dn/dz = \frac{\pi\rho}{Ma} r_o \; (r_o - r_p) \; [\frac{1}{8\eta} \frac{\partial P}{\partial x} (r_o - r_p)^2 + V]$$

dn/dz - leakage rate

ρ - density of the leakage gas

Ma - molecular weight of the leaking gas

r_o - inner radius of the barrel

r_p - radius of the piston

η - viscosity of the leaking gas

V - piston velocity

$\frac{\partial P}{\partial x}$ - pressure gradient along the piston

Heat loss through the walls of the compressor and end plugs (one of which is the piston) is approximated by the cylindrical heat loss formula:

$$\frac{\partial T}{\partial T} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right)$$

Boundary effects between the assumed homogeneous, turbulent test gas and the compressor walls are approximated by:

$$Q = \left(\frac{T\ wall - T\ gas}{R} + \frac{T\ plug - T\ gas}{R\ plug}\right) \Delta t$$

where Q - heat lost during time step

Δt - time step in seconds

T wall - temperature of compressor walls

T plug - temperature of end plug (piston)

R, R plug - resistance to heat flow

$$R^{-1} = \min \begin{matrix} 4\pi xk \\ 2\pi\theta xh \end{matrix}$$

x - length of bore occupied by test gas

K - conductivity of the test gas

h - convective heat transfer coefficient of the test gas

$$h = \frac{KZ}{D}\left(\frac{nVD}{V_o n}\right)^{0.8}\left(\frac{(r+C_v)\partial}{K}\right)^{0.3}$$

Z - Calibration factor

n - Moles of test gas

Vo - volume of test gas

D - bore diameter

r - ideal gas constant

C_v - constant volume specific heat

A simple model is used to describe the fast burst reactor:

$$\frac{dn}{dt} = \frac{\rho - B}{\ell} n$$

where: ρ - reactivity

B - delayed neutrons

ℓ - neutron lifetime

n - neutron

This approximation is meaningful only for sufficiently large reactivity, that is, all neutron sources except prompt neutrons may be neglected [4].

The "shock wave" shutdown mechanism is approximated by:

$$\rho = \rho_o - \alpha T$$

Where α is the negative of the temperature coefficient of reactivity and T is the increase in temperature above its initial value. The maximum power of the Godiva fast burst reactor is given by: [5]

$$\hat{n} = \ell w^2 / 2\alpha K$$

where $w = \frac{\rho - B}{\ell}$

K - is the reciprocal heat capacity.

The energy released per unit time is then:

$$n = \frac{\ell W^2}{2\alpha K} \operatorname{sech}^2(wt/2)$$

This is the equation used in the BCCC to model the Godiva reactor.

The full width at half maximum is given by:

$t = 3.524/W.$

A more detailed description of the algorithums used in the BCCC is presented in reference [3].

III. THE NUMERICAL SIMULATION

A. Physical Data

The objective of the anticipated experiment is to produce a hot dense gas mixture of uranium hexafluoride in the field of a neutron flux of sufficient intensity to induce measurable changes in thermodynamic and optical properties of the compressed UF_6 gas.

The initial temperature and pressure of the uranium hexafluoride is achieved in the ballistic compressor. In the base case, the initial conditions of the compressor are taken to be:

Reservoir Pressure	= 240 psig.
Uranium Hexafluoride Partial Pressure	= 0.10 atm.
Helium Partial Pressure	= 0.90 atm.
Piston Gap Calibration Constant	= 0.01 cm.
Convection Calibration Constant	= 0.1 dimensionless
Heat Transport Calibration Constant	= 0.2 dimensionless
Piston Length Calibration Constant	= 25.0 cm.

In the BCCC computer codes calibration factors are used which relate the actual gas leakage past the piston clearance to the computed leakage assuming a nominal clearance. The calibration factors obtained in the nonfissioning experiments are assumed to be valid also for the fissioning experiment and are so used in this simulation.

B. Square Wave

The initial modeling of the neutron flux is with a step insertion of fission energy:

$E(t) = E_1$ (ergs/sec) $t_1 \leq t \leq t_2$

Where $[t_1, t_2]$ is the interval during which E_1 is inserted.

C. Analytic Energy Profile

Hetrick [6] developed a theoretical model of the reactor burst more suitable for this analysis. As discussed previously, the flux or fluence as a function of time is given by:

$$\phi = \ell w^2/2\alpha K \operatorname{sech}^2 (wt/2)$$

the energy produced during time Δt is:

$$E = \Delta t\ n\sigma a\rho w^2/2\alpha K \operatorname{sech}^2 (wt/2)\ (ergs/sec)$$

where:
- a - energy per fission (ergs/interaction)
- ϕ - neutron flux (n/cm^2 sec)
- Δt - time interval (sec)
- n - number of U^{255} atoms
- σ - absorption cross (cm^2)

Let $b_1 = a\ \sigma_a\ \ell w^2/2\alpha K$

and $b_2 = wt/2$

The range of values the parameters b_1 and b_2 assume are:

b_1 - $[10^{13}, 10^{17}]$ ergs/sec

b_2 - $[10^3, 10^5]$ sec^{-1}

D. Temperature Anomilie (Limit of Model)

Earlier investigations with the square wave fission energy profile demonstrated the limits of the model. Specifically, the high temperatures induced by the fission energy exceeded those temperatures over which the equation used to model the viscosity was fitted. The result was temperature singularities, followed by the leakage of all test gas past the piston.

E. Limit on Viscosity

Further investigations with the square wave and all cases with the analytic energy profile were calculated with the maximum viscosity limited to the value experienced at 2000°K.

IV. RESULTS OF NUMERICAL SIMULATIONS

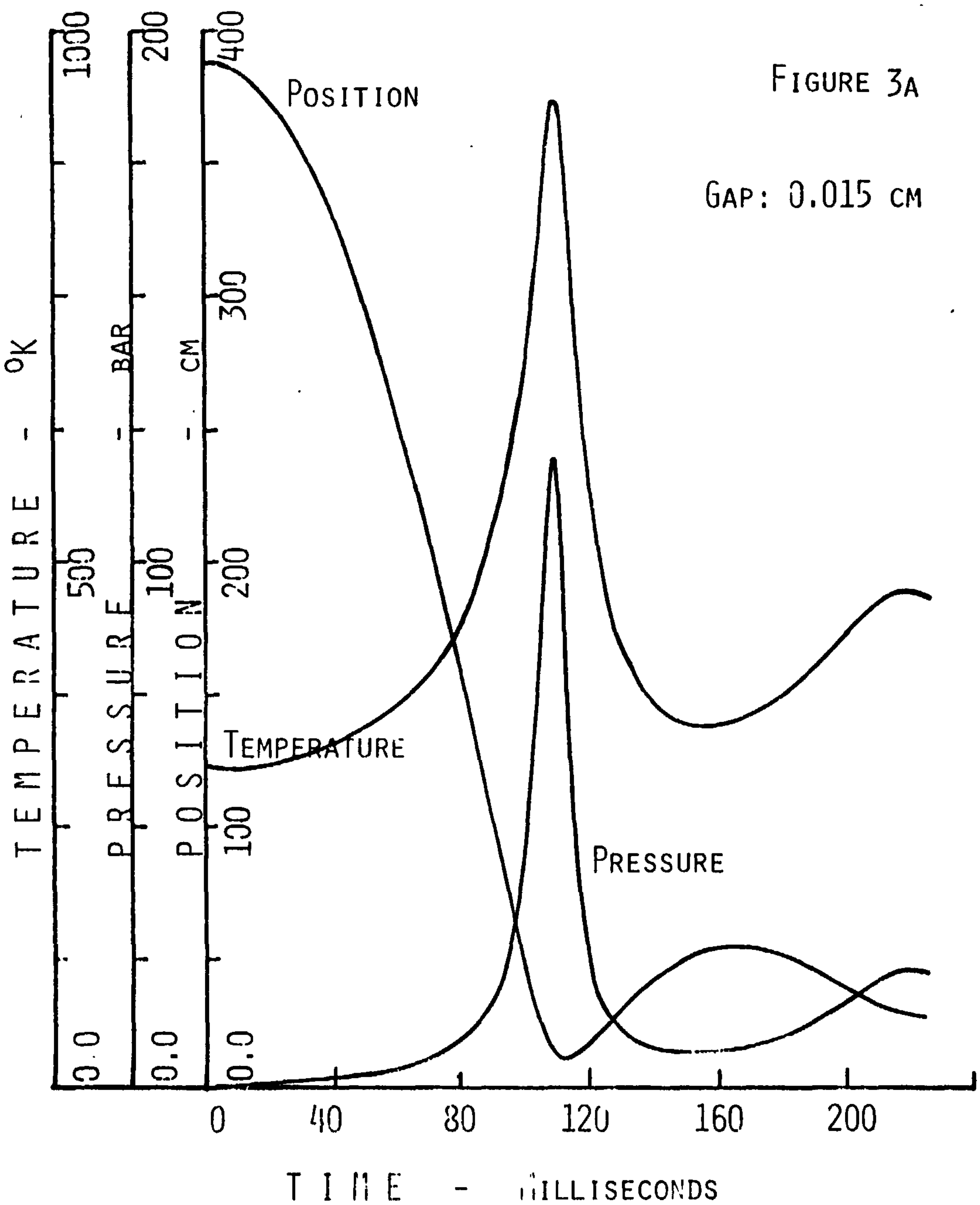
One objective of the simulation was to determine the sensitivity of the major physical variables on the results of the experiment.

The maximum pressure is sensitive to the piston gap (i.e., leaking clearance between piston and bore wall). For this reason, the sensitivity of the maximum pressure and temperature to changes in the piston gap is examined in Figures 3, A-1 and A-2 (Figure A-1 and A-2 are in the appendix), and summarized in Table I.

TABLE I

Figure	Gap (cm)	Maximum Pressure (atm)	Density @ P max (#/cm^3)	Maximum Temperature (^{o}K)
A-2	.0050	1600	$6.9\cdot10^{20}$	1643
	.0075	867	$3.2\cdot10^{20}$	1474
A-1	.0100	423	$1.3\cdot10^{20}$	1283
	.0125	213	$5.9\cdot10^{19}$	1096
3	.0150	117	$3.0\cdot10^{19}$	933

Figures 3a, A-1a and B-1a have to be read as follows: At time t = 0 the piston is at rest about 380 cm away from the point of maximum compression (the test section end) near the breach of the pressure tube (see Figure 1). After the plunger valve is opened at the time t = 0, the piston accelerates and comes to a standstill about 110 milliseconds later. The position value at this time (the minimum in the position-curve) divided by the position value at time t = 0 is the compression ratio. After t = 110 milliseconds the piston starts to accelerate again in the reverse direction (now towards higher position-values) and undergoes a recompression around t = 220,



PISTON POSITION, GAS TEMPERATURE AND PRESSURE AS A FUNCTION OF TIME

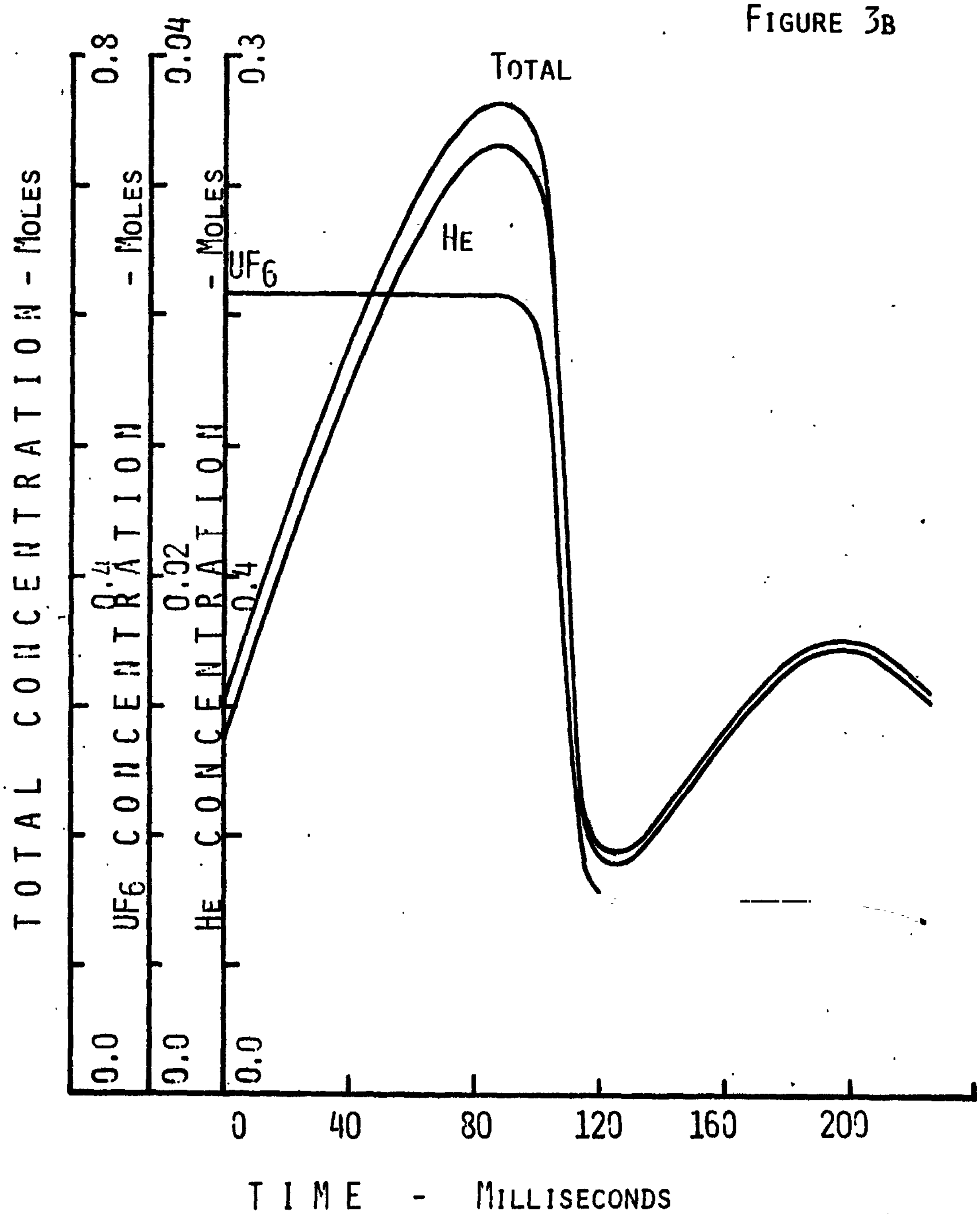
From the time $t = 0$ to $t = 110$ milliseconds--the time of maximum compression--the temperature starts at ambient ($t = 0$, $T = 300^{o}K$) and increases to its maximum value (in case of Figure 3a $T = 933^{o}K$) which coincides with the minimum position value. Later, when the piston recedes, the temperature drops accordingly and rises again at the second recompression.

Figure 3b (also A-1b and A-2b) shows the concentration of He and UF_6 in front of the piston. If there were no piston gap the number of moles in front of the piston should not change. However, due to the existing gap, some of the helium which pushes the piston leaks naturally ahead of it thus increasing the number of moles in front of the piston (test section side). The UF_6 which is only on the test section side of the piston, of course, does not leak over to the helium side, since at this side of the piston the pressure is much higher. Therefore, the UF_6 concentration stays fairly constant up to 100 milliseconds. Shortly after this time (see Figure 3a) maximum compression occurs and the UF_6 rushes past the piston gap into the driver section of the compressor. The UF_6 concentration in the test section drops by a factor of 6. The same happens to the helium which leaked into the test section during the compression stroke.

For this reason, the size of the gap has a rather dramatic influence on pressure and temperature. This is indicated in Figure 4. From previous experiences with UF_6-He mixtures [4] one can say that piston gaps between 50 and 75 micrometers are physically realizable.

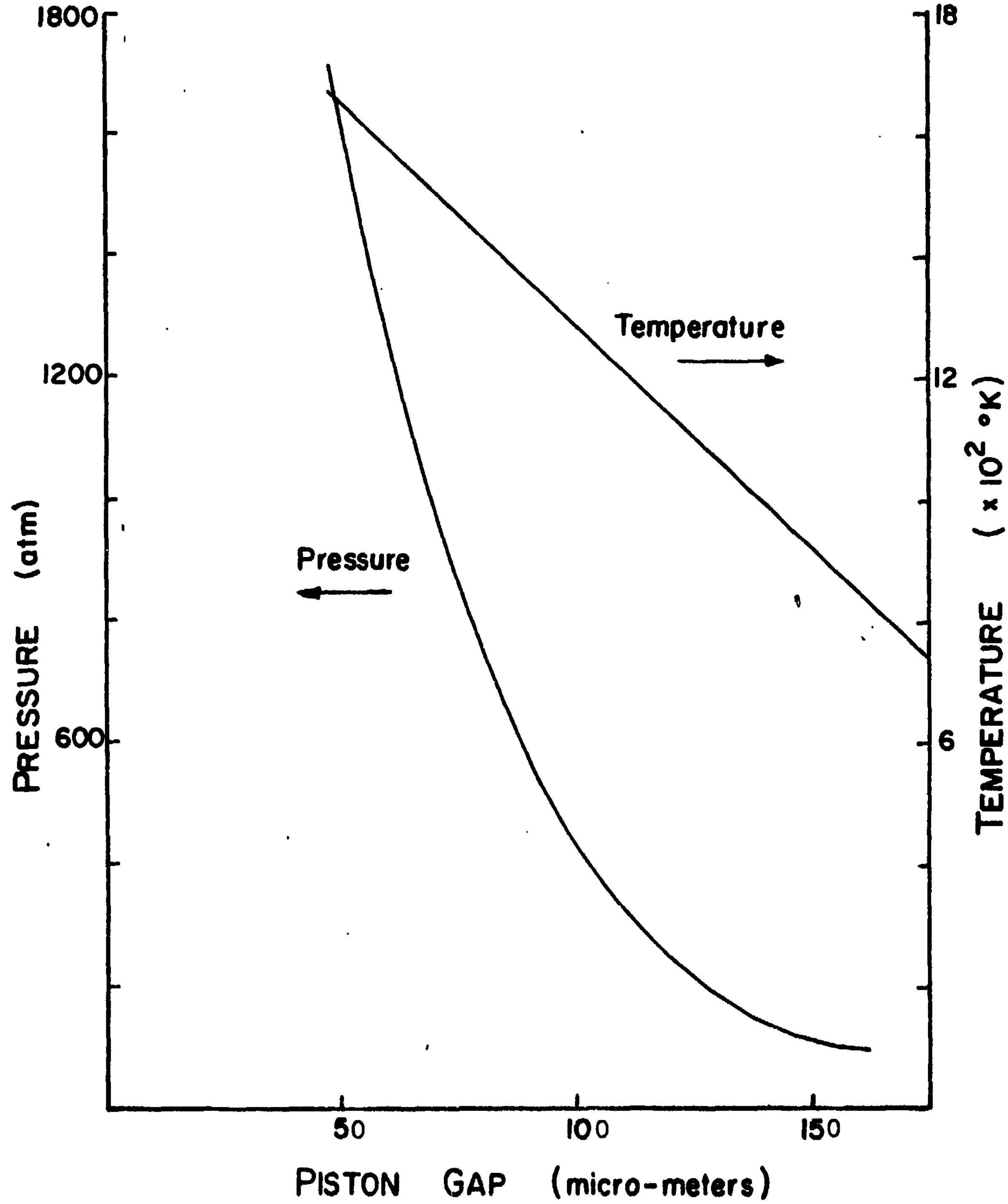
If the compressor is to be operated with fissionable UF_6 gas, the most significant variable next to the piston gap is the neutron flux or fluence to which the compressed gas is exposed. The fissioning events in the gas, due to this external neutron flux, give rise to energy deposited into the gas:

FIGURE 3B



CONCENTRATIONS OF UF_6 AND HE AS A FUNCTION OF TIME

FIGURE 4



INFLUENCE OF PISTON GAP ON PRESSURE AND TEMPERATURE

$$E(t) = \phi\sigma a No N(t)\Delta t/\cosh^2(b_2[t-to]),$$
$$= b_1 N(t)\Delta t/\cosh^2(b_2[t-to]),$$

which gives:

$$b_1 = \phi No\sigma a,$$

where

b_1 = BCCC input - ergs/sec

ϕ = maximum flux n/cm^2 sec

σ = fission cross section, 577 x 10^{-2} cm^2

a = 180 MeV/fission

N(t) = moles U^{235}

Δt = duration of BCCC time step-sec

b_2 = neutron pulse width parameter-sec^{-1}

No = Avagadro's Number.

This energy input relation was used in the compressor simulation.

Table II shows typical results of this calculation. The piston gap used for these calculations was 100 micrometers.

TABLE II

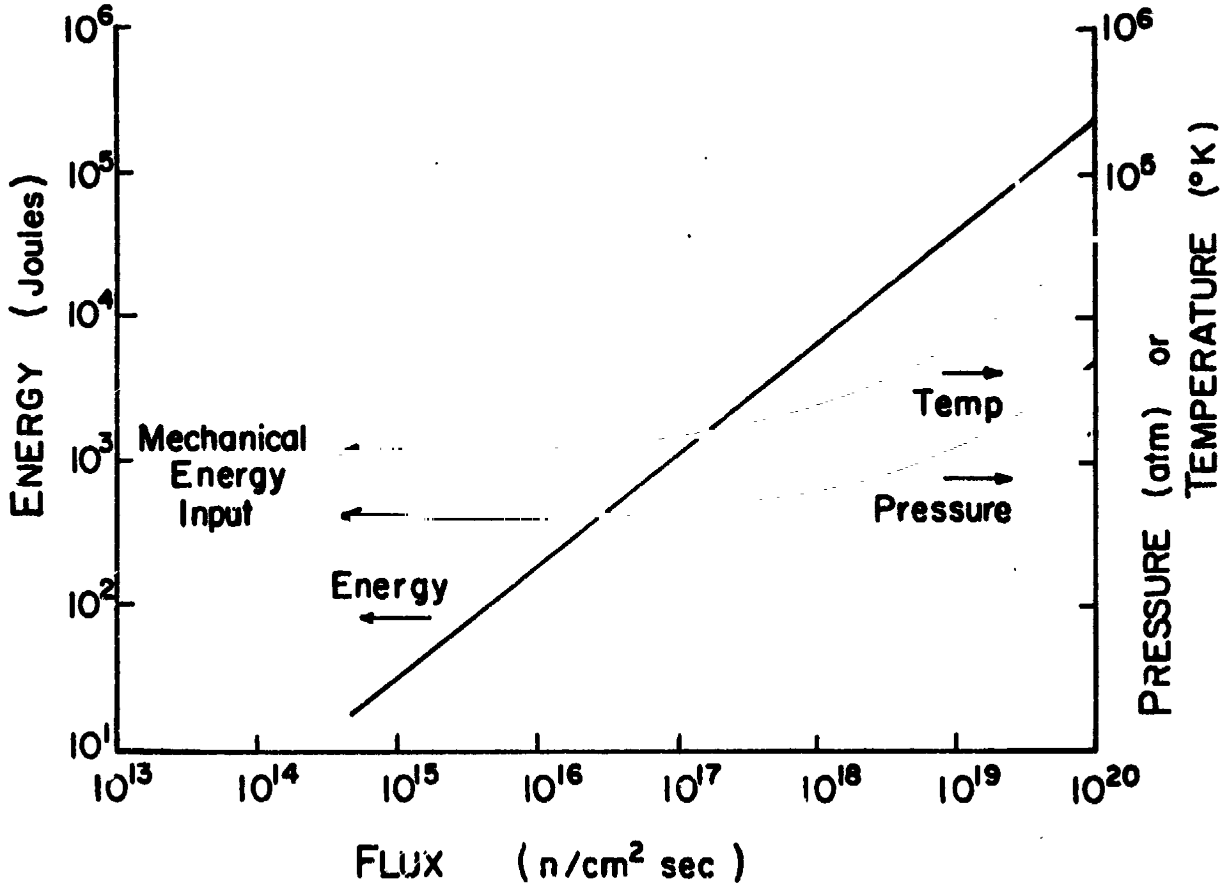
Figure	Maximum Flux	Maximum Pressur (atm)	Temperature °K	Density(#/cm^3)	Total Energy Deposited (Joules)
	0	422	1283	$1.3\cdot10^{20}$	0
A-3	9.5×10^{14}	424	1286	$1.3\cdot10^{20}$	33
6	9.5×10^{15}	438	1337	$1.3\cdot10^{20}$	329
A-4	9.5×10^{18}	1700	6431	$1.9\ 10^{21}$	3.15×10^4
A-5	9.5×10^{19}	4500	32575	$1.2\ 10^{20}$	2.35×10^5

Figure 5 shows the effect of deposition of fission energy into the gas. The curve labelled "Energy" shows the fission energy deposited into the gas as a function of neutron flux. It takes a neutron flux in excess of 10^{15} n/sec-cm^2 to raise pressure and temperature measurably above the values which are prevailing due to the mechanical compression of the gas. Of course, a flux of 10^{20}, if it could be made available, would stress the test section to its limits. The nuclear energy input would, in this case, be more than 2 orders of magnitude higher than mechanical energy input.

Details of the compression for a flux of 10^{15} n/cm^{2}sec can be seen in Figures 6a and 6b. The absolute values of pressure and temperature are slightly higher than in the case without neutron flux.

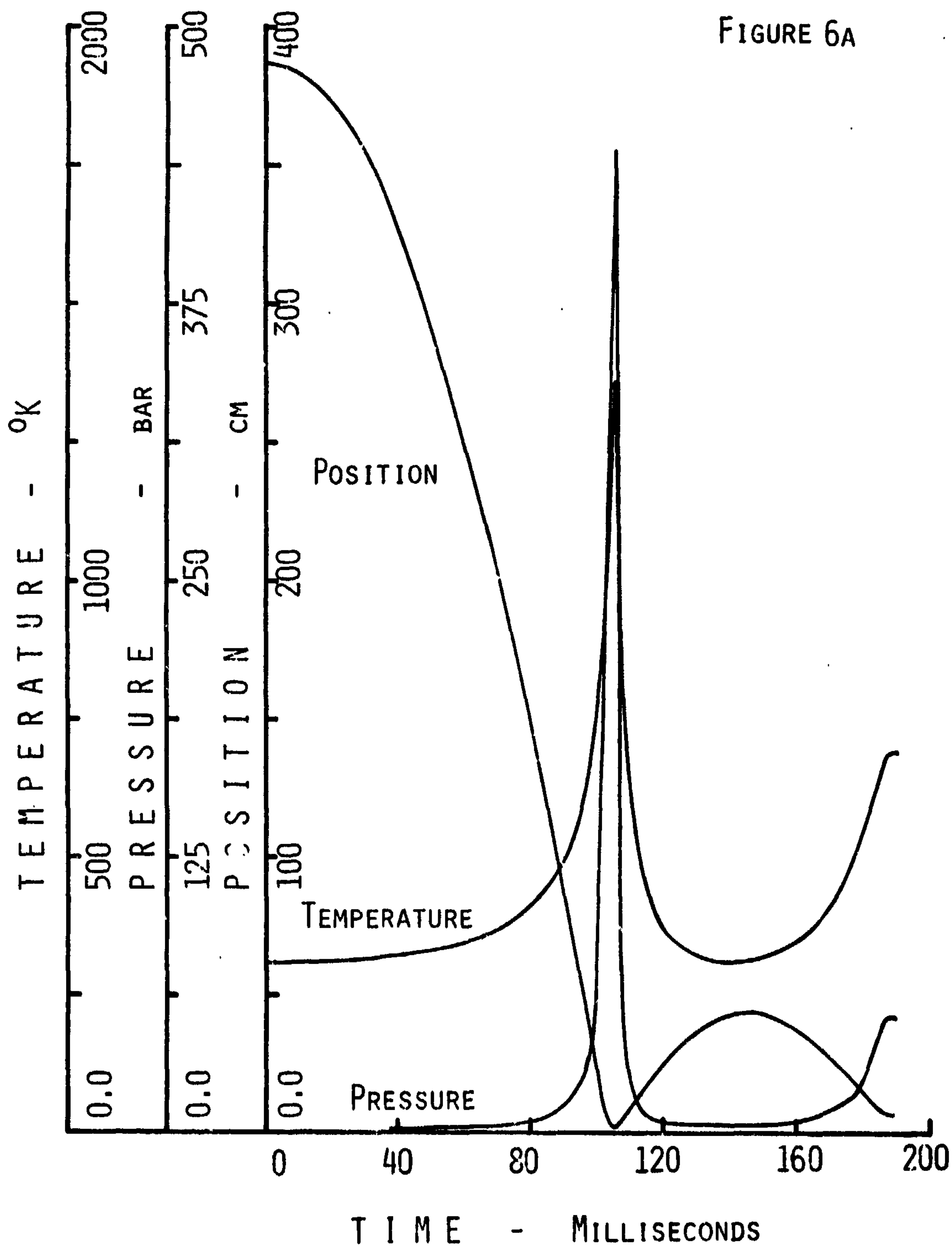
Other than this, the details of the compression are identical to the non-fissioning case. Only if a substantial amount of nuclear energy is inserted (100 times the mechanical energy), a deviation in the compression detail becomes obvious. See e.g., Figures A-3, A-4 & A-5. The nuclear energy is inserted almost instantly (within 100 μsec). Temperature and pressure rises are steeper than in the mechanical case. The retrograde motion of the piston starts earlier and the backswing is much more violent.

FIGURE 5



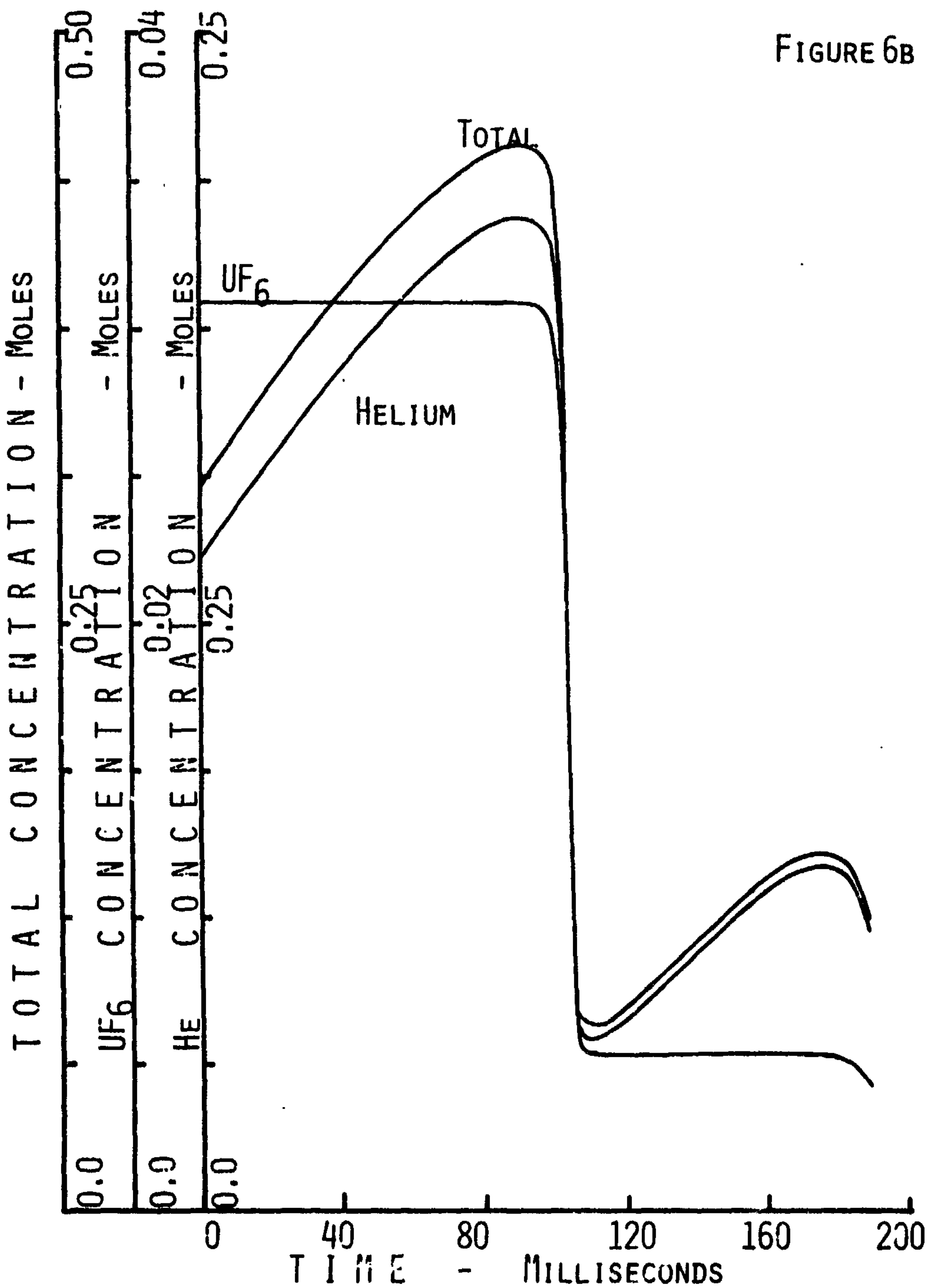
TEMPERATURE, PRESSURE AND FISSION ENERGY AS FUNCTION OF NEUTRON FLUX

FIGURE 6A



PISTON POSITION, GAS TEMPERATURE AND PRESSURE FOR A FLUX OF 10^{15} N/CM SEC AS A FUNCTION OF TIME

FIGURE 6B

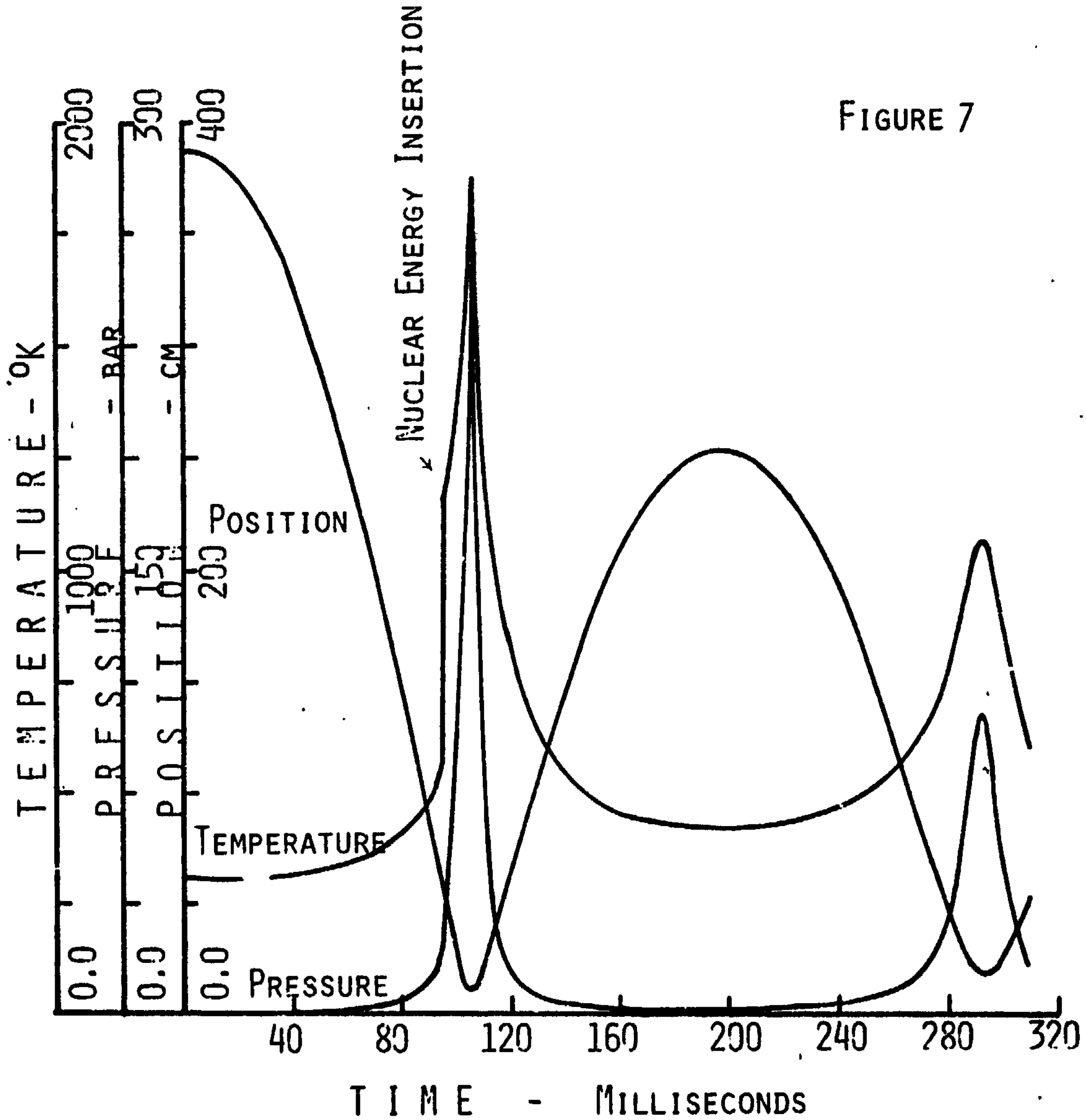


CONCENTRATION OF UF_6 AND HE AS A FUNCTION OF TIME FOR A FLUX OF 10^{15} N/SEC-CM^2

Another important aspect of the successful operation of the ballistic piston compressor is the precision of timing needed to obtain optimum temperature and pressure rise. The maximum compression lasts only about 0.5 millisecond. The neutron burst, which has a duration of about 100 μsec, has to be placed within the limits of the maximum compression time.

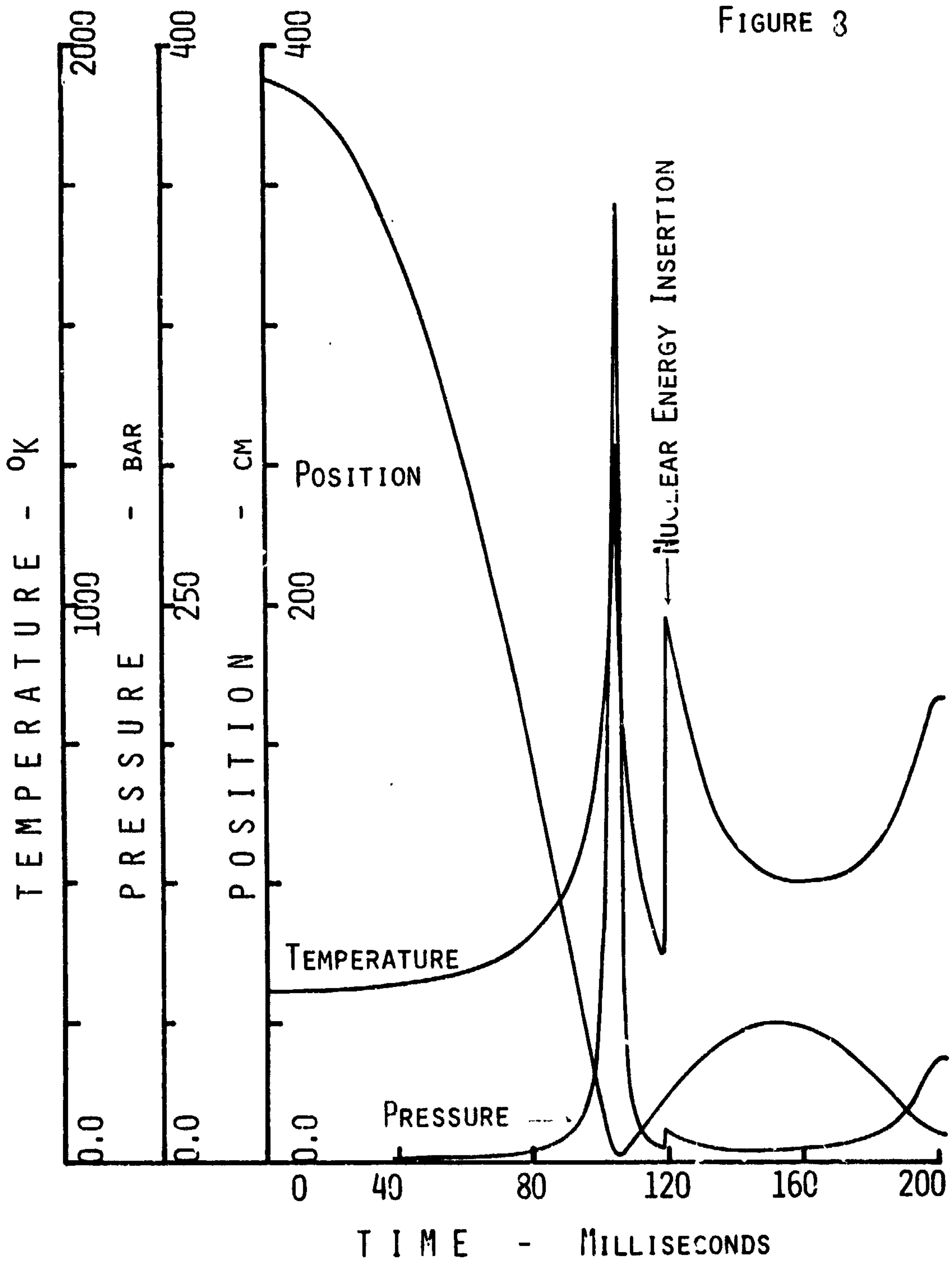
Figures 7 and 8 show the consequences of the neutron burst if placed at the wrong time. In case of Figure 7, the neutron burst is 10 milliseconds early while, in Figure 8, it is 15 milliseconds late. In case the fission energy is inserted too early, the maximum pressure reached is, of course, lower than when placed correctly while an insertion too late creates a separate temperature maximum. Accordingly, in Figure 7 one sees a steep rise in temperature when the nuclear energy insertion takes place; in Figure 8, one can see the temperature rise caused by the nuclear energy separately. A careful analysis of the situation shows that it is advantageous to insert the nuclear energy a short time--200 microseconds--before the maximum pressure is about to be reached. Figure 9 shows the maximum pressure obtained, as a function injection time. Injection time is the time when the nuclear energy is inserted in respect to the time when the maximum compression--due to the kinetic energy of the piston--occurs. An injection time of "0" means that the nuclear energy is inserted at the same time when the maximum compression occurs, while an injection time of - 1 millisecond means that the nuclear energy was inserted 1 millisecond before maximum compression occurs. Figure 9 shows that the optimum injection time is - 200 microseconds.

For safe operation of the device information concerning the highest neutron flux to which the ballistic compressor can be exposed is vital. A numerical simulation to find this highest possible flux was undertaken. The criterion is that if after the maximum compression, the piston returns to its original position, a neutron flux which caused this is no longer acceptable. In Figure



PISTON POSITION, GAS TEMPERATURE AND PRESSURE AS A FUNCTION OF TIME WITH INSERTION OF NUCLEAR ENERGY 10 MILLISECONDS TOO EARLY

FIGURE 3



PISTON POSITION, GAS TEMPERATURE AND PRESSURE AS A FUNCTION OF TIME, WITH INSERTION OF NUCLEAR ENERGY 15 MILLISECONDS LATE

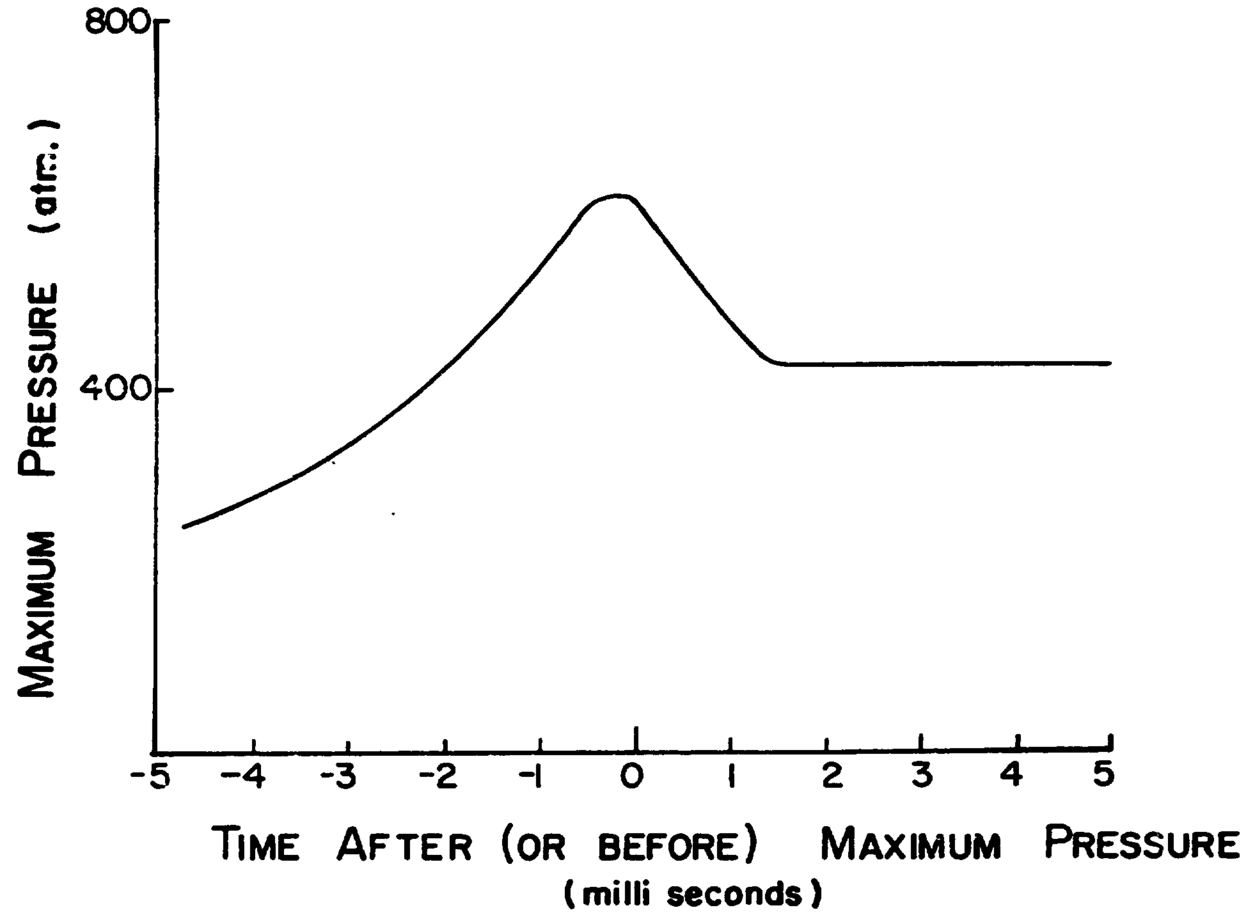


Figure 9. OPTIMAL TIMING OF GAS INSERTION OF NUCLEAR ENERGY

10 a case is shown where this flux is exceeded. The piston returns fast to its original position and overshoots it. The flux computed for this situation was 4.8 x 10^{19} n/cm sec. The result is satisfactory as far as safety considerations are concerned. It is impossible that such a high neutron flux would be made available inadvertently, and even then the damage to the reactor would be much more severe than the damage done to the ballistic piston compressor. Details on the gas mixture for this case can be found in Figure A-7 in the appendix.

The maximum pressure and density achieved during compression may be improved not only by increasing the flux but also by increasing the partial pressure of $U^{235}F_6$. At room temperature the partial pressure of UF_6 is about a tenth of an atmosphere. However, heating the compressor (heating tape) will raise the UF_6 partial pressure above a tenth of an atmosphere.

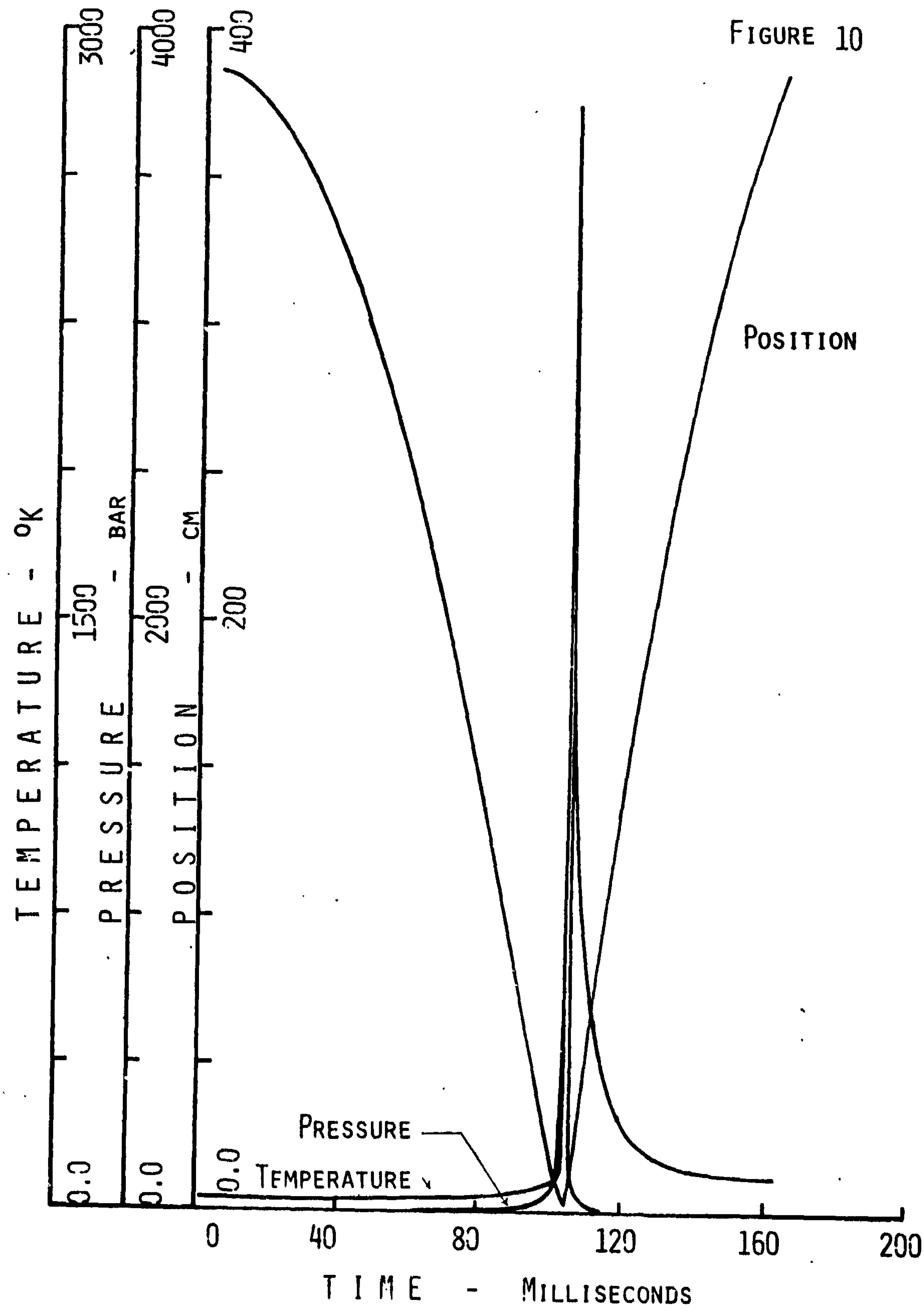
Table III itemizes the results of several variations in the $U^{235}F_6$/He ratio.

Table III

UF_6 Pressure (atm)	Maximum Pressure (atm)	Density @ P max #/cm^2	Maximum Temperature ^oK
.05	368	$5.5 \cdot 10^{19}$	1610
.06	384	$7.0 \cdot 10^{19}$	1548
.07	399	$8.6 \cdot 10^{19}$	1491
.08	415	$1.0\ 10^{20}$	1438
.09	429	$1.2\ 10^{20}$	1389
.10	442	$1.3\ 10^{20}$	1343
.11	454	$1.4\ 10^{20}$	1299
.15	464	--*	1115

*The test gas volume went to zero.

FIGURE 10



PISTON POSITION, GAS TEMPERATURE AND PRESSURE AS A FUNCTION OF TIME FOR A NEUTRON FLUX OF 4.8 x 10^{19} N/SEC CM

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V. CONCLUSIONS AND RECOMMENDATIONS

To maximize temperature or pressure, the insertion of the fission energy should precede the nonfissioning pressure maximum by about 200 microseconds. From the standpoint of undesirable side effects, error in the timing should only result in loss of data and no damage to equipment.

The maximum neutron flux should not exceed 10^{16} n/cm^{2}sec and, if available, should be slowly adjusted upwards as experience provides data on the expected maximum compressor pressure. Care must be taken in increasing the maximum neutron flux, as error could result in destruction of the compressor.

Care in securing the piston's cup seals will help in attaining the highest compressor pressure practicable as well as helping to localize fission products ahead of the piston.

However, operating at a lower flux than 10^{16} n/cm^{2}sec will produce measurable pressure and temperature increases.

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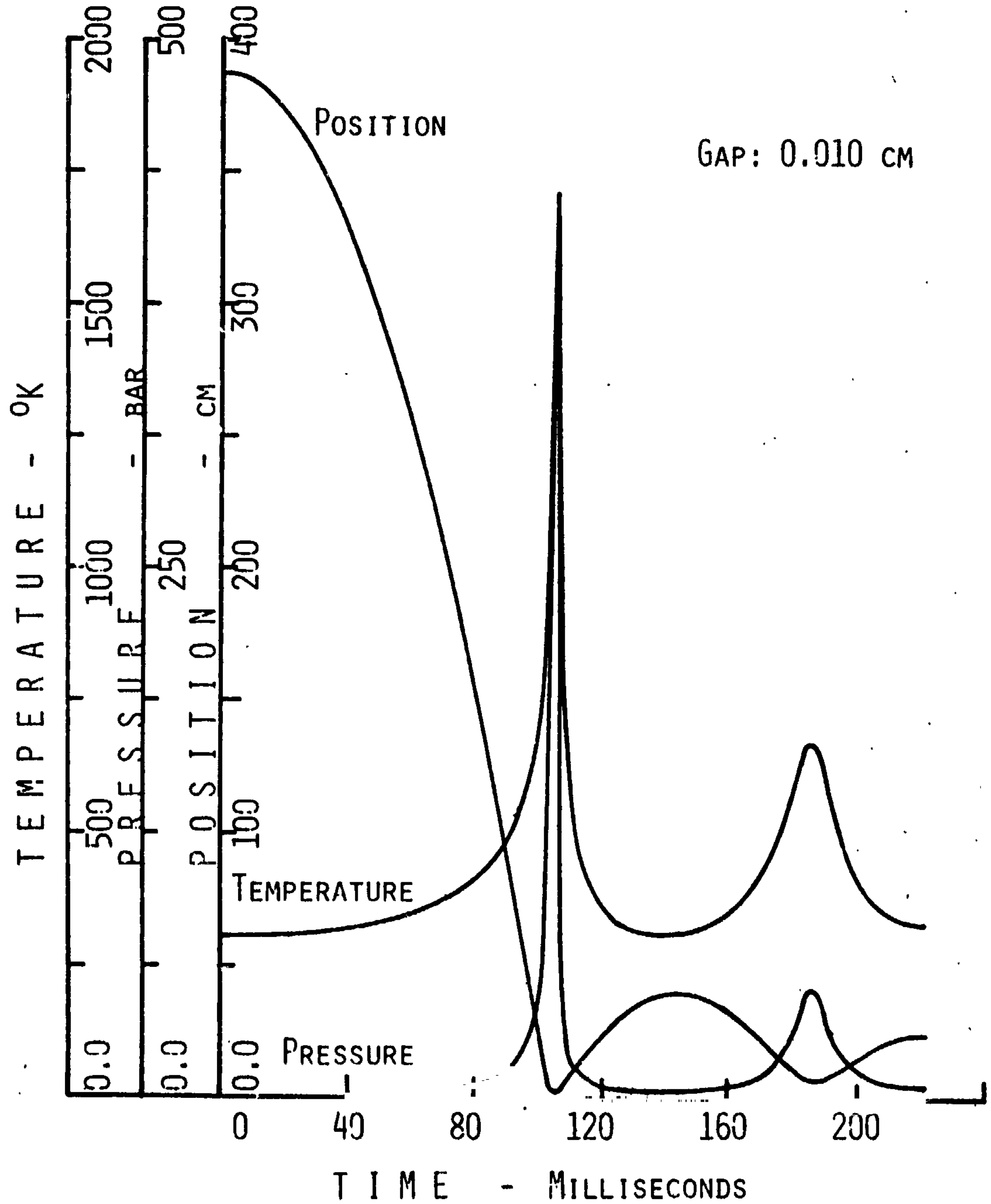
APPENDIX

For explanation of figures, see main text.

FIGURE A-1A



PISTON POSITION, GAS TEMPERATURE AND PRESSURE AS A FUNCTION OF TIME (GAP = 0.010)

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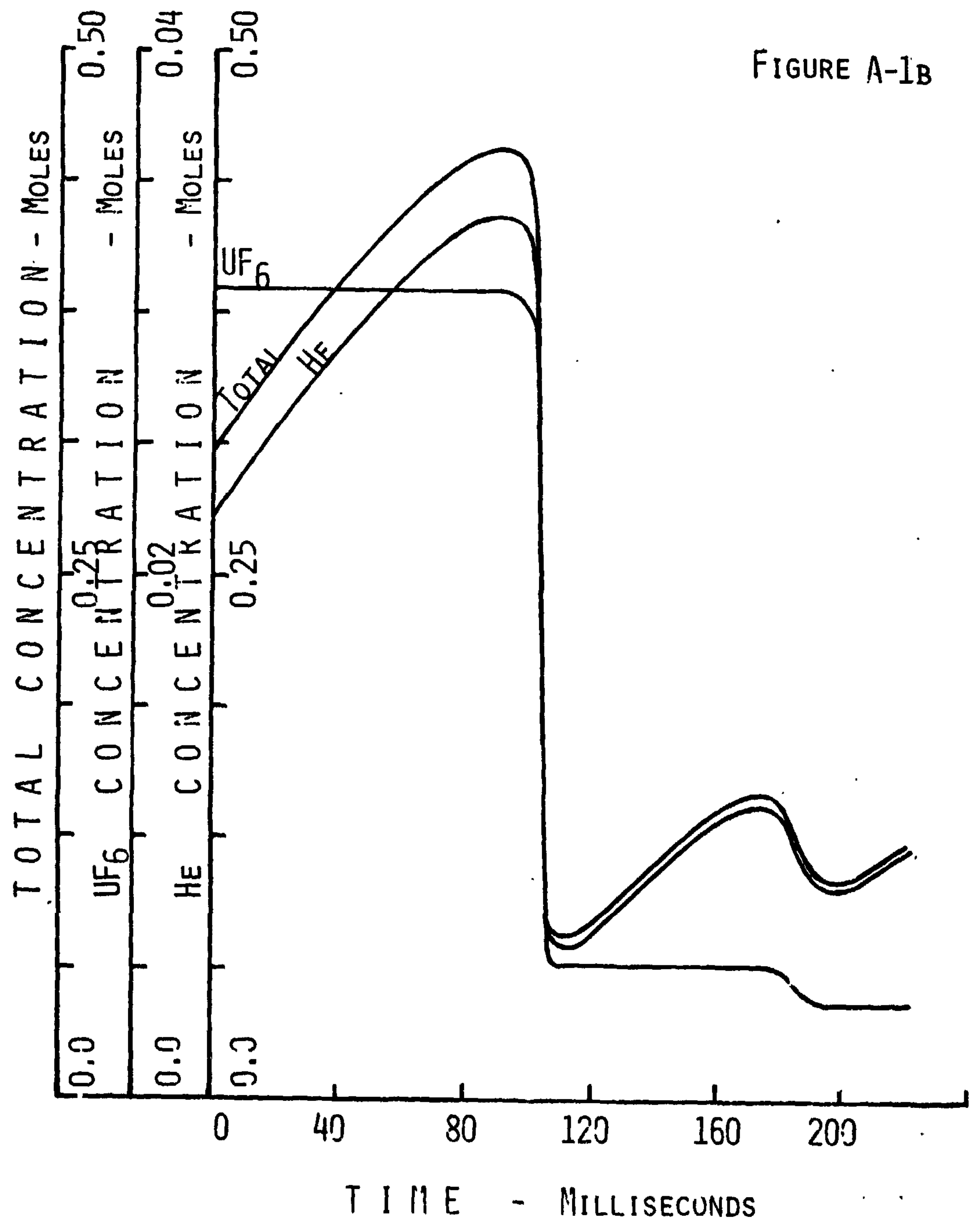
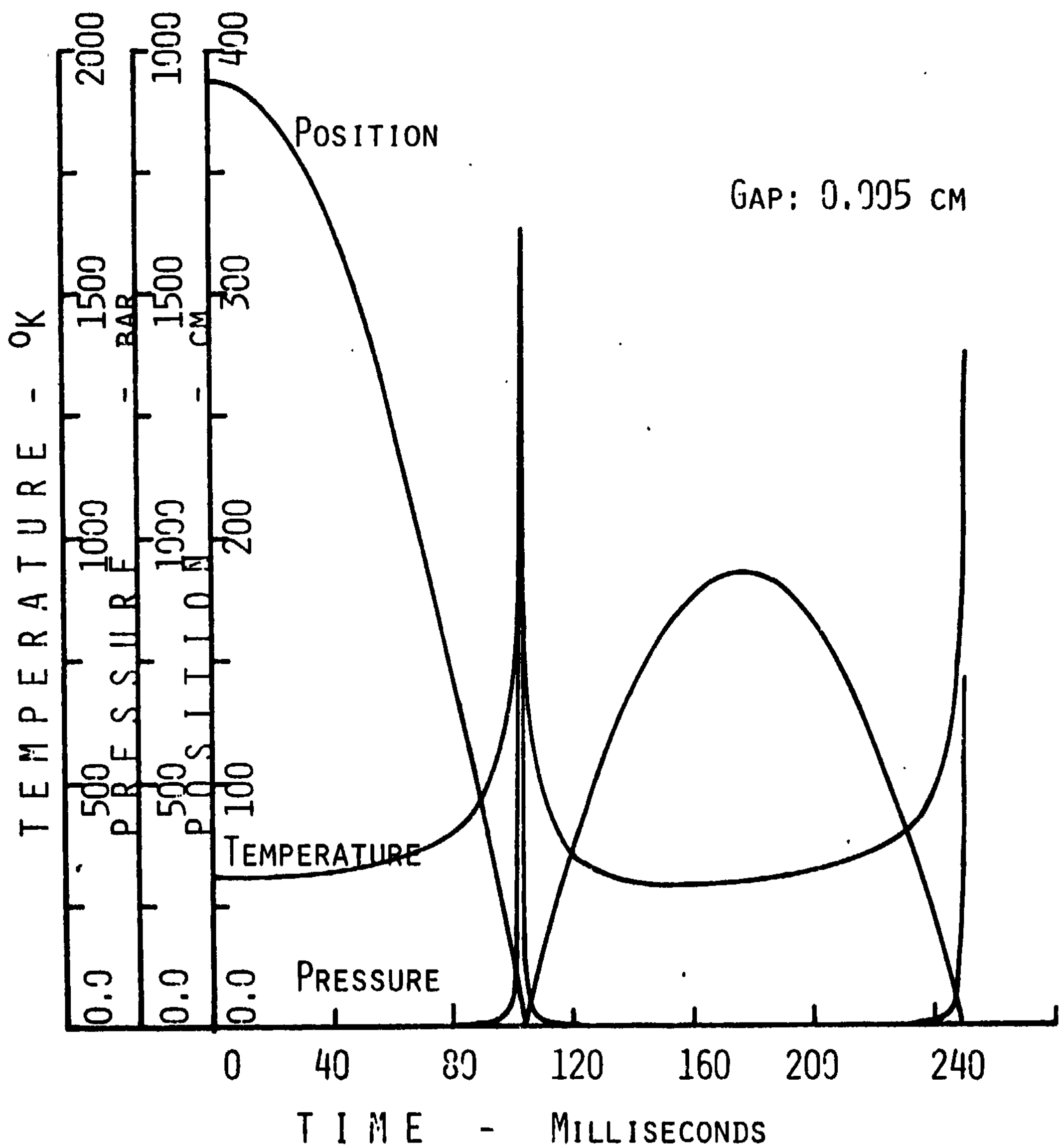
OF POOR QUALITY

FIGURE A-1B



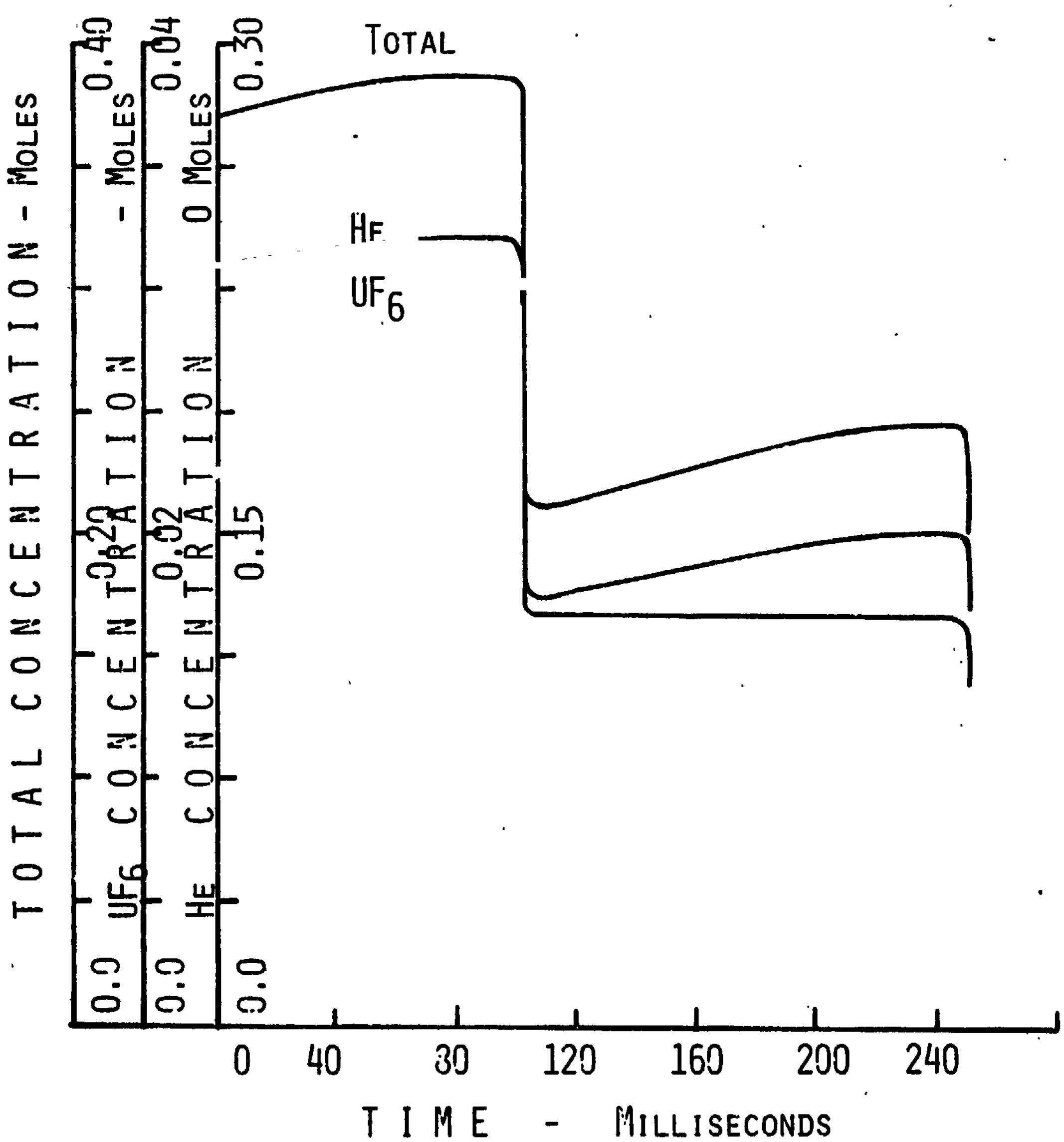
CONCENTRATION OF UF_6 AND HE AS A FUNCTION OF TIME
(GAP: 0.010 CM)

FIGURE A-2A



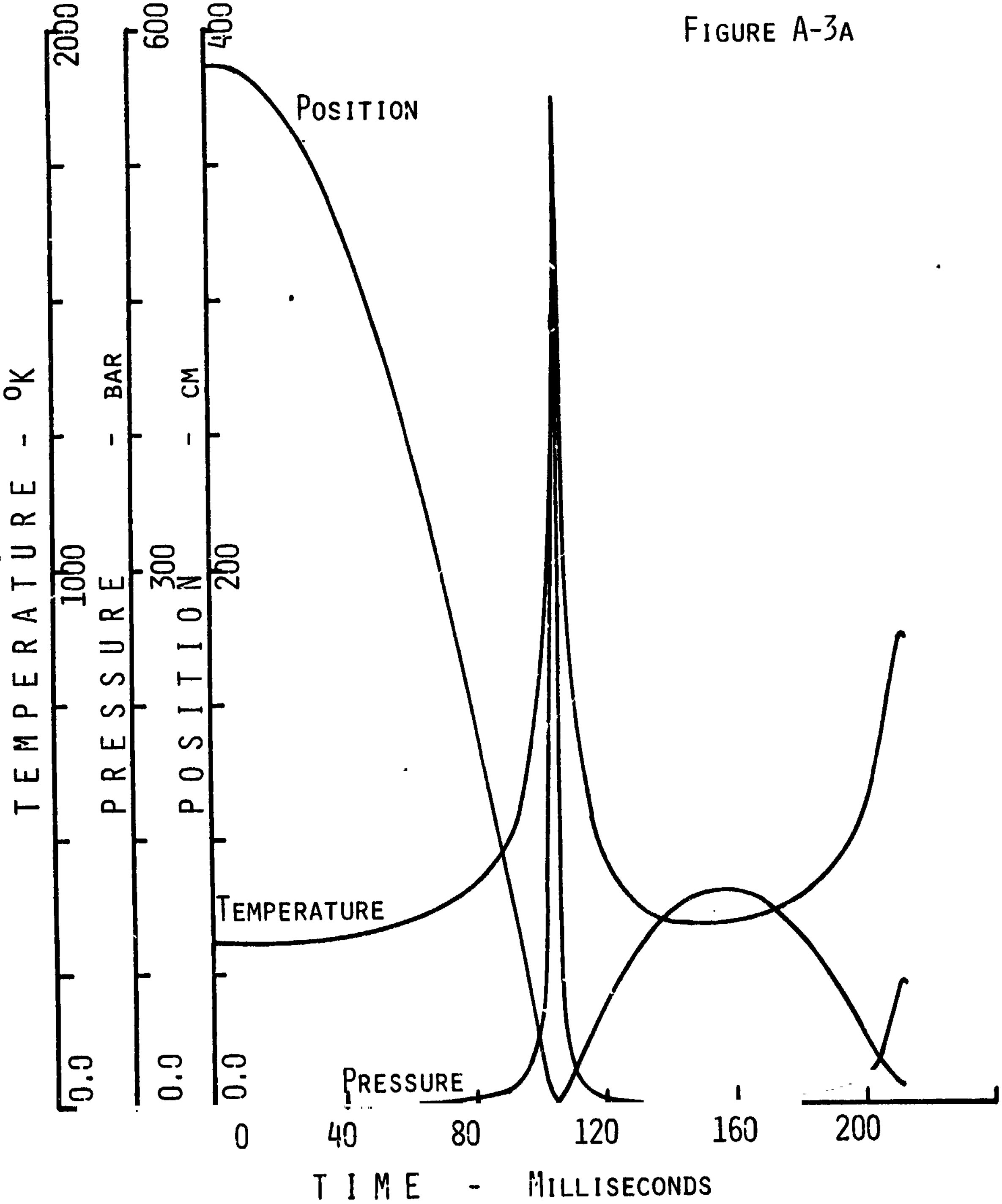
PISTON POSITION, GAS TEMPERATURE AND PRESSURE AS A FUNCTION OF TIME (GAP = 0.005 CM)

FIGURE A-2B



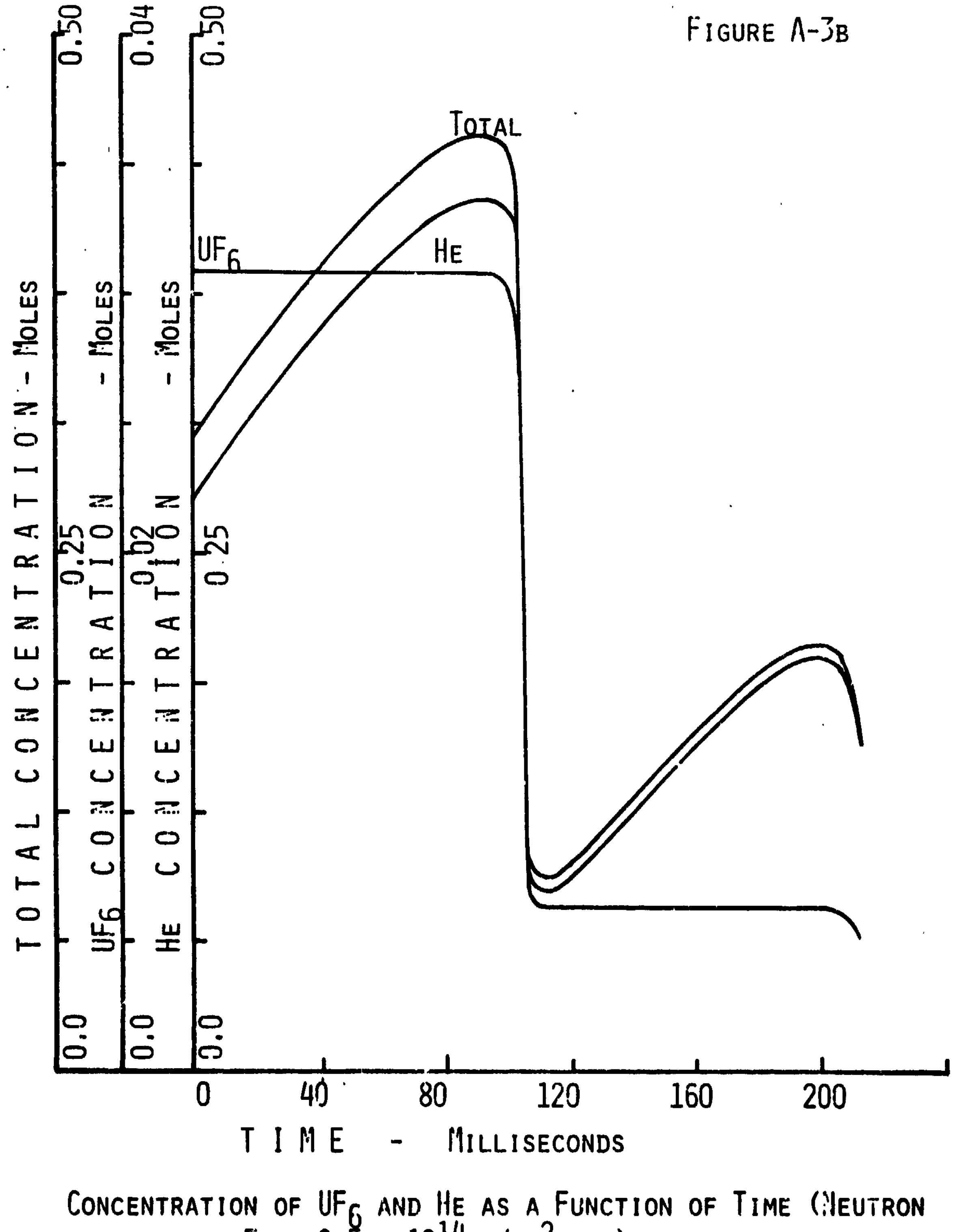
CONCENTRATION OF UF_6 AND HE AS A FUNCTION OF TIME
(GAP: 0.005 CM)

FIGURE A-3A



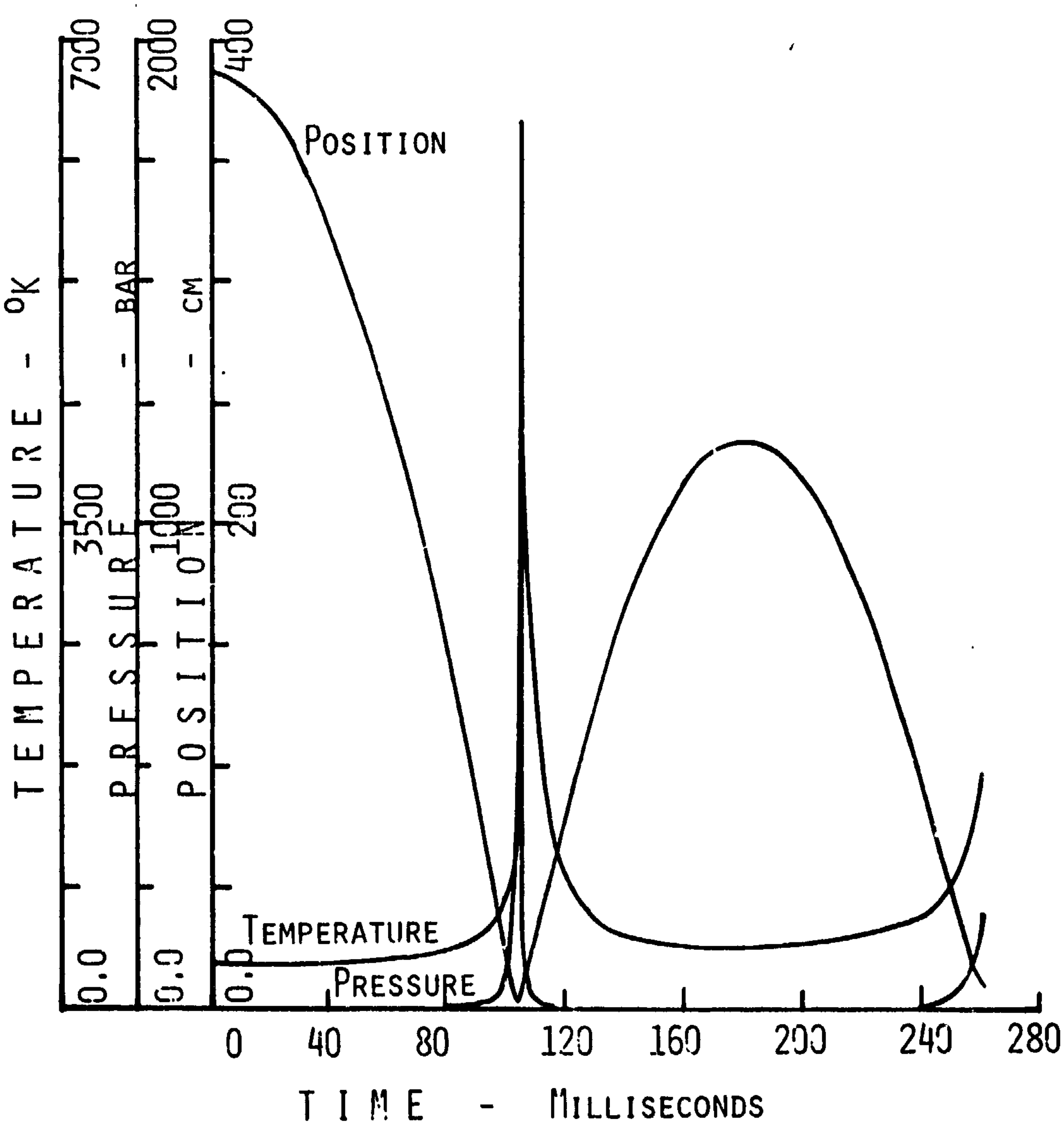
POSITION, GAS TEMPERATURE AND PRESSURE AS A FUNCTION OF TIME (NEUTRON FLUX = 9.5×10^{14} N/SEC CM^2)

FIGURE A-3B



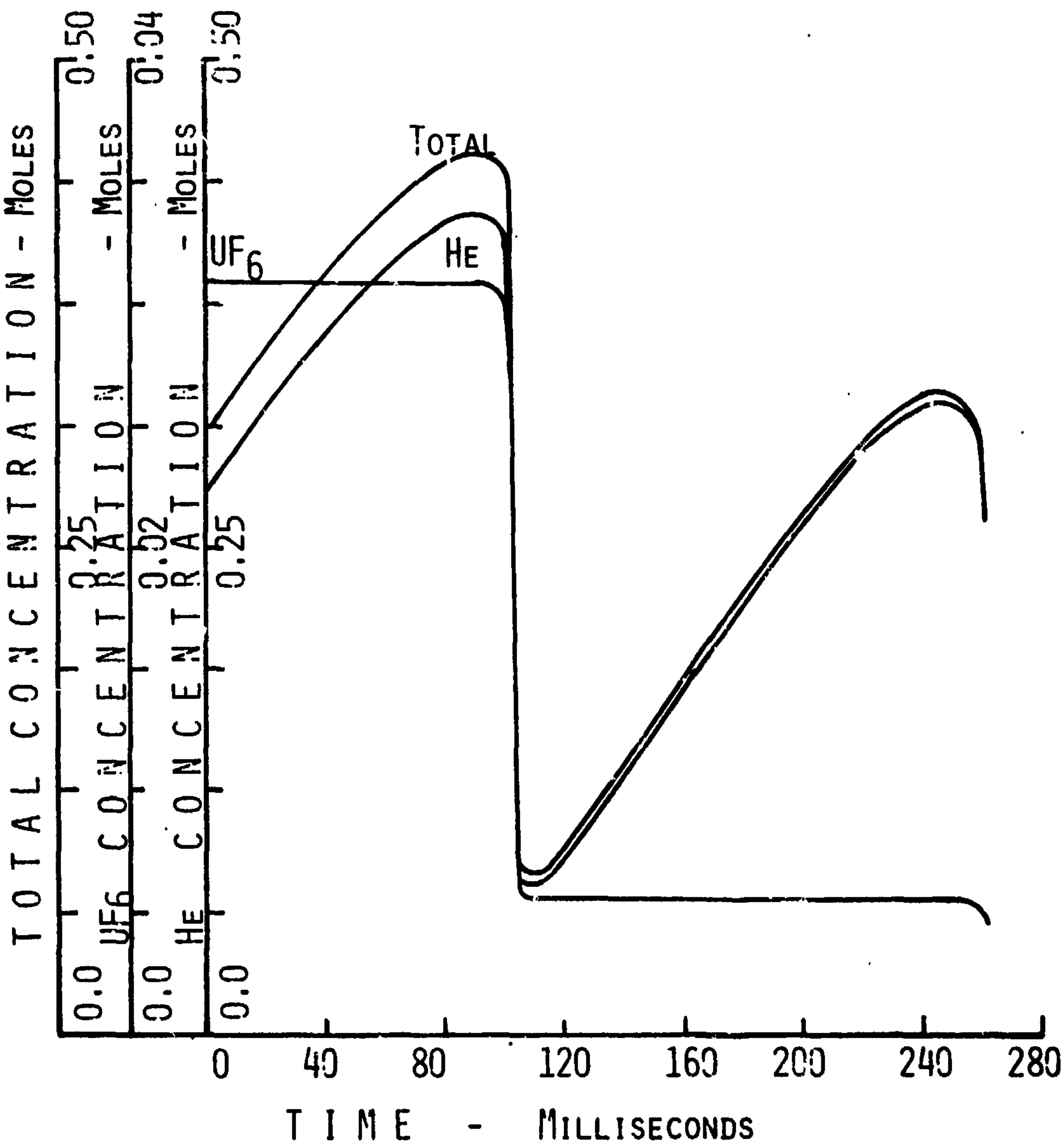
CONCENTRATION OF UF_6 AND HE AS A FUNCTION OF TIME (NEUTRON FLUX 9.5×10^{14} N/CM^2 SEC)

FIGURE A-4A



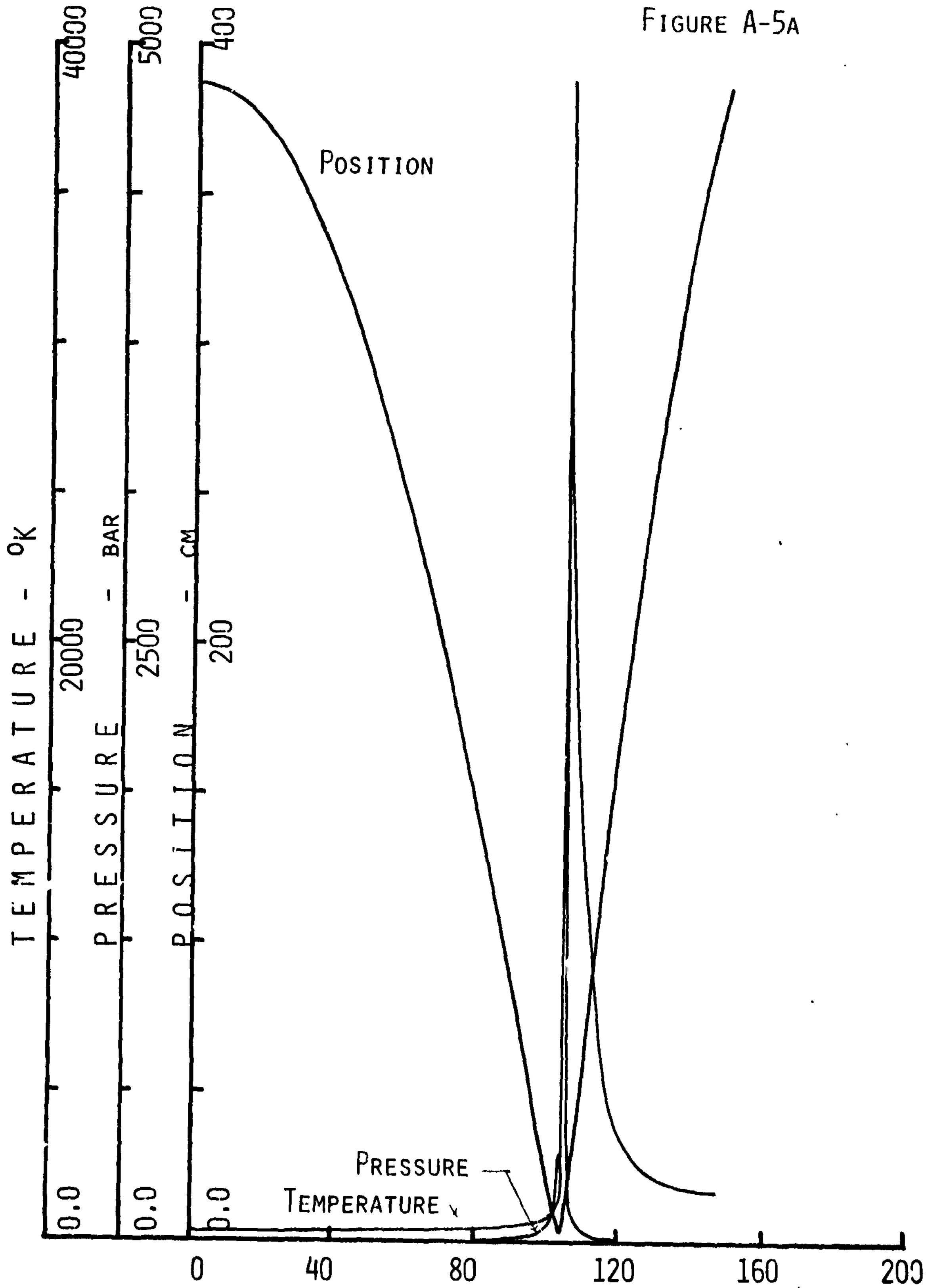
PISTON POSITION, GAS PRESSURE AND TEMPERATURE AS A FUNCTION OF TIME (NEUTRON FLUX 9.5 x 10^{13} N/SEC CM^2)

FIGURE A-4B



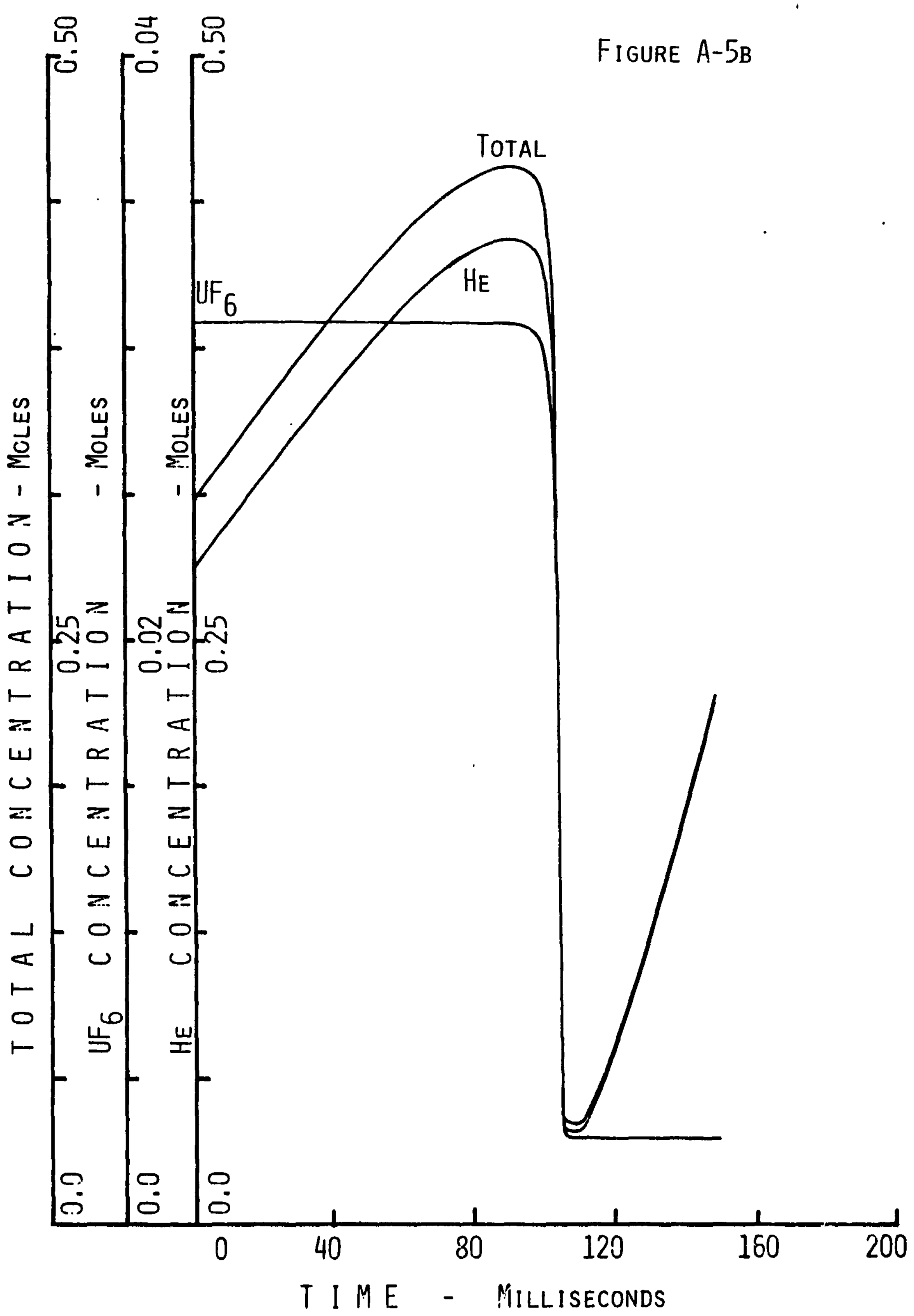
CONCENTRATION OF UF_6 AND HE AS A FUNCTION OF TIME
(NEUTRON FLUX 9.5×10^{13} N/SEC CM^2)

FIGURE A-5A



PISTON POSITION, GAS PRESSURE AND TEMPERATURE AS A FUNCTION OF TIME (NEUTRON FLUX 9.5 x 10^{19} N/CM^{2}SEC)

FIGURE A-5B



CONCENTRATION OF UF_6 AND HE AS A FUNCTION OF TIME
(NEUTRON FLUX 9.5×10^{19} N/CM SEC2)