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THERMODYNAMICS OF ROCKET PROPULSION AND THEORETICAL EVALUATION OF SOME PROTOTYPE PROPELLANT COMBINATIONS

by

Thomas O. Dobbins, 1/Lt USAF

Propulsion Laboratory

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WRIGHT AIR DEVELOPMENT CENTER
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FOREWORD

This report was prepared by 1/Lt Thomas O. Dobbins of the Rocket Propellant Section, Fuels and Oils Branch, Propulsion Sub-Systems Division, Propulsion Laboratory. Work was performed under Project 3148, "Development of Liquid and Solid Rocket Propellants". This work was also submitted by the author as a thesis for the degree Master of Science at the Ohio State University, December 1959.

ABSTRACT

This report presents a concise summary of the thermodynamics of rocket propulsion and the evaluation of 100 prototype propellant combinations. Emphasis is placed on the thermodynamics of chemical propulsion and on flow through the converging-diverging nozzle. From this basic theory, two (2) rigorous methods are developed for conducting theoretical performance calculations. One (1) of these utilizes thermodynamic equilibrium constants while the second utilizes a completely new concept of minimizing the total free energy of the combustion products. Sample calculations are presented for each method. Thermodynamic data are presented and discussed for several reactants and all important products of combustion consisting of the elements carbon, hydrogen, oxygen, nitrogen, chlorine, fluorine, lithium, boron, beryllium, aluminum, and magnesium. A rigorous theoretical evaluation is presented for 100 prototype propellant systems. Specific impulse, chamber temperature, exhaust temperature, characteristic exhaust velocity, and chamber molecular weight are plotted as a function of the propellant composition. Also, complete performance data are tabulated for selected fuel-to-oxidizer ratios.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

C. L. WORD
Chief, Propulsion Sub-Systems Division
Propulsion Laboratory

PREFACE

In this report, the author has attempted to present a concise, comprehensive, fundamental approach to the theoretical evaluation of rocket propellant performance. First, those basic principles of thermodynamics and fluid dynamics directly related to rocket propulsion are reviewed. Although many detailed textbooks have been prepared on these two subjects, fewer attempts have been made to combine the phases applicable to rocketry into one summary. From this fundamental theory, two rigorous methods of calculating propellant performance are presented.

One of these approaches, the minimization-of-free energy at constant enthalpy or constant entropy, has not been published previously. Then, using the latter method of calculation, the author has evaluated the performance of a series of prototype fuels and oxidizers. The basic thermodynamic data used in this evaluation are also presented and discussed.

Many scientists have contributed indirectly to this report by their work in the basic areas of thermodynamics, fluid dynamics and propulsion. Unfortunately, there is no adequate way to repay this debt except through a general acknowledgement. When material has been taken from the publications of others, this has been indicated by footnotes in the text. The author's first specific acknowledgement is to Professor P. R. Jones of West Virginia University and Dr. W. B. Kay of the Ohio State University who introduced him to the science of thermodynamics and kindled his interest in the subject. Furthermore, an additional acknowledgement is made to Dr. Kay for his guidance and interest while serving as adviser to the author on this project. Also, Dr. R. S. Brodkey of the Ohio State University is

recognized for his inspiring teaching of fluid dynamics.

Substantial assistance was provided by several others in preparing specific sections of this report. The author wishes to acknowledge Mr. A. E. Roberts, Jr. of General Kinetics, Inc. who programmed the minimization-of-free energy concept for the Universal Scientific Computer, Model 1103A, and who offered valuable constructive comments on the author's presentation of this theory. Thanks are also due Mr. L. J. Gordon of the Aerojet-General Corporation for his guidance in evaluating the relative importance of propellant density and specific impulse. The author is grateful to Dr. C. B. Henderson and Mr. R. S. Scheffee of the Atlantic Research Corporation for their valuable assistance in assembling thermodynamic data on reactants and products-of-combustion. Additional recognition is given to Dr. D. R. Stull of Dow Chemical Company, Mr. John S. Gordon of Reaction Motors Division of Thiokol Chemical Company, and to Dr. Charles W. Beckett, Jr., and his colleagues at the National Bureau of Standards for their assistance and advice in obtaining accurate thermodynamic data. The unpublished multiphase flow theory of Dr. David Altman of United Aircraft Research also contributes to the comprehensiveness of this report. The interest of each of these gentlemen is sincerely appreciated.

Finally, but certainly not least, thanks are due to Miss Dora M. Wolfe and Mrs. Lavera Howard of Wright Air Development Center for typing the text of this report, and to Mr. Nicholas Engler and Mr. William Powers of the University of Dayton for assisting with the plotting of graphs.

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CHAPTER I

INTRODUCTION

A. Historical Background

Although the concept of rocket propulsion is an old one, in practice it is a relatively new aeronautical science. Professor Robert H. Goddard, hailed as the father of American rocketry, began his studies in the year 1915.[1] For the next 25 years, he and his followers pioneered rocket research within the United States until the outbreak of World War II stimulated considerable interest in their activities. Since that time, rocket research and development has been pursued at an accelerating rate until it now constitutes a significant part of the activity of America's aircraft industry.

From the time of Goddard's early experiments, rocket scientists have needed to know the performance of a rocket propellant system before designing a missile to use it. Originally, thermodynamists theoretically calculated the performance of a few carbon-hydrogen-oxygen propellants by hand. However, the complexity of the calculation coupled with the lack of high temperature thermodynamic data limited their acticity. As some rocket thermodynamists attempted to expand the scope of their work, short-cut methods of calculation were developed. However, these techniques invoked simplifying assumptions which introduced considerable error as the chemical complexity of the propellants increased, particularly if condensed phases were formed as products of combustion.

In the early 1950's, investigators at the Lewis Laboratories of the National Advisory Committee for Aeronautics developed a program for calculating the performance of propellants composed of carbon, hydrogen, oxygen, nitrogen, chlorine, and fluorine on the IBM 650 digital computer. Similarly, investigators at California Institute of Technology's Jet Propulsion Laboratory programmed the Datatron 201 computer. This constituted an advancement in theoretical analysis work. However, these and many similar programs subsequently developed by others have been designed to evaluate specific ingredient elements which form specific products of combustion. In these cases, neither new ingredient elements nor new products of combustion may be considered without re-writing the computer program. Furthermore, the shortage of memory capacity in small and medium-size digital computers has limited the complexity of the propellant system which could be evaluated.

As an extension and expansion of this earlier performance calculation work, a completely general computer program based upon a new concept of the minimization of free energy has been established at Wright Air Development Center. This program, prepared for the Universal Scientific Computer, Model 1103A, is neither limited by the number or type of elemental ingredients nor by the number or state of the products of combustion. For all practical purposes, any propellant system for which thermodynamic data are available may be evaluated. This achievement may be considered a logical outgrowth of the work of earlier investigators.

B. Object and Scope

This report has been prepared as a contribution to the theoretical evaluation of potential fuels and oxidizers as propulsion media. The object

of the report is to present the thermodynamics of rocket propulsion and the evaluation of several prototype propellant combinations. The scope may be divided into four logical areas: (1) a concise, comprehensive treatment of the fundamental theory of rocket propulsion; (2) a detailed description of two rigorous methods for calculating propellant performance; (3) a discussion of the thermodynamic data for a number of selected reactants and products of combustion; and (4) the evaluation of the performance of several prototype propellant systems.

The development of fundamental theory is designed to incorporate all important concepts into one logical, comprehensive summary. The literature has been carefully screened in order to utilize the contributions of previous workers. Emphasis is placed on the thermodynamics of chemical propulsion and on flow through the converging-diverging nozzle. From this basic theory, two rigorous methods are developed for conducting theoretical performance calculations. One of these utilizes thermodynamic equilibrium constants to express the concentrations of minor products of combustion in terms of the major species. The second method utilizes a completely new concept of minimizing the total free energy of the combustion products. Although both methods are equally rigorous, the latter one is more general and was applied to the calculational work.

Thermodynamic data are presented and discussed for several reactants and all important products of combustion consisting of the elements carbon, hydrogen, oxygen, nitrogen, chlorine, fluorine, lithium, boron, beryllium, aluminum, and magnesium. Ten prototype fuels and ten prototype oxidizers were then chosen for rigorous theoretical evaluation. Although a number of

these systems do not constitute workable propellant combinations, they were selected because of the basic combustion information which could be obtained. The study was designed to reveal the relative merits of various elements and chemical bonds as ingredients for chemical propellants. In conducting the calculations, all known products of combustion were assumed to exist. Since the calculational technique was completely rigorous, the accuracy of the calculations in this report is limited only by the accuracy of the basic thermodynamic data used. Therefore, this report is submitted as a comprehensive resume' of the present state-of-the-art in theoretical propellant evaluation.

CHAPTER II

SUMMARY

The evaluation of chemical rocket propellants may be based directly upon the laws of thermodynamics. The energy available from any chemical propellant combination is directly proportional to the square root of the change in enthalpy of the system as it flows through a converging-diverging nozzle. This analysis is equally applicable to both compressible and multiphase flow. In the latter situation, thermal and momentum equilibrium between the gas phase and the condensed phase are very closely approached when the diameter of the condensed particle is less than ten microns. If this size is exceeded, the momentum lag may cause a loss of useful energy. Although the density of a propellant combination must be considered in evaluating its effectiveness in a given missile application, the specific impulse is the most significant parameter in screening propellants.

Rigorous performance calculations must be made by assuming adiabatic combustion in the chamber and isentropic expansion through the nozzle. This may be accomplished by either the method of equilibrium constants or the method of minimization-of-free energy. The latter is recommended for conducting calculations on a high-speed digital computer because of its completely general approach.

High temperature thermodynamic data are available for the products of combustion of most of the interesting propellant ingredients. However, in many cases these data are extrapolated from experimental studies at

lower temperatures. Therefore, additional experimental studies are needed to refine the thermodynamic properties of many substances. This is particularly true of the compounds of the light metals lithium, aluminum, beryllium, boron, and magnesium.

Fluorine and oxygen difluoride were found to be excellent oxidizers for most of the prototype fuels studied. Hydrogen and beryllium hydride were universally energetic fuels. For oxidizers, the O-F bond was found more energetic than the N-F bond which, in turn, surpassed the Cl-F bond. For fuels, hydrogen was found to be an essential ingredient for high energy. Nitrogen appears more desirable than carbon as a carrier element. Beryllium appears to be the most promising of the light metals, although boron and aluminum offer considerable energy. Lithium is considerably more energetic if oxidized with fluorine than if oxidized with oxygen.

CHAPTER III

FUNDAMENTAL THEORY OF ROCKET PROPULSION

A. Rocket Propulsion Principles

1. General Principles

All known methods for propelling a body through a fluid medium are based upon the reaction principle. One of these methods is rocket propulsion, which may be defined as a means of locomotion through which reaction is imparted to a vehicle by the momentum of ejected matter.[2] The matter is ejected as a high-speed gas stream, which is generated by chemical reaction between a fuel and an oxidizer stored within the vehicle. By accelerating the gas stream through a converging-diverging nozzle, supersonic velocities are attained. Thus, rocket propulsion is achieved by the conversion of the thermal energy of a chemical reaction into the translational energy of the products of combustion.

The theory of propulsion was first presented by Sir Isaac Newton in the year 1686 with the publication of his three fundamental laws of motion in Philosophiae Naturalis Principia Mathematica. These laws state that: (1) every body tends to continue either in a state of rest or in a state of uniform motion unless acted upon by external forces; (2) a change of motion is proportional to the force introducing the change and occurs in a straight line along which the force acts; and (3) the action of a force is always opposed by an equal and opposite reaction. Newton's second law of motion constitutes the fundamental principle of fluid dynamics. Combining the second and third laws, the magnitude and direction of all momentum changes are defined.

In addition to Newton's laws, the behavior of compressible fluids is also governed by the law of conservation of mass, the first law of thermodynamics, and the second law of thermodynamics. These laws are completely independent of the nature of the propelling medium. For a specific rocket propulsion process, additional subsidiary laws may be introduced which are related to the particular nature of the propelling medium. These include the equation of state and equations expressing the thermodynamic properties of the fluid.

2. The Momentum Principle

From the laws of motion, momentum is shown to be a vector quantity possessing the direction of the velocity vector. The time rate of change of the total momentum of a bounded body of fluid is equal to the resultant of the external forces acting on the boundaries, i.e.

$$\Sigma F' = \frac{d}{dt}(mv) \qquad (1)$$

The net external force is also a vector quantity having the same magnitude and direction as the velocity vector representing the change in the rate of momentum.

In applying the principle of momentum to rocket propulsion, another term must be added to the momentum equation when a difference in pressure exists between the emergent fluid jet and the surrounding fluid medium. Thus, the total thrust imparted to a vehicle moving through a homogeneous external fluid is composed of the momentum thrust and the pressure thrust. The former is the product of the mass flow rate of propellant and the exhaust velocity of the emergent fluid stream relative to the vehicle. The latter is the product of the cross-sectional

area of the emergent stream and the difference in pressure between this stream and the surrounding medium. Mathematically,

$$F' = \frac{m}{g} v_e + (p_e - p_a) A_e \qquad (2)$$

where
F' = thrust
m = mass flow rate
g = acceleration of gravity
v_e = velocity of exhaust gases at nozzle exit
p_e = nozzle exit pressure
p_a = external surrounding pressure
A_e = exit area of nozzle

When the exhaust pressure is exactly equal to the pressure of the external fluid medium, the pressure thrust term becomes zero. This condition defines the optimum thrust obtainable from isentropic flow through a converging-diverging nozzle, and will be discussed in more detail in a subsequent section. When the nozzle exit pressure exceeds the external pressure, the nozzle area is not sufficiently large to permit complete expansion of the working fluid. On the other hand, if the exhaust gases are overexpanded to a pressure less than the external pressure, a shock wave will occur in the nozzle. Thus, either overexpansion or underexpansion induces a loss of energy and a corresponding reduction in the exhaust velocity.

Actually, only the axial component of velocity will produce a net thrust in a converging-diverging nozzle. Therefore, in comparing experimental and theoretical thrust values, a geometric correction must be applied, i.e.

$$F' = \frac{1}{2g} (1 + \cos\alpha) m v_e + (p_e - p_a) A_e \qquad (3)$$

where α is the half angle of nozzle divergence. Thus, the effective exhaust velocity for the general case is defined as

$$v' = \frac{F'g}{\dot{m}} = \frac{1}{2}\,(1 + \cos\alpha)\, v_e + \frac{(p_e - p_a)A_e \cdot g}{\dot{m}} \qquad (4)$$

This, in turn, leads to the definition of specific impulse, which is one of the most important parameters for evaluating rocket performance.

3. Useful Rocket Parameters

Specific impulse is defined as

$$Isp = \frac{F'}{\dot{m}} = \frac{v'}{g} \qquad (5)$$

or the pounds of thrust obtained per pound of propellant flow per second. In practice, the dimensions of specific impulse are reduced to seconds. It will be shown later that specific impulse is a property of the chemical composition of the propellant and can be theoretically evaluated by thermodynamic analysis.

In ordinary engineering practice, variations in gravity are unimportant, and mass and weight quantities are used interchangeably. Although the thrust of a rocket is actually a function of the mass flow rate (not of the weight flow rate), weight terminology is still preferred for use by the rocket industry. Actually, specific impulse is independent of gravity and other external effects and, in mass terminology, would have the dimentions of ft/sec and be numerically equal to the effective exhaust velocity.[3]

In most experimental rocket motor tests, the following quantities are either measured or known:

(1) Thrust, F'
(2) Combustion pressure, p_c
(3) Exit pressure, p_e
(4) Nozzle throat area, A^*
(5) Nozzle exit area, A_e
(6) Mass rate of propellant flow, $\dot{m}$
(7) Propellant composition

The overall performance, as measured by specific impulse or exhaust velocity, is evaluated experimentally from items (1) and (6) or computed theoretically from items (2), (3), and (7). However, in some test work it is desirable to individually analyze the combustion and the expansion processes. The combustion process should determine the ability of a propellant combination to generate useful energy while the expansion process should determine the effectiveness of utilizing that energy. For this reason, two experimental quantities, the characteristic velocity and the nozzle thrust coefficient, are defined respectively as

$$c^* = \frac{p_c A^* g}{\dot{m}} \tag{6}$$

and

$$c_F = \frac{F'}{p_c A^*} \tag{7}$$

The characteristic velocity is actually the velocity of sound at the nozzle throat. In essence, this is a measure of the effectiveness with which the combustion products are generated in the rocket chamber. Closely related to the characteristic velocity is the weight flow coefficient, or discharge coefficient, which is defined as

$$c_w = \frac{\dot{m}}{p_c A^*} \tag{8}$$

This parameter gives a direct measure of the rate of consumption of the propellant. The product of the thrust coefficient and the characteristic velocity equals the exhaust velocity.

The total impulse may be expressed either as a function of thrust or of specific impulse:

$$I = F't = Isp \cdot W_p \qquad (9)$$

where
I = total impulse
t = operating time
W_p = total weight of propellant consumed
Isp = specific impulse
F' = thrust

This is a measure of the total energy possessed by a given missile, and may consist of a large thrust lasting for a short duration or a smaller thrust acting for a longer time.

B. Analysis of the Ideal Rocket

1. Fundamental Technical Assumptions

The quantitative treatment of fluid dynamics may be based directly upon the laws of thermodynamics.[4] A strictly thermodynamic approach does not require any consideration of the mechanism of flow. Rather, it constitutes an energy analysis and establishes the limiting, ideal conditions of flow. A frictionless, one-dimensional flow is assumed which is independent of fluid viscosity, the transport property of momentum. This approach is quite justified from an engineering viewpoint since the viscous forces are negligible compared to the inertial forces.

Frequently, the measured performance of rocket engines exceeds 95% of the ideal, theoretical values. Furthermore, the accepted practice for designing rocket engines is to utilize ideal rocket parameters and modify these by empirical corrections.

Before introducing the equations of thermodynamics which govern rocket propulsion, the assumptions invoked in analyzing the combustion and expansion processes will be discussed. The thermodynamic approach must possess a maximum sophistication in order to place the minimum amount of limitation upon the theoretical results. Therefore, assumptions are limited to those justified by theoretical or experimental evidence, those introducing a negligible effect on the final results, and those representing the ideal limit for chemical and physical phenomena which lack experimental verification. These assumptions are the following:

(1) The gaseous species behave ideally, i.e. obey the perfect gas law.

(2) Dalton's Law applies.

(3) Molar enthalpies of all species are independent of pressure.

(4) Molar entropies of condensed phases are independent of pressure.

(5) Steady-state conditions exist during combustion and expansion.

(6) Condensed phases occupy a negligible volume.

(7) The entropy of mixing is negligible for condensed phases.

(8) Vapor pressures of condensed phases are independent of total pressure.

(9) The combustion process is adiabatic.

(10) Combustion occurs at constant pressure.

(11) Thermal and chemical equilibria exist in the combustion chamber.

(12) Homogeneous mixing is attained.

(13) The combustion products in the chamber have zero bulk velocity with respect to the walls of the chamber.

(14) Isentropic, frictionless, one-dimensional flow occurs in the nozzle.

(15) The exit velocity of the combustion products is uniform across any section normal to the nozzle axis.

(16) The gases are insoluble in the condensed phase, and the condensed phases themselves are immiscible.

(17) The particles are thermodynamically macroscopic.

(18) Condensed phases are in thermal and velocity equilibrium with the gas stream during the expansion process.

2. Discussion of the Assumptions

The first five of these assumptions may be considered as justified by existing experimental evidence. The only questionable point appears to be the assumption of ideal behavior for the vapors of the metal oxides. Because of their high boiling points, these compounds could conceivably deviate somewhat from ideality at combustion conditions. However, the relatively small concentrations of these vapors in the combustion products will tend to minimize the significance of any possible non-ideal behavior. The ideal gas approximation has been found to be quite adequate for the more common combustion products.

Assumptions six, seven, and eight are made to simplify the calculation procedure. In these cases, correction is not particularly difficult, but the effect upon the final results is negligible.

Any error introduced by these assumptions is certainly insignificant compared to uncertainties in the basic high-temperature thermodynamic data themselves.

Assumptions nine through fifteen are peculiar to the rocket propulsion process itself, i.e. an adiabatic combustion followed by an isentropic expansion through a converging-diverging nozzle. These assumptions represent the ideal, limiting conditions of energy utilization and overall efficiency, and are approached experimentally in large rocket engines. In practice, the geometry of the rocket engine may affect the attainment of equilibrium. A short reaction chamber may not afford a sufficiently long residence time for some chemical reactions to reach equilibrium. In the nozzle, the attainment of equilibrium could conceivably be inhibited by the nature of the chemical reaction and the existing physical conditions. For example, associative reactions would be less likely at lower pressures when fragments would be more remote and their probability of collision relatively less. The one-dimensional flow approximation is an excellent one in short ducts of variable cross-sectional area. In this case, the fundamental cause for the change in flow conditions is the variation in the area, and other causes, such as boundary layer development and skin friction, have only a secondary influence.[5] Changes in properties normal to the streamline are considered negligible compared to changes in the direction of flow. Hence, average properties over the cross-section are evaluated. Errors are minimized when the change in cross-sectional area per unit length is small, when the radius of curvature is large compared to the diameter, and when the shapes of the velocity and temperature profiles remain constant with length.[6]

Assumptions sixteen through eighteen represent ideal, limiting approximations for unproved physical and chemical phenomena. The questions of gas solubility in condensed species and of the miscibility of liquid phases are worthy of consideration. These phenomena could bear some significance, particularly for cases in which liquid metal oxides constitute a relatively large percentage of the total mass of combustion products. However, assumption eighteen is probably a greater potential source of error. The degree of thermal equilibrium between the gas and condensed phases is dependent upon the rate of heat transfer, while the degree of acceleration of the condensables by the gas is dependent upon the rate of momentum transfer. Both transfer rates are greatly affected by the particle sizes of the condensed phases. As the particle size of the condensable decreases, both thermal and momentum equilibrium are approached to a greater degree. Efforts have been made to predict the degree of approach to these equilibria by the use of empirical rate constants.[7,8] The tentative conclusion of these studies was that both thermal and momentum equilibrium are very nearly approached in two-phase flow provided the particle diameter of the non-gaseous phase does not exceed ten microns.

The expansion process through the converging-diverging nozzle may be analyzed by four basic approaches. These are:

(1) Shifting chemical equilibrium accompanied by complete phase equilibrium.

(2) Shifting chemical equilibrium with frozen phase equilibrium.

(3) Frozen chemical equilibrium with complete phase equilibrium, i.e. equilibrium condensation.

(4) Frozen chemical equilibrium and frozen phase equilibrium.

The first basis is the most ideal one and establishes the maximum theoretical performance of a given propellant combination at an established set of operating conditions. On the other hand, the fourth basis represents the lower limit of performance. Experimental evidence indicates that the equilibrium conditions of the chamber are shifted to a certain degree during the expansion process. Only the degree of the shift is questionable, and this undoubtedly is dependent upon the particular propellant combination. Therefore, for practical purposes, if both the first and fourth approaches are evaluated, the theoretical performance may be "bracketed" by establishing its maximum and minimum limits.

3. Uncertainties in Performance Calculations

Practically all of the fundamental uncertainties related to theoretical performance calculations are concerned with the phenomenon of two-phase flow. Until more basic information is obtained on this phenomenon, theoretical performance calculations cannot be refined further. The particular problem areas related to rocket propulsion which are in need of more basic study include:[9]

(1) The extent of approach to thermal equilibrium between the gaseous and condensed phases.

(2) The extent to which the velocity of the condensed phases lags behind that of the gas phase.

(3) The rate of formation and growth of the condensed particles.

(4) The effect of miscibility of two or more condensed phases and the effect of solubility of the gas phase constituents in the condensed phase.

(5) The degree of non-ideality of the vapors of condensed phases, particularly in the region of saturation conditions.

C. Thermodynamic Significance of Specific Impulse

1. Fundamental Thermodynamic Concepts

Thermodynamics is the science which deals with the relationships between various forms of energy. Applied to chemical reactions, thermodynamics not only reveals whether or not a reaction is possible but also specifies the quantitative change in energy which occurs during the reaction. Thermodynamics is independent of the path of a chemical reaction; only the initial and final states need be considered. However, thermodynamics has its limitations. Since it is not concerned with time, thermodynamics will yield no information concerning the rate and mechanism of a reaction.

The first law of thermodynamics is the law of conservation of energy. This states that the total energy entering a process, plus any addition during the process, must equal the total energy of the system leaving the process, i.e.

$$dE = dq - dw \tag{10}$$

where
- E = internal energy of the system
- q = energy absorbed by the system from its surroundings
- w = work done by the system on the surroundings

The second law of thermodynamics may be considered as a measure of the degree to which energy can be transformed into useful work. The point property which measures the amount by which the energy of a system is degraded in going from one state to another is called entropy, and is defined by the second law as

$$dS = \frac{d_{q_r}}{T} \tag{11}$$

where

S = entropy of the system
T = temperature of the system
q_r = reversible energy change at constant temperature

Interpreted statistically, the second law states that, on the average, the entropy of an isolated system increases continuously until that system reaches a state of maximum probability. In reality, all spontaneous reactions are to some extent irreversible and are accompanied by a degradation of energy. Finally, the third law of thermodynamics states that the absolute entropy of any homogeneous substance which is in complete internal equilibrium is zero at 0°K. The first two laws are explicitly involved in the analysis of rocket propulsion, while the third law is utilized implicitly.

Utilizing the first law, enthalpy is defined as

$$dH = dE + d(pV) \tag{12}$$

where

H = enthalpy
E = internal energy
p = pressure
V = volume

Since enthalpy is defined in terms of functions of state, it is also a function of the state of a system. By re-writing the first law in the form

$$dq = \left(\frac{\partial E}{\partial T}\right)_V dT + \left[\left(\frac{\partial E}{\partial V}\right)_T + P\right] dV \tag{13}$$

the specific heat capacities are defined as

$$C_V = \left(\frac{\partial E}{\partial T}\right)_V \tag{14}$$

$$c_p = \left[\frac{\partial(E+pV)}{\partial T}\right]_p = \left(\frac{\partial H}{\partial T}\right)_p \qquad (15)$$

for constant volume and constant pressure, respectively. For the general case,

$$c_p - c_V = \left[p + \frac{\partial E}{\partial V}\right]_T \left(\frac{\partial V}{\partial T}\right)_p \qquad (16)$$

but for ideal gases this relationship reduces to $c_p - c_V = R$. (17)

In order to express the first and second laws explicitly in terms of temperature and pressure, the Gibb's free energy is defined as

$$dF = dH - d(TS) \qquad (18)$$

or $$dF = dE + pdV + Vdp - TdS - SdT \qquad (19)$$

Under reversible conditions in which all work is accomplished by expansion,

$$dE = TdS - pdV. \qquad (20)$$

Combining these equations,

$$dF = Vdp - SdT. \qquad (21)$$

This is probably the most useful combined statement of the first and second laws since pressure and temperature are the independent variables. The concept of free energy is extremely useful as a criterion of chemical equilibrium, and is related to the equilibrium constant by the equation

$$dF = RT\ d\ \ln K. \qquad (22)$$

At equilibrium, the free energy change of a chemical reaction is zero.

2. Application of Thermodynamics to Rocket Propulsion

All of these general thermodynamic relationships are employed in the analysis of the combustion and expansion processes of rocket propulsion. However, the particular thermodynamic significance of specific impulse is derived from the law of conservation of energy. For the macroscopic, steady-state flow process, Bernoulli's general energy equation per unit of mass becomes

$$\left[E_2 + Z_2 + \frac{v_2^2}{2g} + p_2V_2 \right] - \left[E_1 + Z_1 + \frac{v_1^2}{2g} + p_1V_1 \right] = q - W_o \qquad (23)$$

where

E = internal energy of the fluid
Z = potential energy of position
v = fluid velocity
pV = work of expansion
q = energy absorbed by the system from the surroundings
W_o = non-expansion work done by the system

Position 1 represents the nozzle exhaust conditions while position 2 represents the combustion chamber conditions. Since the velocity is zero at stagnation conditions, v_2 drops from the equation. Also, the difference in potential energy between the chamber and the nozzle exit is negligible. Thus, the equation reduces to

$$\Delta E + \Delta(pV) - \frac{v_1^2}{2g} = q - W_o \qquad (24)$$

or

$$\Delta H - \frac{v_1^2}{2g} = q - W_o \qquad (25)$$

For an adiabatic process in which all work is accomplished by expansion,

$$\Delta H = \frac{v_1^2}{2g} \qquad (26)$$

or $$v_1 = \sqrt{2g\,\Delta H} \tag{27}$$

For the case of optimum expansion,

$$Isp = \frac{v_e}{g} = \sqrt{\frac{2J}{g}\,\Delta H} \tag{28}$$

where
- Isp = specific impulse
- v_e = exhaust velocity
- g = acceleration of gravity
- J = mechanical equivalent of heat
- ΔH = enthalpy change

Thus, specific impulse may be defined rigorously from the total enthalpy change of the system between the combustion chamber and the nozzle exit. Numerically evaluating the specific impulse equation in English units,

$$Isp = 6.940\sqrt{H_c - H_e} \tag{29}$$

where
- H_c = enthalpy of chamber gases, Btu/lb
- H_e = enthalpy of exhaust gases, Btu/lb
- Isp = lb thrust/lb mass/second
- J = 778 ft-lb/Btu
- g = 32.2 ft/sec^2

Similarly, evaluating the equation in metric units,

$$Isp = 9.330\sqrt{H_c - H_e} \tag{30}$$

where
- H_c = enthalpy of chamber gases, calories/gram
- H_e = enthalpy of exhaust gases, calories/gram
- Isp = lb thrust/lb mass/second

These equations are rigorous and apply to isentropic two-phase flow as well as to isentropic compressible flow. In the latter case, another form of the specific impulse equation may be utilized. Since $\left(\frac{\partial H}{\partial p}\right)_T = 0$ for an ideal gas, the adiabatic change in enthalpy is

$$H = \int c_p \, dt \tag{31}$$

Since
$$c_p = \frac{k}{k-1} R \tag{32}$$

$$\Delta H = \frac{k}{k-1} \cdot \frac{R}{MW} (T_o - T_e). \tag{33}$$

Under isentropic conditions,

$$T_e = T_o \left[\frac{p_e}{p_o}\right]^{\frac{k-1}{k}} \tag{34}$$

and
$$\Delta H = \frac{k}{k-1} \cdot \frac{RT_o}{MW} \left[1 - \left(\frac{p_e}{p_o}\right)^{\frac{k-1}{k}}\right] \tag{35}$$

Therefore,
$$v_e = \sqrt{\frac{2g\,R\,k}{k-1} \cdot \frac{T_o}{MW} \left[1 - \left(\frac{p_e}{p_o}\right)^{\frac{k-1}{k}}\right]} \tag{36}$$

from which
$$Isp = \sqrt{\frac{2R}{g} \cdot \frac{k}{k-1} \cdot \frac{T_o}{MW} \left[1 - \left(\frac{p_e}{p_o}\right)^{\frac{k-1}{k}}\right]} \tag{37}$$

where
- T_o = combustion or stagnation temperature
- MW = mean molecular weight of combustion products
- k = mean ratio of the specific heat capacities of the exhaust gas, c_p/c_v
- p_o = chamber or stagnation pressure
- p_e = exhaust pressure
- Isp = specific impulse
- R = gas constant
- g = acceleration of gravity

When R = 1544 ft-lb/(mole)(^{o}R), g = 32.2 ft/sec^2, and T_o = ^{o}R,

$$Isp = 9.797 \sqrt{\frac{k}{k-1} \cdot \frac{T_o}{MW} \left[1 - \left(\frac{p_e}{p_o} \right)^{\frac{k-1}{k}} \right]} \qquad (38)$$

D. Steady, One-Dimensional, Isentropic, Compressible Flow

1. General Principles

An isentropic process is both reversible and adiabatic and may be considered as the limit to be approached by real adiabatic processes. As was discussed earlier, this approximation constitutes a limiting condition for expansion through a converging-diverging rocket nozzle. Compressible flow implies variations in density throughout the field of flow, resulting primarily from changes in pressure. The rate of change of density with respect to pressure is an important variable in the analysis of compressible flow and is inherently related to the velocity of propagation of a pressure disturbance.[10] The one-dimensional flow approximation implies that the rate of change of fluid properties normal to the streamline is negligible compared to the rate of change along the streamline. If condensed phases are present during the expansion process, the concept of compressibility discussed in this section must be modified. Nevertheless, the principles which follow constitute a basic, useful approach to the analysis of rocket propulsion.

2. Velocity of Pressure Wave Propagation

For compressible flow, the Navier - Stokes' solution to the general equations of change may be written as[11]

$$\frac{DV_o}{Dt} = - (\nabla p) + \mu \left[\nabla \cdot (\nabla V_o) \right] + \frac{1}{3} \left[\nabla (\nabla \cdot V_o) \underline{\underline{U}} \right] + \Sigma \rho_i F_i \qquad (39)$$

In the absence of external and viscous forces, the Navier-Stokes' solution reduces to

$$\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} = - \frac{1}{\rho} \cdot \frac{\partial p}{\partial x} = - \frac{1}{\rho} \cdot \frac{\partial p}{\partial \rho} \cdot \frac{\partial \rho}{\partial x} \qquad (40)$$

for one-dimensional flow. Similarly, the general equation of continuity for the fluid as a whole is

$$\frac{D\rho}{Dt} = - \rho (\nabla \cdot V_o) \qquad (41)$$

which reduces to

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial v_x}{\partial x} + v_x \frac{\partial \rho}{\partial x} = \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho v_x) = 0 \qquad (42)$$

for one-dimensional flow. Under steady-state conditions, these equations become[12]

$$v_x \frac{\partial v_x}{\partial x} = - \frac{1}{\rho} \cdot \frac{\partial p}{\partial \rho} \cdot \frac{\partial \rho}{\partial x} \qquad (43)$$

and

$$\rho \frac{\partial v_x}{\partial x} = - v_x \frac{\partial \rho}{\partial x} \qquad (44)$$

Simultaneous solution of the above equations defines the velocity of propagation of a pressure disturbance, or the velocity of sound, for one-dimensional, steady-state, ideal flow. As a limit, this velocity of propagation may be considered as isentropic for an infinitesimal

pressure distrubance, and expressed mathematically as

$$v_x = c = \sqrt{(\partial p / \partial \rho)_s} \tag{45}$$

For the isentropic flow of a perfect gas, $p/\rho = RT$ and p/ρ^k is a constant. Therefore,

$$\frac{dp}{p} = k \frac{d\rho}{\rho} \tag{46}$$

and

$$\left(\frac{\partial p}{\partial \rho}\right)_s = k \frac{p}{\rho} = kRT. \tag{47}$$

The velocity of sound may now be expressed as

$$c = \sqrt{\frac{kp}{\rho}} = \sqrt{kRT} \tag{48}$$

where

p = pressure
ρ = density
k = mean specific heat capacity ratio, c_p/c_v
R = universal gas constant
T = absolute temperature
c = velocity of sound

3. Basic Flow Equations

Velocity, temperature, pressure, and density are the four independent properties selected to describe the state of the system. Therefore, four independent equations are required to express the relationship between these properties at any two points in the nozzle. These equations are: (1) the equation of conservation of mass; (2) the equation of conservation of momentum; (3) the equation of conservation of energy; and (4) the equation of state.

Under steady-state conditions, the mass rate of flow through a differential length of nozzle is

$$A\rho\frac{\partial x}{\partial t} = A\rho v \tag{49}$$

where
A = cross-sectional area
ρ = fluid density
v = fluid velocity
x = distance along nozzle axis
t = time

Therefore, the equation of conservation of mass is

$$\frac{d}{dx}(A\rho v) = 0 \tag{50}$$

which, upon integration, becomes

$$\frac{m}{A} = \rho v \tag{51}$$

or

$$m = \frac{Av}{V'} \tag{52}$$

where
m = mass rate of flow
V' = specific volume of fluid

The rate of change of momentum at a particular inlet position is

$$A\rho v\frac{\partial x}{\partial t} = A\rho v^2 \tag{53}$$

while the rate of change of momentum at any downstream point is

$$A\rho v^2 + \frac{d}{dx}(A\rho v^2)dx \tag{54}$$

From Newton's laws of motion, the difference in these rates of change of momentum equals the resultant of the forces acting on the inclosed volume of fluid. These forces are an upstream force A_p on the inlet section, a downstream force $A_p + \frac{d}{dx}(A_p)dx$ on the exit section, and a

force $P_p \alpha dx$ exerted by the walls of the nozzle. In this latter case, P is the perimeter of the section and α is the half-angle of divergence of the nozzle. Thus,

$$- \frac{d}{dx} (A_p)dx + P_p \alpha dx = \frac{d}{dx} (A\rho v^2)dx \tag{55}$$

However, $dA = Pdx \tan\alpha$ or $dA = P\alpha dx$ since α is small. Therefore, the equation of conservation of momentum may be written

$$- \frac{d}{dx} (A_p) + p \frac{dA}{dx} = \frac{d}{dx} (A \rho v^2) \tag{56}$$

or

$$A \frac{dp}{dx} + \frac{d}{dx} (A \rho v^2) = 0 \tag{57}$$

The total energy contained by the fluid stream consists of its internal energy and its kinetic energy. Using the previously developed nomenclature, the rate in influx of energy is

$$A\rho v (E + \tfrac{1}{2} v^2) \tag{58}$$

while the rate of efflux of energy at a downstream position is

$$A\rho v (E + \tfrac{1}{2} v^2) + \frac{d}{dx} \left[A\rho v(E + \tfrac{1}{2} v^2) \right] dx \tag{59}$$

However, external forces are doing work on the gas at a rate Apv on the inlet surface and at a rate $Apv + \frac{d}{dx} (Apv)dx$ on the outlet surface. Therefore, the total energy balance through the nozzle becomes

$$- \frac{d}{dx} (Apv)dx = \frac{d}{dx} \left[A\rho v (E + \tfrac{1}{2} v^2) \right] dx \tag{60}$$

or

$$\frac{d}{dx} \left[A\rho v (E + \frac{p}{\rho} + \tfrac{1}{2} v^2) \right] = 0. \tag{61}$$

In terms of enthalpy, the equation of conservation of energy is

$$\frac{d}{dx}\left[A\rho v \left(H + \frac{1}{2} v^2\right) \right] = 0. \tag{62}$$

The equation-of-state for an ideal gas is $p/\rho = RT$. Since $dE = c_V dT$ and $c_p - c_V = R$,

$$d\left(\frac{p}{\rho}\right) = (c_p - c_V) \frac{dE}{c_V} \tag{63}$$

or

$$dE = \frac{1}{k-1} d\left(\frac{p}{\rho}\right) \tag{64}$$

Upon integration,

$$E = \frac{1}{k-1} \cdot \frac{p}{\rho} \tag{65}$$

4. Significance of the Mach Number

The equation of conservation of mass, the equation of conservation of momentum, and the Mach number are each independent of either the adiabatic or the isentropic restriction. This latter term, the Mach number, is a dimensionless quantity obtained from inspection analysis of the Navier-Stokes equations, and is defined as the ratio of stream velocity to the local velocity of sound, i.e.

$$M = \frac{V}{c} \tag{66}$$

The Mach number has a profound influence upon the nature of compressible flow, as shown by the following rigorous mathematical derivation.

By combining the continuity equation and the law of conservation of energy, the Bernoulli equation is obtained in differential form as

$$dH = -d\left(\frac{v^2}{2}\right) = -v\,dv \tag{67}$$

From thermodynamics,

$$TdS = dH - \frac{dp}{\rho} \tag{68}$$

which, at constant entropy, reduces to

$$dH = \frac{dp}{\rho} \tag{69}$$

Thus,
$$dp = -\rho v\,dv \tag{70}$$

This is Euler's equation of motion for an inviscid fluid, showing that pressure decreases with acceleration of flow and increases with deceleration of flow. Expressing the equation of continuity in logarithmic differential form,

$$d\ln p + d\ln A + d\ln v = 0 \tag{71}$$

or
$$\frac{dp}{p} + \frac{dA}{A} + \frac{dv}{v} = 0. \tag{72}$$

Substituting and rearranging,

$$\frac{dA}{A} = \frac{dp}{p}\left[\frac{1}{v^2} - \frac{d\rho}{dp}\right] \tag{73}$$

or
$$\frac{dA}{A} = \frac{dp}{\rho v^2}\left[1 - \frac{v^2}{c^2}\right] = \frac{1-M^2}{\rho v^2}\,dp. \tag{74}$$

Thus, the following conclusions are reached:[13]

(1) For subsonic flow $(M<1)$,

$$\frac{dA}{dp} > 0 \quad \frac{dA}{dv} < 0 \tag{75}$$

(2) For sonic flow (M = 1),

$$\frac{dA}{d_p} = 0 \qquad \frac{dA}{dv} = 0 \tag{76}$$

(3) For supersonic flow (M>1),

$$\frac{dA}{d_p} < 0 \qquad \frac{dA}{dv} > 0. \tag{77}$$

From these relationships, it is seen that the effect of an area change is exactly the opposite for subsonic and supersonic flow. This leads to the interesting conclusion that an accelerating stream starting from rest must first decrease in cross-sectional area until a velocity of Mach = 1 is attained. Then, the same stream must increase in cross-sectional area in order to reach supersonic velocities. In practice, this phenomenon is achieved with the converging-diverging nozzle.

5. Adiabatic Flow Relations

Since all possible states of isentropic flow lie on a line of constant entropy, one of these states must correspond to zero velocity. The conditions at this point, referred to as the stagnation conditions, are independent of any changes which may occur downstream. The stagnation enthalpy, temperature, and pressure are designated H_o, T_o, and p_o respectively. Although the expansion process through the nozzle is isentropic, several useful flow restrictions are dependent only upon the adiabatic restriction. From the first law of thermodynamics, the total energy between the stagnation point and any downstream position must be conserved, i.e.

$$H_o = H + \frac{v^2}{2g} \tag{78}$$

Also, under ideal conditions,

$$\Delta H = c_p \Delta T \tag{79}$$

$$c_p - c_V = R \tag{80}$$

$$c_p/c_V = k \tag{81}$$

$$c_p = \frac{k}{k-1} R \tag{82}$$

Thus, the velocity at any position may be expressed in terms of the stagnation temperature as

$$v = \sqrt{2 c_p (T_o - T)} = \sqrt{\frac{2k}{k-1} R (T_o - T)} \tag{83}$$

The ratio of the stagnation temperature to any adiabatic downstream temperature may be expressed in terms of Mach number and specific heat ratio. Again by the first law of thermodynamics,

$$\frac{T_o}{T} = 1 + \frac{v^2}{2c_p T} = 1 + \frac{v^2}{kRT} \cdot \frac{kR}{2c_p} \tag{84}$$

However, $c_p = \frac{k}{k-1} R$ and $c^2 = kRT$

Therefore,

$$\frac{T_o}{T} = 1 + \frac{k-1}{2} \cdot \frac{v^2}{c^2} \tag{85}$$

or

$$\frac{T_o}{T} = 1 + \frac{k-1}{2} M^2 \tag{86}$$

Finally, the flow per unit area for any adiabatic process may be expressed as

$$\frac{m}{A} = \rho v = \frac{p}{RT} v = \frac{pv}{\sqrt{kRT}} \sqrt{\frac{k}{R} \cdot \frac{T_o}{T} \cdot \frac{1}{T_o}} \tag{87}$$

or
$$\frac{m}{A} = \sqrt{\frac{k}{R}} \cdot \frac{p}{\sqrt{T_o}} \cdot M \sqrt{1 + \frac{k-1}{2} M^2} \tag{88}$$

6. Isentropic Flow Relations

Under the conditions of isentropic flow, the pressure-volume-temperature relationship for ideal gases becomes

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{V_1}{V_2}\right)^{k-1} \tag{89}$$

Utilizing this, the pressure and density at any downstream position may be evaluated from the equations

$$\frac{p_o}{p} = \left[1 + \frac{k-1}{2} M^2\right]^{\frac{k}{k-1}} \tag{90}$$

and
$$\frac{\rho_o}{\rho} = \left[1 + \frac{k-1}{2} M^2\right]^{\frac{1}{k-1}} \tag{91}$$

Furthermore, the flow per unit area of cross-section now becomes

$$\frac{m}{A} = \sqrt{\frac{k}{R}} \cdot \frac{p_o}{\sqrt{T_o}} \cdot \frac{M}{\left[1 + \frac{k-1}{2} M^2\right]^{\frac{k+1}{2(k-1)}}} \tag{92}$$

By differentiating this equation with respect to M and setting the derivative equal to zero, it is found that the maximum m/A exists at the throat where M=1.[14] Thus, the maximum flow per unit area of cross-section is

$$\left(\frac{m}{A}\right)_{max} = \frac{m}{A^*} = \frac{p_o}{\sqrt{T_o}} \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{93}$$

where A^* denotes the throat area, or critical area, at $M = 1$. An area ratio between the throat and any downstream position may now be expressed as

$$\frac{A}{A^*} = \frac{m/A^*}{m/A} = \frac{1}{m}\left[\left(\frac{2}{k+1}\right)\left(1 + \frac{k-1}{2} M^2\right)\right]^{\frac{k+1}{2(k-1)}} \qquad (94)$$

For each equation containing the term M^2, there is both a subsonic solution and a supersonic solution. It has been shown that the subsonic solution applies to the converging portion of the nozzle while the supersonic solution is valid in the diverging portion. Corresponding to any given value of Mach number, there is one precise value of p/p_o, T/T_o, ρ/ρ_o, and A/A^* which can be evaluated from equations already discussed. Shapiro has tabulated a set of working tables in which these dimensionless ratios are summarized for an ideal gas having $k = 1.4$.

7. Choking and Nozzle Expansion

The fact that the mass flow rate per unit area possesses a maximum value at the throat leads to a phenomenon called choking. For a given converging-diverging nozzle operation under fixed stagnation conditions, the nature of the flow depends upon the pressure ratio p_e/p_o. If the external downstream pressure is gradually reduced from an initial condition of $p_e = p_o$, the velocity through the converging section of the nozzle increases until $M = 1$ at the throat. This is the critical pressure ratio. Further reduction in the external pressure will result in supersonic flow being maintained beyond the throat. However, true isentropic flow beyond the throat can exist only if the external

pressure is equal to or less than the one specific ideal exhaust pressure defined by the nozzle area ratio. If the external pressure exceeds the ideal exhaust pressure but is less than the critical throat pressure, irreversible discontinuities occur in the diverging section of the nozzle. Although these discontinuities, called normal shock waves, may occur adiabatically, the entropy of the fluid is always increased. The normal discontinuity always involves a change from supersonic flow to subsonic flow accompanied by a pressure rise and an energy loss. The magnitude of this energy loss may be evaluated from the Fanno and Rayleigh curves for the particular expansion process. The Fanno line is the locus of points which satisfies the energy equation, continuity equation, and the equation of state. On the other hand, the Rayleigh line is the locus of points satisfying the momentum equation, the continuity equation, and the equation of state. A straight line connecting the two points of intersection of these loci represents the normal shock wave. Shapiro has also developed a set of working tables which relate the pressure ratio, density ratio, temperature ratio, and area ratio across the shock wave to the upstream and downstream Mach numbers.[15]

If the nozzle exit pressure exceeds the external pressure, the fluid will continue to expand after being exhausted from the nozzle. However, no useful work is derived from this free expansion. Three-dimensional turbulence occurs in the immediate region outside the nozzle. Again a loss of energy is incurred. Thus, either overexpansion or underexpansion of the working fluid results in reduced performance. Ideally, the nozzle exhaust pressure should equal the external downstream pressure.

8. Isentropic Flow Performance Parameters

By introducing the isentropic flow relationships into the velocity equations already developed, the exhaust velocity is evaluated as

$$v_e = \sqrt{\frac{2k}{k-1} R' \cdot g \frac{T_o}{MW} \left[1 - \left(\frac{p_e}{p_o} \right)^{\frac{k-1}{k}} \right]} \qquad (95)$$

where MW = molecular weight
R' = gas constant expressed in work units

The maximum possible exhaust velocity is obtained at an infinite pressure ratio p_o/p_e, for which the ideal cycle efficiency

$$\eta = 1 - \left(\frac{p_e}{p_o} \right)^{\frac{k-1}{k}}$$

becomes unity. When p_o/p_e becomes infinite,

$$v_{max} = \sqrt{2g \cdot R \frac{k}{k-1} \cdot \frac{T_o}{MW}} \qquad (96)$$

Simultaneously, T/T_o and ρ/ρ_o become zero while A/A^* becomes infinite. This leads to the interesting conclusion that the maximum attainable exhaust velocity is finite even though the working fluid is expanded to an infinitely low pressure, temperature, and density. Earlier, the exhaust velocity was shown to be related to specific impulse by the equation

$$v_e = Isp \cdot g$$

for ideal expansion.

Although the characteristic velocity c* is readily evaluated from experimental data, its theoretical evaluation requires a knowledge of throat conditions. By combining the definition of c* and the equation of continuity, the theoretical relationship becomes

$$c^* = \frac{p_c}{\rho^* v^*} \tag{97}$$

The conditions at the throat can be expressed in terms of the stagnation conditions as

$$\frac{p^*}{p_o} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{98}$$

$$\frac{T^*}{T_o} = \frac{2}{k+1} = \left(\frac{c^*}{c_o}\right)^2 \tag{99}$$

$$\frac{\rho^*}{\rho_o} = \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \tag{100}$$

where k is the average specific heat ratio between stagnation and throat conditions. However, an accurate determination of c* is difficult because of the change of k with chemical reaction. Probably the most rigorous approach is to maximize ρv by calculating this quantity at several assumed throat pressures.

Since

$$v^* = c^* = \left(\frac{\partial p}{\partial \rho}\right)_s^{1/2} \tag{101}$$

and

$$p^* \cdot MW^* = \rho^* \cdot RT^* \tag{102}$$

$$c^* = \frac{p_o}{p^*} \cdot \frac{RT^*}{k^*MW^*} = \frac{p_o}{p^*} \left(\frac{T^*}{T_o}\right)^{1/2} \left(\frac{RT_o}{k^*MW^*}\right)^{1/2} \tag{103}$$

$$c^* = \sqrt{\frac{RT_o}{k^*MW^*} \left[\frac{k+1}{2}\right]^{\frac{k+1}{k-1}}} \tag{104}$$

For the case of a non-reacting gas with constant specific heat, this equation is readily evaluated. Otherwise, a trial-and-error solution is required. In general, c* may be considered as being affected by conditions upstream of the throat but as being independent of downstream conditions.

Theoretical evaluation of the thrust coefficient is also somewhat involved although its experimental evaluation is straightforward:

$$c_F = \frac{\frac{1}{2g}(1 + \cos\alpha)mv_e + (p_e - p_a)A_e}{p_c A^*} \tag{105}$$

or

$$c_F = \frac{v'}{c^*} + \frac{p_e - p_a}{p_o} \cdot \frac{A_e}{A^*} \tag{106}$$

Unlike c*, c_F is a function of exit pressure and of nozzle geometry downstream of the throat. For ideal expansion, i.e. when pe=pa,

$$c_F = \frac{v_e}{c^*} \tag{107}$$

Expressing this relationship in terms of the flow equations for a chemically-reacting gas with variable specific heat,

$$c_F = \sqrt{\frac{2\bar{k}k^*}{\bar{k}-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \left[1 - \left(\frac{p_e}{p_o}\right)^{\frac{\bar{k}-1}{\bar{k}}}\right]} \tag{108}$$

where $\bar{k}$ = average specific heat ratio during expansion
k = average specific heat ratio between the chamber and the throat
k^* = average specific heat ratio at the throat

The thrust imparted to a missile may be expressed in terms of the thrust coefficient as

$$F' = A^* p_o c_F + (pe-pa)Ae \tag{109}$$

This applies either theoretically or experimentally. Finally, the area ratio may be expressed in terms of the pressure ratio and the specific heat ratio as

$$\frac{A}{A^*} = \frac{\left(\frac{p_o}{p}\right)^{\frac{1}{k}}}{\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \sqrt{\frac{k+1}{k-1}\left[1-\left(\frac{p}{p_o}\right)^{\frac{k-1}{k}}\right]}} \tag{110}$$

or in terms of the thrust coefficient as

$$\frac{A}{A^*} = \frac{k}{c_F}\left[\frac{2}{k+1}\right]^{\frac{k+1}{k-1}}\left[\frac{p_o}{p}\right]^{\frac{1}{k}} \tag{111}$$

E. Steady, One-Dimensional, Isentropic, Multi-Phase Flow

1. General Principles

The previous analysis of isentropic, compressible flow is completely rigorous only if all the products of combustion are ideal gases. Theoretical analysis of the expansion process becomes considerably more complicated if a condensed phase is present during all or part of the expansion. Either solids, liquids, or both may be present in the products of combustion, depending upon the composition of the propellant and the operating conditions.

In any flow system consisting of more than one phase, the general equations of change apply in each phase. Furthermore, the solutions to the equations of change in the individual phases must be matched at the interfaces. In view of the fact that the mechanisms of the various interphase transfers have not been completely defined, a general multiphase transport solution to the general equations of change has not been obtained.[16] The problems of two-phase momentum transfer alone are quite complex and not adaptable to a simple, rigorous analytical solution. The simultaneous occurrence of heat and mass transfer adds to the complexity of the problem. Therefore, discussion of multiphase flow in a converging-diverging nozzle will be limited to a semi-quantitative treatment. Using this approach, the degree of attainment of thermal and momentum equilibrium between the gas phase and the condensed phases can be analyzed.

By applying the assumptions which were presented and discussed previously, thermodynamic relations can be formulated for: (1) the case of a condensed phase existing in constant concentration throughout

the expansion; and (2) the case of condensation during expansion. In the latter case, the concentration of the condensed phase is a function of the temperature, pressure, and rate of condensation. Whereas for isentropic flow of a perfect gas,

$$pv^k = \text{constant} \tag{112}$$

the corresponding relationship for isentropic, multiphase flow is[17]

$$pV^{\phi} = \text{constant} \tag{113}$$

where

$$\phi = \frac{a_1 R + a_1 c_{V_g} + MW a_2 c_{p_s}}{a_1 c_{V_g} + MW a_2 c_{p_s}} \tag{114}$$

p	=	pressure
V	=	volume
cV_g	=	constant volume specific heat capacity of the gas phase
c_{p_s}	=	constant pressure specific heat capacity of the condensed phase
MW	=	mean molecular weight of the gas phase
a_1	=	mass fraction of gas phase
a_2	=	mass fraction of condensed phase
k	=	c_{p_g}/c_{V_g}
R	=	gas constant ($c_{p_g}-c_{V_g}$)

This latter equation includes the specific heat capacity of the condensed phase while retaining the form of the equation for the isentropic flow of gases. Evaluating the relationship between k and ϕ,

when $a_2 = 0$, $\phi = \frac{R+c_{v_g}}{c_{v_g}} = k$

when $a_2 > 0$, $k > \phi > 1$

2. Flow with Constant Concentration of Condensables

For the case in which a condensed phase exists in constant concentration during the expansion process, the enthalpy balance for adiabatic, frictionless flow is[18]

$$dH = c_{p_g}\, dT_g + f\, c_{p_s}\, dT_s = V'_g\, d_p = \bar{R} T_g \frac{d_p}{p} \qquad (115)$$

where

H	=	enthalpy of multiphase system
c_{p_g}	=	specific heat of gas per unit mass
c_{p_s}	=	specific heat of condensed phase per unit mass
f	=	mass ratio of solid to gas
T_g	=	temperature of gas
$\bar{T}_s$	=	temperature of condensed phase
$\bar{p}$	=	pressure
V'_g	=	specific volume of gas
$\bar{R}$	=	R/MW

Integrating,

$$H_c - H_e = c_{p_g} (T_c - T_{e_g}) + f c_{p_s} (T_c - T_{e_s}) = \frac{1}{2} (v_g^2 + f v_s^2) \qquad (116)$$

where c denotes chamber conditions
e denotes exhaust conditions

The relationship between temperature, pressure, and heat capacity is

$$\left[c_{p_g} + f\, c_{p_s} \frac{dT_s}{dT_g} \right] \frac{dT_g}{T_g} = \bar{R} \frac{d_p}{p} \qquad (117)$$

Assuming that $\frac{dT_s}{dT_g}$ varies linearly with pressure, the integrated form of the above equation becomes

$$\frac{T_{e_g}}{T_c} = \left[\frac{p_e}{p_c}\right]^{\frac{\bar{R}}{c_{p_g} + f\, c_{p_s} \frac{dT_s}{dT_g}}} \tag{118}$$

For the limiting condition of $T_s = T_g = T$,

$$\frac{T_e}{T_c} = \left[\frac{p_e}{p_c}\right]^{\frac{\bar{R}}{c_{p_g} + f\, c_{p_s}}} \tag{119}$$

while for the other extreme of $T_s = T_c$, $dT_s = 0$

and

$$\frac{T_e}{T_c} = \left[\frac{p_e}{p_c}\right]^{\frac{\bar{R}}{c_{p_g}}} \tag{120}$$

For the general case,

$$\left[c_{p_g} + f\, c_{p_s} \frac{dT_s}{dT_g}\right] (T_c - T_{e_g}) = \tfrac{1}{2} v_g^2 \left[1 + f \left(\frac{v_s}{v_g}\right)^2\right] \tag{121}$$

3. Flow with Simultaneous Condensation

If condensation occurs during the expansion, the flow conditions are altered considerably since the phase change from gas to liquid or solid is accompanied by the release of heat and a decrease in the quantity of working fluid. Assuming thermal and kinetic equilibrium for the condensed phase, the enthalpy balance is[19]

$$dH = c_{p_g}\, dT + f\, c_p\, dT + \Delta H_v\, dn_g = V'_g\, d_p \tag{122}$$

where

ΔH_v = molar latent heat of phase change
n_g = moles of gas
c_p = specific heat capacity of the newly formed condensed phase (solid or liquid)

By applying the ideal gas law,

$$\left[c_{p_g} + f\, c_{p_e} + \Delta H_v \left(\frac{dn_g}{dT}\right) \frac{dt}{dT} \right] \frac{dT}{T} = n_g R \frac{dp}{p} = \bar{R} \frac{dp}{p} \qquad (123)$$

This equation can be solved only if $\frac{dn_g}{dt}$, the rate of condensation or nucleation, is known as a function of temperature and pressure. Although a considerable amount of work has been done on the rates of nucleation, the equations are too complex to be readily solved. Qualitatively, the theory shows that the rate of condensation increases with the ratio of the actual vapor pressure to the saturation vapor pressure.[20] During a flow process, the rate of condensation will always lag somewhat behind that value required to maintain equilibrium.

4. Approach to Momentum Equilibrium

In order to evaluate the order of magnitude of momentum and heat transfer between the gas and condensed phases, the semi-quantitative treatment will be extended to these phenomena. The condensed particles will be assumed to be spherical. Using this approximation, the force or drag acting on a moving spherical body is

$$F_p = m'a' = \tfrac{1}{2} C_D A' \rho_g (v_g - v_s)^2 \qquad (125)$$

where

F_p = force acting on the particle
m' = mass of particle
a' = acceleration of particle
C_D = drag coefficient
ρ_g = density of gas
A' = frontal area of body $= \pi r^2$
v_g = velocity of gas phase
v_s = velocity of condensed particle

The mass of the particle is

$$m' = \frac{4}{3}\pi \rho_s r^3 \tag{126}$$

from which the acceleration of the particle is

$$a' = \frac{dv_s}{dt} = \frac{3\rho_g C_D}{8\rho_s r}(v_g - v_s)^2 \tag{127}$$

Although a rigorous solution of this equation requires the experimental evaluation of the drag coefficient, an approximate treatment may be based upon Stokes' Law. The equation of motion for spherical particles under the influence of Stokes' drag is

$$m' \frac{d^2x}{dx^2} = 6\pi\mu_g r (v_g - v_s) \tag{128}$$

where
m' = mass of particle
μ_g = viscosity of the gas (assumed constant)
r = radius of particle

This equation cannot be integrated directly for the general case, but an exact solution is obtained for linear acceleration of the gas stream, i.e.

$$v_g = (v_{g_o} + 2a'x)^{\frac{1}{2}} \tag{129}$$

By combining these two equations and using the relationship $v_s = \frac{dx}{dt}$, [21]

$$m\frac{d^2x}{dt^2} + 6\pi\mu_g r \frac{dx}{dt} - 6\pi\mu_g r (v_{g_o}^2 + 2ax)^{\frac{1}{2}} = 0 \tag{130}$$

where v_{g_o} = gas velocity at the instant the particle under consideration is injected into the gas stream

A more useful expression of these relationships is

$$\frac{dv_s}{dx} = \frac{6\pi\mu_g}{m' v_{go}} \left[\frac{v_s}{v_g} - 1 \right] \tag{131}$$

and

$$\left(\frac{v_g}{v_{go}}\right)^2 = 1 + \frac{2a'x}{v_{go}^2} \tag{132}$$

where $\frac{v_g}{v_{go}} = 1$ and $\frac{v_s}{v_{go}} = 0$ at $x = 0$.

In rapidly accelerating flow, the Reynold's number for the particle may readily exceed the limit for Stokes' drag. The equation of motion then takes the non-linear form[22]

$$m' \frac{d^2x}{dt^2} = \frac{\pi}{2} C_D r^2 (v_g - v_s)^2 \tag{133}$$

However, provided the Stokes' drag coefficient is $c_d = 24/Re$, the acceleration is found to be

$$\frac{dv_s}{dt} = \frac{9\mu_g}{2r^2} (v_g - v_s) \tag{134}$$

This equation may be solved with the aid of the equation for the conservation of energy and the equation for the rate of temperature change dT/dt. Maxwell reports that when $r = 5 \times 10^{-5}$ cm, $v_s = 0.98\ v_g$ after only 4% of the particle's residence time in the nozzle has elapsed.[23]

5. Approach to Thermal Equilibrium

Analysis of thermal equilibrium between the gas and condensed phases is somewhat more complex because three major heat transfer mechanisms are involved. These are convective heat transfer between the particles and the gas , heat transfer within the particle, and radiation from the particle. The convective heat transfer from the

condensed particle to the gas may be represented by

$$\frac{dq'}{dt} = h A' (T_s - T_g) \tag{135}$$

where
h = average heat transfer coefficient
A' = effective surface area
q' = total heat transferred

Assuming instantaneous heat transfer within the particle,

$$\frac{dq'}{dt} = - c_{ps} \frac{dT_s}{dt} = hA'(T_s - T_g) \tag{136}$$

and for spherical particles

$$- \frac{dT_s}{dt} = \frac{3h}{\rho_s c_{ps} r}(T_s - T_g) \tag{137}$$

This shows that the rate of heat transfer increases as the particle size decreases. Altman and Carter report that $T_s - T_g$ will be less than 100°K provided r does not exceed 10^{-4} cm diameter.[24] Assuming that heat transfer is rapid at the surface of the particle, the limitation on the rate of transfer will be thermal conductivity within the particle. Altman and Carter have also shown that this is rapid for particles of less than 10^{-5} cm diameter. The borderline for adequate conduction appears to lie between diameters of 10^{-3} and 10^{-4} cm.

The energy emitted from the condensed particle by radiation is

$$- \frac{dE'}{dt} = 4\pi r^2 \epsilon \sigma T^4 \tag{138}$$

where
σ = Stefan-Boltzmann constant
ϵ = emissivity constant
E' = energy transferred by radiation

For spherical particles,

$$-\frac{dT}{dt} = \frac{3\epsilon T^4 \sigma}{\rho_s c_{p_s} r} \tag{139}$$

Altman and Carter report that very little energy is lost by radiation from particles which exceed 10^{-2} cm diameter. On the other hand, the rate of the temperature drop of particles less than 10^{-5} cm diameter can exceed that of the gas during expansion.[25] Maxwell reports that particles not exceeding 5×10^{-5} cm diameter can decrease in temperature as rapidly as the gas with a temperature difference of 20°K being maintained between phases.[26]

From the previous discussion, it may be concluded that both momentum and thermal equilibrium between the gas phase and the condensed phase are rapidly approached provided the particle diameters are less than 10^{-4} cm. As the particle size increases, the degree of attainment of equilibrium decreases. The following table, prepared by Altman and Carter, shows a tabulation of specific impulse values for both complete thermal equilibrium and complete lack of thermal equilibrium at various assumed particle velocities corresponding to a mass fraction of 20% solid:[27]

$\frac{v_s}{v_g}$	Isp at $T_s=T_g$	Isp at $T_s=T_c$
0	206	203
0.25	217	214
0.50	224	221
1.00	230	227

From a practical viewpoint, this table shows that the attainment of momentum equilibrium has more significance than the attainment of thermal equilibrium. Under Altman's assumed set of conditions, a maximum Isp change of 1 1/2% can result from non-thermal equilibrium while a maximum Isp change of almost 10% can result from non-momentum equilibrium.

6. Fundamental Equations of Flow

Assuming the validity of thermal and momentum equilibrium between the gas phase and condensed phase, there is no difference between the properties of the multiphase mixture and the ideal gas considered in the previous section on compressible flow. The general equations of conservation of mass, momentum, and energy remain valid. The equation of state is now expressed as

$$E = \frac{1}{\phi - 1} \cdot \frac{p}{\rho} \tag{140}$$

where ϕ has replaced k. Similarly, the isentropic flow relations and the isentropic performance parameters for compressible flow may be adapted to multiphase flow by replacing k by the modified specific heat ratio ϕ.

Since ϕ is less than k, the volume of the system becomes more sensitive to adiabatic pressure variations when condensed phases are present. This result applies only to adiabatic pressure changes when both compressibility and heat transfer are involved. As the concentration of the condensed phase is increased, the nozzle discharge coefficient increases. This is to be expected since the condensed

phase possesses a much greater density. Hence, the condensed phase is more readily transported through the nozzle throat where the rate of flow is limited by choking. The presence of a condensed phase has a relatively minor effect on the nozzle thrust coefficient. In fact, this is also as expected since the thrust coefficient is comparatively insensitive to variations in the adiabatic exponent k for pure gases. The presence of a condensed phase necessitates a somewhat larger nozzle area ratio in order to achieve optimum results. From a practical standpoint, phase separation is more likely to occur as the concentration of condensables is increased. Therefore, a smaller angle of divergence is desirable in the nozzle.

7. Uncertainties in Multi-Phase Flow

Earlier it was pointed out that the only fundamental uncertainties related to theoretical performance calculations are those concerned with the phenomenon of multi-phase flow. Additional fundamental studies are needed on the attainment of momentum equilibrium between phases, particularly when the condensed-phase content of the system is 80-90% by weight. Existing data are confined to the range of 20-35% by weight condensables. Conceivably, the energy losses due to drag could be more appreciable at the higher condensed particle loading. Also, upon expanding such systems to sub-atmospheric pressures, phase separation in the nozzle may be a more severe problem. Another fundamental uncertainty of potential significance involves the rate of formation and growth of condensed particles. This factor affects not only the size of the condensed particles but also the attainment of chemical and phase equilibrium during combustion and expansion. The questions of miscibility between condensed species, gas solubility in condensed phases, and non-ideality of condensable vapors are, in all probability of lesser consequence.

F. Ballistic Importance of Specific Impulse

From the previously developed equations, it has been shown that specific impulse rigorously defines the amount of useful energy which may be obtained from the combustion and expansion of a fuel and oxidizer. As an approximation, specific impulse is directly proportional to the square root of the combustion temperature divided by the mean molecular weight of the exhaust products. The effect of the specific heat ratio upon specific impulse is not as significant as the effect of the combustion temperature and the mean molecular weight of the exhaust products.

In addition to its thermodynamic significance, specific impulse also possesses an inherent ballistic importance. The burnout velocity, the vertical range, the horizontal range, the payload weight, and the physical size of a missile are all influenced by the specific impulse of the propellant. Tormey lists the general relationships between specific impulse and these various vehicle performance characteristics as:[28]

$$\text{(1) Burnout velocity} = I_{sp} \cdot g \cdot \ln \frac{W_i}{W_f} \qquad (141)$$

$$\text{(2) Vertical range} = h_{bo} + K' I_{sp} \ln \left[\frac{W_i}{W_f}\right]^2 \qquad (142)$$

$$\text{(3) Horizontal range} = 2S_{bo} + K' I_{sp} \ln \left[\frac{W_i}{W_f}\right]^2 \qquad (143)$$

$$\text{(4) Payload} = f\,(I_{sp})(W_e)(W_s) \qquad (144)$$

$$\text{(5) Physical size} = f\,(I_{sp})(\rho_{bulk}) \qquad (145)$$

where

I_{sp} = specific impulse, seconds
W_i = total initial mass of the vehicle and its propellant
W_f = total final mass of vehicle after burnout
g = acceleration of gravity
h_{bo} = height of missile at burnout
S_{bo} = horizontal distance of the missile from its launching point at burnout
K' = physical constant
ln = natural logarithm to the base e

These five equations are necessarily quite general and are presented to convey the concept rather than the quantitative relationship between specific impulse and the performance parameters. In practice, exact values for range, payload, size, and vertical height must be determined by a detailed analysis of the powerplant and the rocket vehicle. These values are dependent upon a series of arbitrary design choices, e.g. thrust-to-weight ratio, staging, trajectory, etc. Nevertheless, the preceding equations point out the overall importance of specific impulse in rocketry and that increases in specific impulse will lead to increases in missile performance.[29] The first equation of the series, which relates specific impulse to the burnout velocity of the missile, is examined in more detail in the next section.

G. Relationship between Specific Impulse and Propellant Density

1. Introduction

Specific impulse is the criterium generally used for comparing the relative capabilities of propellant combinations. However, in applying rocket propellants to a specific unit of hardware, the propellant density must also be considered in order to optimize performance.

Both of these parameters influence the incremental boost velocity imparted to a missile by the combustion of a propellant. The actual relationship between specific impulse and propellant density is a complicated one, particularly for multistage missiles, and depends upon the specific missile application. Such a detailed analysis is beyond both the theoretical and calculational scope of this report. However, a simplified theoretical discussion is presented to point out the roles of both parameters in the application of propellant systems to actual missiles.

2. The Mass-to-Volume Ratio Approach

The combined effect of specific impulse and density on the incremental boost velocity imparted to a missile is obtained by applying Newton's laws of motion to the missile:[30]

$$W_m \frac{dv_b}{dt} = -Isp \cdot g \frac{dW_m}{dt} + g \cdot Ae(p_e - p_a) - W_m \cdot g' \sin\beta - u^2 \gamma \qquad (146)$$

where

W_m = total mass of missile
v_b = velocity of the missile
t = time
Isp = propellant specific impulse
g = acceleration of gravity (32,174 ft/sec^2)
g' = local acceleration of gravity
Ae = nozzle exit area
p_e = nozzle exhaust pressure
p_a = external surrounding pressure
β = angle of trajectory with the horizontal
γ = empirical coefficient dependent upon physical conditions of the system and surroundings, e.g. missile surface area, density of surrounding medium, etc.

This generalized equation includes the effects of pressure thrust, gravity, and aerodynamic drag, in addition to momentum thrust. However, for the ideal case, only the momentum thrust must be considered. Then, the previous equation reduces to

$$W_m \frac{dv_b}{dt} = - Isp \cdot g \cdot \frac{dW_m}{dt} \qquad (147)$$

Integrating, $$v_b = Isp \cdot g \cdot \ln \frac{W_m}{W_f} = Isp \cdot g \cdot \ln \frac{W_m}{W_m - W_p} \qquad (148)$$

where
v_b = incremental increase in missile velocity
W_m = total mass of missile (hardware and propellant)
W_p = mass of propellant
W_f = mass of missile hardware (payload and inert arts)

or

$$v_b = Isp \cdot g \cdot \ln \left[1 + \frac{W_p}{W_f} \right] \qquad (149)$$

Since

$$W_p = V_p \rho \qquad (150)$$

$$v_b = Isp \cdot g \cdot \ln \left[1 + \frac{V_p}{W_f} \right] \qquad (151)$$

or

$$v_b = Isp \cdot g \cdot \ln \left[1 + \frac{\rho}{W_f / V_p} \right] \qquad (152)$$

where
ρ = density of the propellant
V_p = volume of propellant in missile
W_f = mass of hardware

This equation enables the ideal boost velocity to be expressed in terms of the propellant density and specific impulse for a given mass-to-volume ratio, i.e. for a given mass of hardware per volume of propellant. This, of course, represents a simplified situation. In practice, a

change of propellant usually is accompanied by a change in hardware design. Nevertheless, the previous equation shows that the incremental boost velocity becomes independent of propellant density when the mass-to-volume ratio becomes zero. On the other hand, density becomes equally significant with specific impulse only at an infinite mass-to-volume ratio. Therefore, a change in specific impulse is always more significant than a corresponding change in propellant density on overall missile performance.

3. The Relative Effectiveness Approach

For the same situation in which various propellants are compared in a given unit of hardware, the relationship between specific impulse and density may also be evaluated by Geckler's approach.[31] Neglecting the effect of aerodynamic drag and incremental changes in gravity,

$$v_b = Isp \cdot g \ln \frac{W_m}{W_f} = Isp \cdot g \ln \frac{W_m}{W_m - W_p} \qquad (153)$$

where

v_b = burnout velocity of missile
Isp = specific impulse of propellant
g = acceleration of gravity
W_m = total mass of missile
W_p = mass of propellant
W_f = final mass at burnout $(W_m - W_p)$

Differentiating,

$$dv_b = Isp \cdot g \, d\left[\ln \frac{W_m}{W_f}\right] + \ln \frac{W_m}{W_f} \cdot d\,(Isp \cdot g) \qquad (154)$$

or

$$dv_b = Isp \cdot g \cdot d\left[\frac{W_m}{W_f}\right] \cdot \frac{1}{W_m/W_f} + \ln \frac{W_m}{W_f} \cdot d\,(Isp \cdot g) \qquad (155)$$

Dividing by v_b, $\frac{dv_b}{v_b} = \frac{Isp \cdot g}{v_b} \cdot d\left[\frac{W_m}{W_f}\right] \cdot \frac{1}{W_m/W_f} + \frac{\ln(W_m/W_f)}{v_b} \cdot d\,(Isp \cdot g)$ (156)

and $$\frac{dv_b}{v_b} = \frac{d(Isp \cdot g)}{Isp \cdot g} + \frac{Isp \cdot g}{v_b} \cdot d\left[\frac{W_m}{W_f}\right] \cdot \frac{1}{W_m/W_f} \qquad (157)$$

For a constant volume of propellant, changes in mass arise only from a change in propellant density, so

$$dW_p = V_p\, d\rho \qquad (158)$$

and $$d\left[\frac{W_m}{W_f}\right] \cdot \frac{1}{W_m/W_f} = \frac{V_p\, d\rho}{W_m} = \frac{W_p}{W_m} \cdot \frac{d\rho}{\rho} \qquad (159)$$

Hence, $$\frac{dv_b}{v_b} = \frac{d(Isp \cdot g)}{Isp \cdot g} + \frac{Isp \cdot g}{v_b} \cdot \frac{W_p}{W_m} \cdot \frac{d\rho}{\rho} \qquad (160)$$

The term $$\frac{Isp \cdot g}{v_b} \cdot \frac{W_p}{W_m}$$

must be unity in order for the density and specific impulse to be equally influential on burnout velocity. This term, which may be considered a "relative effectiveness coefficient", can be expressed as

$$\frac{\frac{W_p}{W_m}}{\ln\left[\frac{1}{1 - \frac{W_p}{W_m}}\right]}$$

where W_p/W_m is the propellant mass fraction. Upon numerical evaluation, the following relationship is found:[32]

Propellant Mass Fraction	Relative Effectiveness of Density to Specific Impulse
0.95	0.317
0.90	0.391
0.85	0.448
0.80	0.497
0.75	0.541
0.70	0.581
0.60	0.656
0.50	0.721
0.40	0.783
0.30	0.839
0.20	0.896
0.10	0.958

For example, for a missile with a propellant mass fraction of 0.90, a change in density is 39.1% as significant as a corresponding percentage change in specific impulse.

4. The Arbitrary Parameter Approach

A third semi-rigorous approach has been presented by L.J. Gordon in which an arbitrary parameter is defined in terms of specific impulse and density as[33]

$$b = Isp \cdot \rho^{s} \qquad (161)$$

where
- Isp = specific impulse
- ρ = density
- b = arbitrary parameter proportional to boost velocity
- s = empirical constant dependent upon missile design conditions

The parameter b is approximately proportional to the boost velocity for a propellant under the missile design conditions used for computing the exponent s, which is always contained within the limits $0 \leq s \leq 1$.

Also, the exponent s is assumed to be independent of density. In logarithmic form, the previous equation becomes

$$\log b = \log Isp + s \log \rho \tag{162}$$

This is the slope-intercept form of the equation for a straight line and enables propellants to be compared graphically as a series of straight lines for a fixed design condition. The ordinate corresponding to s = 0. is the log Isp.

Previously, the ideal boost velocity was shown to be

$$v_b = Isp \cdot g \ln \frac{W_m}{W_f} = Isp \cdot g \ln \left[1 + \frac{\rho}{W_f / V_p} \right] \tag{163}$$

From this, the exponent s is defined as

$$s = \frac{\left(\frac{\partial v_b}{v_b} \right)_{Isp}}{\left(\frac{\partial \rho}{\rho} \right)_{Isp}} = \frac{\rho}{v_b} \left(\frac{\partial v_b}{\partial \rho} \right)_{Isp} \tag{164}$$

For the simplified case of a constant ratio of hardware mass to propellant volume, the exponent s may be evaluated as

$$s = \frac{\frac{V_p}{W_f} \cdot \rho}{\left[1 + \frac{V_p}{W_f} \cdot \rho \right] \ln \left[1 + \frac{V_p}{W_f} \cdot \rho \right]} = \frac{B-1}{B \ln B} \tag{165}$$

where $$B = 1 + \frac{V_p}{W_f} \cdot \rho \qquad (166)$$

When $W_f/V_p = 0$, the exponent $s = 0$. When $W_f/V_p = \infty$, the exponent $s = 1$. By evaluating s for various propellant densities, it can be shown that s possesses a relatively constant value at fixed design conditions.

Another fundamental design situation is that of constant hardware and propellant weight, with the volume of propellant being a variable. In this situation, rigorous evaluation of

$$s = \frac{\rho}{v_b}\left(\frac{\partial v_b}{\partial \rho}\right)_{Isp} \qquad (167)$$

yields a cumbersome mathematical expression. However, by assuming differential increments of v_b and ρ over a small range, it can be shown that the exponent s is much less than for the previous case of constant missile volume. Both of these cases have considered single stage missiles only.

Calculations of single stage boost velocities based on constant volume of propellant ignore the fact that the stage weight varies with density. Neglecting structural features, thrust levels, and other variables which may have to be changed if a stage weight is changed, Gordon has also examined the effect of changing the propellant density in the second stage of a two-stage missile on the mass ratio of the first stage.[35] It is assumed that the two-stage missile has been designed to give equal boost velocity increments when both stages are loaded with the same propellant. However, this condition will not be maintained if different propellants are considered in each stage.

The total boost velocity may be expressed as

$$v_b = v_{b_1} + v_{b_2} = (Isp)_1 g_o \ln\left(\frac{W_m}{W_f}\right)_1 + (Isp)_2 g_o \ln\left(\frac{W_m}{W_f}\right)_2 \quad (168)$$

Applying the concept of $b = Isp \cdot \rho^s$, the exponent s must now be defined as

$$s = \frac{\frac{\rho}{v_b}\left(\frac{\partial v_b}{\partial \rho}\right)_{Isp}}{\frac{Isp}{v_b}\left(\frac{\partial v_b}{\partial Isp}\right)_\rho} = \frac{\rho}{Isp}\left(\frac{\partial v_b}{\partial \rho}\right)_{Isp}\left(\frac{\partial Isp}{\partial v_b}\right)_\rho = -\frac{\rho}{Isp}\left(\frac{\partial Isp}{\partial \rho}\right)_{v_b} \quad (169)$$

This implies that s is the rate at which a change in propellant density affects the boost velocity relative to the rate at which a change in specific impulse affects the boost velocity. A rigorous mathematical solution of the previous equation would be quite cumbersome. However, by assuming incremental numberical changes in specific impulse and density, Gordon has shown that the resultant value of s is about one-half that for a single stage vehicle at the same ratio of W_e/V_p.[36] Hence, the effect of propellant density on overall missile boost velocity is only about one-half as great in the second stage of a two-stage missile as in a single state vehicle having the same fixed design criteria. This furtner emphasizes the relative importance of propellant specific impulse as the key parameter in overall missile performance.

CHAPTER IV

THERMODYNAMIC ANALYSIS OF PROPELLANT PERFORMANCE

In the previous discussion of the fundamental theory of rocket propulsion, specific impulse was shown to be measured by the change in enthalpy of the combustion products during an isentropic expansion through a converging-diverging nozzle. Also, the basic assumptions to be employed in performance calculations were presented and discussed as were the fundamentals of both compressible and multiphase nozzle flow. In this section, two rigorous methods of conducting performance calculations are presented. The basic thermodynamic properties of temperature, enthalpy, and entropy of the combustion products are calculated at the chamber and at the nozzle exit in each method. By using these properties and the chemical composition of the combustion products, other properties, such as the moles of gas, the specific heat capacity, the specific heat ratio, and the molecular weight of the products may be evaluated.

In the first method, thermodynamic equilibrium constants are utilized to express the concentration of certain chosen species in terms of the concentrations of other more abundant species. The solution is a trial-and-error one in which the chamber enthalpy balance and the nozzle entropy balance are conducted as assumed chamber and exit temperatures, respectively. The second method, which was utilized in the calculations presented later in this report, is a more general one and is applicable to all equilibrium reactions. Instead of utilizing arbitrary equilibrium constants, solution is obtained by minimizing the

total chemical potential, or free energy, of the complex mixture of combustion products. The combustion and exhaust temperatures are obtained as part of the solution so that these quantities do not enter into the trial-and-error iteration. The accuracy of both methods is dependent only upon the accuracy of the basic thermodynamic data for the reactants and the products of combustion. Sample performance calculations for both methods are included as Appendices.

A. Method of Thermodynamic Equilibrium Constants

1. General Approach

This method may be subdivided into the following steps, each of which will be presented and discussed in detail:

(1) The propellant composition, the combustion pressure, and exhaust pressure are selected.

(2) The products of combustion are qualitatively selected, and independent mass balance and chemical equilibria equations are written to allow simultaneous solution of the system.

(3) At an assumed combustion temperature, the composition of the chamber products is calculated to a predetermined degree of accuracy.

(4) An enthalpy balance is made at the assumed combustion temperature by comparing the enthalpy of the chamber products to the enthalpy of the propellant. Steps (3) and (4) are repeated until the combustion temperature is defined, i.e. the enthalpy balance is satisfied.

(5) The entropy of the combustion products is calculated at the correct chamber temperature.

(6) At an assumed exhaust temperature, the composition of the exhaust products is calculated to a predetermined degree of accuracy.

(7) An entropy balance is made at the assumed exhaust temperature by comparing the entropy of the combustion products in the chamber and at the nozzle exit. Steps (6) and (7) are repeated until the exhaust temperature is defined, i.e. the entropy balance is satisfied.

(8) The enthalpy of the exhaust products is calculated at the correct exhaust temperature.

(9) The various other thermodynamic and rocket performance parameters are evaluated.

2. Selection of Operating Conditions

To determine the optimum performance of a given propellant system, detailed calculations must be made at several fuel-oxidizer ratios. In practice, the operating and exhaust pressures are dictated by the rocket hardware and the mission to be performed. However, since specific impulse is dependent upon the combustion and exhaust pressures, a standard basis of comparison must be chosen for theoretical calculations. By tradition most solid propellant performance calculations are reported at chamber pressures of 1000PSIA expanded to 14.7 PSIA. On the other hand, liquid propellant performance calculations are frequently reported at chamber pressures of 300 PSIA, 500 PSIA, or 600 PSIA expanded to 14.7 PSIA. However, recently the desire has been expressed to standardize all performance calculations at chamber pressures of 1000 PSIA expanded to 14.7 PSIA. This practice has been followed in the calculations presented later in this report, particularly in view of their basic prototype nature.

3. Mass Balances and Chemical Equilibria

The composition of the combustion products is obtained by the simultaneous solution of independent equations expressing mass balances and chemical equilibria. The total number of equations to be solved must equal the number of individual species present in the combustion products. One mass balance may be written for each element present in the propellant. The remainder of the equations must come from equilibria relationships. Although the total moles of gaseous products is also a variable, this quantity may be obtained from the summation of the individual contributions of the various gaseous species.

For the general chemical reaction

$$aA + bB \rightleftharpoons cC + dD + eE + fF \tag{170}$$

the equilibrium constant may be expressed as

$$K_p = \frac{p_C^c \cdot p_D^d \cdot p_E^e \cdot p_F^f}{p_A^a \cdot p_B^b} \tag{171}$$

or

$$K_n = \frac{n_C^c \cdot n_D^d \cdot n_E^e \cdot n_F^f}{n_A^a \cdot n_B^b} \tag{172}$$

where

A, B, C, etc. = chemical reactants or products

a, b, c, etc. = number of moles or the respective components A,B,C, etc. in the balanced equation

p_A, p_B, p_C, etc. = partial pressures of the components at the assumed reaction temperature

n_A, n_B, n_C, etc. = actual molar concentrations at the assumed temperature

K_p = equilibrium pressure constant

and K_n = equilibrium concentration constant

While mass balances are preferably written on a mole basis, thermodynamic equilibrium constants are usually expressed in terms of the partial pressures or activities of the chemical species. However, use of the equilibrium pressure constant enables all unknowns to be expressed in mole units. According to Dalton's Law,

$$p_j = \frac{n_j}{n_T} p_T \tag{173}$$

where p_j = partial pressure of the j th product
n_j = moles of the j th product
n_T = total gaseous moles
p_T = total pressure

Then,

$$K_p = \frac{\left(\frac{n_C}{n_T} \cdot p_T\right)^c \left(\frac{n_D}{n_T} \cdot p_T\right)^d \left(\frac{n_E}{n_T} \cdot p_T\right)^e \left(\frac{n_F}{n_T} \cdot p_T\right)^f}{\left(\frac{n_a}{n_T} \cdot p_T\right)^a \left(\frac{n_b}{n_T} \cdot p_T\right)^b} \tag{174}$$

$$K_p = \frac{n_C{}^c \cdot n_D{}^d \cdot n_E{}^e \cdot n_F{}^f}{n_A{}^a \cdot n_B{}^b} \left(\frac{p_T}{n_T}\right)^{\Delta n} \tag{175}$$

$$K_p = K_n \left(\frac{p_T}{n_T}\right)^{\Delta n} \tag{176}$$

where Δn = the number of moles of products minus the number of moles of reactants

Knowledge of the chemical species existing at the combustion temperature is a prerequisite to making accurate performance calculations. In general, every compound that can theoretically exist will be present in some concentration and must be considered until it is proven to exist in negligible quantities. For example, in a propellant system containing

carbon, hydrogen, oxygen, and nitrogen, at least the following species must be considered as products of combustion:[37]

$$H_2O,\ H_2,\ CO,\ CO_2,\ O_2,\ N_2,\ OH,\ NO,\ H,\ \text{and}\ O.$$

The appropriate mass balances may be expressed as:

$$(1)\quad n_T = n_{H_2O} + n_{H_2} + n_{CO} + n_{CO_2} + n_{O_2} + n_{N_2} + n_{OH} + n_{NO} + n_H + n_O \qquad (177)$$

$$(2)\quad n_H = 2n_{H_2} + 2n_{H_2O} + n_{OH} + n_H \qquad (178)$$

$$(3)\quad n_O = n_{H_2O} + n_{CO} + 2n_{CO_2} + 2n_{O_2} + n_{NO} + n_{OH} + n_O \qquad (179)$$

$$(4)\quad n_C = n_{CO} + n_{CO_2} \qquad (180)$$

$$(5)\quad n_N = 2n_{N_2} + n_{NO} \qquad (181)$$

The following chemical equilibria may be chosen and their equilibrium constants expressed as follows:

$$(6)\quad CO_2 + H_2 \rightleftharpoons CO + H_2O$$

$$K_p = \frac{p_{CO}\cdot p_{H_2O}}{p_{CO_2}\cdot p_{H_2}} \qquad K_n = \frac{n_{CO}\cdot n_{H_2O}}{n_{CO_2}\cdot n_{H_2}} = K_p\left[\frac{n_T}{p_T}\right]^0 \qquad (182)$$

$$(7)\quad H_2O + 1/2\ N_2 \rightleftharpoons H_2 + NO \qquad (183)$$

$$K_p = \frac{p_{H_2}\cdot p_{NO}}{p_{H_2O}\cdot p_{N_2}^{1/2}} \qquad K_n = K_p\left[\frac{n_T}{p_T}\right]^{1/2}$$

$$(8)\quad 2H_2O \rightleftharpoons 2H_2 + O_2 \qquad (184)$$

$$K_p = \frac{p_{H_2}^2\cdot p_{O_2}}{p_{H_2O}^2} \qquad K_n = K_p\left[\frac{n_T}{p_T}\right]^1$$

(9) $1/2\ H_2 \rightleftharpoons H$ (185)

$$K_p = \frac{p_H}{p_{H_2}^{1/2}} \qquad K_n = K_p\left[\frac{n_T}{p_T}\right]^{1/2}$$

(10) $H_2O \rightleftharpoons 1/2\ H_2 + OH$ (186)

$$K_p = \frac{p_{H_2}^{1/2} \cdot p_{OH}}{p_{H_2O}} \qquad K_n = K_p\left[\frac{n_T}{p_T}\right]^{1/2}$$

Since ten independent equations have been expressed in ten unknowns, the product composition can be determined by simultaneous solution.

The use of specific chemical equilibria, as shown above, is quite desirable for hand calculations. However, this approach is less desirable for programming a high speed digital computer since the incorporation of a new product of combustion into the study requires a modification to the program. To avoid this, a more general equilibria approach is to utilize the equilibrium constants for the formation of each product of combustion from its monatomic gaseous species. For example,

$$Al + 3Cl \rightleftharpoons AlCl_3$$

$$K_p = \frac{p_{AlCl_3}}{p_{Al} \cdot p_{Cl}^3} = K_n\left[\frac{n_T}{p_T}\right]^3 \qquad (187)$$

4. Chamber Composition Iteration

Since the previous composition calculation may involve fifty or more simultaneous equations, direct algebraic solution is not generally feasible. Therefore, some type of iterative solution is most conveniently

used, depending on the chemistry of the system. Typical methods of iteration are discussed in the literature.[38, 39, 40] Iteration is continued until the quantity of each product converges within a predetermined degree of accuracy, e.g. 1.0×10^{-6} gram-moles per gram of propellant.[41] In view of these detailed, repetitive procedures, high-speed digital computers are profitably utilized for obtaining rapid rigorous solutions. In fact, the complexity of the problem almost dictates the use, both economically and technically, of a large digital computer, such as the IBM 704 or the Remington-Rand 1103A.

5. Enthalpy Balance

After determining the chamber composition at the assumed combustion temperature, an enthalpy balance is made. The enthalpy of the products of combustion may be obtained by integrating the energy equation

$$\left(\frac{\partial H}{\partial p}\right)_T = V - T\left(\frac{\partial V}{\partial T}\right)_p \qquad (188)$$

along an isotherm between a very low pressure p° and any pressure p at which the gas mixture is ideal. This gives[42]

$$H = H^\circ + \int_{p^\circ}^{p} \left[V - T\left(\frac{\partial V}{\partial T}\right)_p\right] dp \qquad (189)$$

and subsequently

$$H = \sum n_j H_j \qquad (190)$$

where H = enthalpy of the complex mixture
n_j = moles of the j th product
H_j = enthalpy of the j th product

The enthalpy of mixing is zero for a mixture of ideal gases. When the enthalpy of the products of combustion above a standard reference temperature equals the heat of reaction of the propellant, the adiabatic combustion temperature is defined. Mathematically,

$$-\Sigma n_j(H_j)_p = \Delta H_R = \Sigma n_j (\Delta H_{fj})_p - \Sigma n_j (\Delta H_{fj})_r \qquad (191)$$

where
H_j = enthalpy of the j th component at 298°K
ΔH_R = heat of reaction at 298°K
n_j = moles of the j the component
ΔH_{fj} = heat-of-formation of the j th component at 298K

and
p = products
r = reactants

Recombining the above equation,

$$\left[\Sigma n_j(H_j)_p\right]_{298}^{T_c} + \Sigma n_j (\Delta H_{fj_{298}})_p = \Sigma n_j (\Delta H_{fj_{298}})_r \qquad (192)$$

This states that the summation of the heat-of-formation at the standard temperature plus the change in enthalpy above that temperature of all the combustion products must equal the heat-of-formation of the propellant at the standard temperature. For each assumed combustion temperature, the chamber composition and the chamber enthalpy balance must be calculated as described above. These steps are repeated until the enthalpy balance is satisfied.

6. Calculation of Chamber Entropy

After the combustion temperature, composition, and enthalpy have been defined, the entropy of the complex mixture is calculated. Each individual product of combustion contributes to the total entropy of the mixture, as in the calculation of total enthalpy. However, the direct mixing of gases at constant pressure and temperature is an irreversible process, so there is an additional entropy-of-mixing contribution. In order to evaluate this

entropy change, a reversible process must be devised so that the second law of thermodynamics applies, i.e.

$$ds = \frac{dqr}{T} \tag{193}$$

The total work done by each gas specie as it is expanded isothermally from the initial total pressure to its equilibrium partial pressure is

$$w = -RT \sum n_j \ln n_j \tag{194}$$

per mole of mixture. By the first law,

$$\Delta E = q - w \tag{195}$$

but $\Delta E = 0$ for all isothermal changes of ideal gases. Therefore,

$$q = -RT \sum n_j \ln n_j \tag{196}$$

or

$$\Delta S = -R \sum n_j \ln n_j \tag{197}$$

Although the effect of pressure on ideal enthalpy is zero, this contribution must also be added to the total entropy. For one mole of mixture,

$$\Delta S = R \ln p_T \tag{198}$$

Combining these three contributions, the total entropy of the combustion products in the combustion chamber is

$$S_c = \sum n_j S_j - n_T R \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T R \ln p_T \tag{199}$$

where

S_c = chamber entropy
n_j = moles of the j th product
S_j = ideal entropy of the j th product at T_c
n_T = total moles of gaseous products
p_T = total chamber pressure
R = universal gas constant

When solids or liquids are present as products of combustion, they are assumed to occupy no volume. Consequently, they are included in the $n_j S_j$ summation but do not contribute to the entropy of mixing or the effect of pressure on entropy. As was presented earlier, the entropy of mixing of liquid products is considered negligible.

7. Exhaust Composition Iteration

The products of combustion are expanded isentropically through the converging-diverging nozzle to an established pressure and an unknown temperature. Again, using mass balances and equilibria relationships, the exhaust composition is calculated at the exhaust pressure and an assumed exhaust temperature. As before, iteration is continued until the quantity of each product converges within a pre-determined degree of accuracy.

8. Entropy Balance

After determining the exhaust composition at the assumed exhaust temperature, an entropy balance is made. The balance is satisfied when the change in entropy between the chamber and nozzle exit is zero, i.e.

$$\left[\Delta S\right]_{T_e}^{T_c} = 0 = \left[\sum n_j S_j - n_T R \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T R \ln p\right]_c - \left[\sum n_j S_j - n_T R \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T R \ln p\right]_e \quad (200)$$

In all probability, several assumptions of temperature will have to be made before a solution is obtained. Both the exhaust composition iteration and the entropy balance are repeated until the solution is reached.

9. Exhaust Enthalpy

After determining the exhaust temperature and composition at constant entropy, the enthalpy of the exhaust products is evaluated as

$$H_e = \left[\sum n_j H_j\right]_{298}^{T_e} + \sum n_j \Delta H_{f_{j298}} \quad (201)$$

Previously, the enthalpy of the chamber products was evaluated as

$$H_c = \left[\sum n_j H_j\right]_{298}^{T_c} + \sum n_j \Delta H_{f_{j298}} \quad (202)$$

It is important to note that the n_j are the actual equilibrium concentrations of the various product species at the exhaust and chamber temperature, respectively. Thus, the total enthalpy change through the nozzle is

$$\Delta H = H_c - H_e \tag{203}$$

10. Rocket Performance Parameters

From the previously calculated properties, specific impulse is rigorously evaluated as

$$\text{(a)}\quad Isp = \sqrt{\frac{2J}{g}(H_c - H_e)} \tag{204}$$

The volumetric specific impulse, the specific heat capacity, and the mean molecular weight of the products may be rigorously evaluated as

$$\text{(b)}\quad Ivsp = \rho \cdot Isp \tag{205}$$

$$\text{(c)}\quad c_p = \Sigma n_j c_{p_j} \tag{206}$$

$$\text{(d)}\quad MW = \frac{100 \text{ grams propellant}}{n_T} \tag{207}$$

It should be noted that 100 gm of propellant is a standard basis upon which to calculate propellant performance.

The preferred method of evaluating the other performance parameters may depend upon the nature of the propellant system. When all products of combustion are gases, the following approach is rigorous;

$$\text{(e)}\quad \frac{c_p}{c_v} = k = \frac{1}{1 - \frac{\ln T_c/T_e}{\ln p_c/p_e}} \tag{208}$$

$$\text{(f)}\quad c_F = \sqrt{\frac{2k^2}{k^2-1}\left[\frac{2}{k+1}\right]^{\frac{2}{k-1}}\left[1 - \frac{T_e}{T_c}\right]} \tag{209}$$

$$(g)\quad \frac{A_e}{A^*} \quad \frac{k}{c_F}\left[\frac{2}{k+1}\right]^{\frac{k+1}{k-1}} \left[\frac{p_c}{p_e}\right]^{\frac{1}{k}} \tag{210}$$

$$(h)\quad c^* = \frac{Isp \cdot g}{c_F} \tag{211}$$

However, these equations require some adjustment when multiphase flow exists, i.e. when solids or liquids are present as products of combustion. In this case, the following approach is preferred:

$$(g)\quad \frac{c_p}{c_v} = k = \frac{c_p}{c_p - n_T R} \tag{212}$$

$$(h)\quad \frac{p_e A_e}{m} = \frac{1}{a} \cdot n_T \frac{T_e}{Isp} \tag{213}$$

$$a = \frac{g(100 \text{ gm propellant})}{R(3.08595 \text{ ft-lb/cal})\ (453.59 \text{ gm/lb})} = 1.1567 \tag{214}$$

$$(i)\quad \frac{g}{c^*} = a^{1/2}\left[\frac{k}{n_T T_c}\right]^{1/2} \cdot \left[\frac{2}{k+1}\right]^{\frac{k+1}{2(k-1)}} \tag{215}$$

$$(j)\quad c_F \text{ (approx.)} = \frac{Isp \cdot g}{c^*} \tag{216}$$

$$(k)\quad \frac{A_e}{A^*} \text{ (approx.)} = \frac{g}{c^*} \cdot \frac{p_c}{p_e} \cdot \frac{p_e A_e}{m} \tag{217}$$

Since different values of specific impulse, exhaust temperature, and specific heat ratio will exist for shifting and frozen flow, the parameters $p_e A_e/m$, c_F, and A_e/A^* will also vary. The characteristic exhaust velocity c* can be rigorously evaluated only if throat conditions are accurately known. However, this requires some detailed point-to-point calculations. A good approximation to c* is obtained by using the chamber temperature and specific heat ratio in the above equation.

B. Method of Minimization of Free Energy

1. General Concepts

For the determination of the equilibrium composition of a complex mixture, the only thermodynamic property required is the Gibbs' standard free energy. Earlier, this was shown to be

$$dF = Vdp - SdT \tag{218}$$

under adiabatic, reversible conditions in which all work is accomplished by expansion. This is probably the most useful combined statement of the first and second laws of thermodynamics since pressure and temperature are the independent variables. However, a more direct approach to the calculation of propellant performance may be achieved through the basic definition of free energy

$$F = H - TS \tag{219}$$

Substituting the expressions of enthalpy and entropy developed in the previous section,

$$F = \sum n_j H_j - T \sum n_j S_j + RTn_T \sum \ln \frac{n_j}{n_T} + RTn_T \ln p_T \tag{220}$$

where
F = total free energy of the combustion products
n_j = moles of the j th product
H_j = enthalpy of the j th product
S_j = entropy of the j th product
T = temperature
R = universal gas constant
n_T = total gaseous moles
p_T = total pressure

The equilibrium composition may be determined by finding the set of positive values n_j which minimize the previous equation while simultaneously satisfying the mass balances.

A procedure for applying the method of the minimization of free energy to propellant performance calculations was first presented by White, Johnson, and Dantzig.[43] In their approach, the free energy function F/RT is minimized at constant temperature instead of utilizing equilibrium equations as was done in the previously discussed calculation method. Another feature of their approach was the derivation of the method of "steepest descent" for solving a symmetric set of linear equations by the matrix technique in the iteration procedure. Only m + 1 linear equations in m + 1 unknowns need to be solved where m represents the number of elements present in the mixture. Thus, the number of simultaneous equations to be solved is usually much smaller than the number of products of combustion. This advantage is particularly adaptable to linear programming for a large, high-speed digital computer. However, the principal limitation of the White, Johnson, and Dantzig method is that, as developed, it is applicable only to complex mixtures in which all the constituents are gases. This is unsatisfactory for the evaluation of many prototype propellant systems in which solid or liquid products of combustion are formed.

More recently, an improved technique for the minimization of free energy was developed by A. E. Roberts.[44] Instead of minimizing the free energy of a complex mixture at constant temperature, Roberts' method allows both temperature and composition to vary while maintaining either constant enthalpy or constant entropy. This method has been programmed for the Remington-Rand 1103A computer and is applicable to evaluating the equilibrium composition of complex mixtures containing solid, liquid, and gaseous constituents. Since this method was used for conducting the performance calculations presented later in this report, the important programming

concepts as well as the computational technique will be discussed in detail.

2. Establishing the Mass Balances

In programming notation, Roberts' method designates the elemental mass balance as[45]

$$\sum_j A_{ij} M_j = E_i \qquad (221)$$

where
- i = ingredient element
- j = exhaust specie
- E_i = total gram-atoms of the i th element present in the propellant formulation
- M_j = moles of the j th exhaust specie present in the equilibrium mixture
- A_{ij} = atoms of the i th element present in the j th exhaust specie. A_{ij} must be a positive, whole integer.

The maximum possible concentration of any given specie is defined by the minimum quantity of any ingredient element that is available from any of the applicable mass balances, i.e.

$$0 \leq M_j \leq \min \frac{E_i}{A_{ij}} = B_j \qquad (222)$$

Thus, the most restrictive mass balance defines B_j, the maximum number of moles of a given specie j which can possibly be formed. For example, the value of B_j for CO_2 would be smaller of the following:

$$0 \leq n_{CO_2} \leq \frac{\Sigma O}{2} = B_j \qquad (223)$$

$$0 \leq n_{CO_2} \leq \Sigma C = B_j \qquad (224)$$

For programming convenience, let $x_j = \frac{M_j}{B_j}$. Then, the mass balance may be re-stated as

$$\sum_j A_{ij} B_j x_j = E_i \qquad (225)$$

or

$$\frac{\sum_j A_{ij} B_j x_j}{E_i} = 1 \qquad (226)$$

Now, let

$$a_{ij} = \frac{A_{ij}}{E_i} B_j = \frac{A_{ij}}{E_i} \min \frac{E_i}{A_{ij}} = \frac{\min \frac{E_i}{A_{ij}}}{\frac{E_i}{A_{ij}}} \tag{227}$$

Both x_j and a_{ij} vary in value between 0 and 1.

Thus, the mass balance may be expressed in standard normalized form as

$$\sum_j a_{ij} x_j = 1 \tag{228}$$

for which the coefficients a_{ij} are stored in matrix form. The quantities x_j are proportional to the mole fraction of the respective exhaust species.

The total moles of gas are expressed as

$$M_o = \sum_{j=1}^{m+n} M_j \tag{229}$$

where m = gaseous elements
n = gaseous molecules
p = condensed phases

The maximum possible number of gaseous moles would occur if the entire propellant formulation existed as gaseous elements. Thus, the limits for M_o are

$$0 < M_o < \Sigma E_i = B_o \tag{230}$$

Letting $M_o = B_o x_o$,

$$B_o x_o = \sum_{j=1}^{m+n} B_j x_j \tag{231}$$

or

$$x_o = \sum_{j=1}^{m+n} \frac{B_j}{B_o} x_j \tag{232}$$

The quantity x_o is another programming convenience which varies in value between 0 and 1. It should also be noted that $B_j x_j$ represents the moles of

any species j present in the equilibrium mixture while B_o x_o represents the total gaseous moles at any one time. From Dalton's Law, the partial pressure contributed by each gaseous specie j is

$$p_j = \frac{x_j B_j}{x_o B_o} p_T \qquad (233)$$

where B_j, B_o, and p_T remain constant while x_o and x_j are variables.

The various x_j's indicate the degree to which a specie contributes to completing each mass balance. To insure operability, the x_j's are ordered in magnitude for each trial solution, i.e. all species j which contain element i are listed in order of decreasing concentration. Since the x_j's are proportional to the mole fraction of each respective specie j, this ordering procedure establishes priority for choosing a basis upon which to define the dependent variables. The species possessing the greatest x_j are chosen as the basic variables, with these species being selected as the basis in the mass balance for which they possess the greatest A_{ij}. For example, any concentration of CO_2 contributes more to the oxygen balance than to the carbon balance. Thus, CO_2 would be considered as a basis only in the oxygen balance. Then, it could be eliminated from the carbon balance. In this manner, a set of majors and minors is inherently established, i.e. a limited number of dependent basis variables are chosen while the remaining species are independent variables. The number of basis variables is limited to the number of elements in the propellant formulation. The concentration of any of the independent variables may be changed by an arbitrary amount. Then, the concentrations of the basis variables are determined from the mass balances and the concentrations of the independent variables. When the order of priority changes, the basis is revised. Both the mass balance equations

and the total gaseous moles equation are maintained throughout the transformations of the matrices. Previously, the free energy equation was written

$$F = \sum n_j H_j - T \sum n_j S_j + RTn_T \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + RTn_T \ln p_T \qquad (234)$$

Incorporating the program notation, this becomes

$$F = \sum_{j=1}^{m+n+p} H_j(B_j x_j) - T \sum_{j=1}^{m+n+p} S_j(B_j x_j) + RT \sum_{j=1}^{m+n} (B_j x_j) \ln \frac{B_j x_j}{B_o x_o} + RT \sum_{j=1}^{m+n} B_j x_j \ln p_T \qquad (235)$$

or

$$F = \sum_{j=1}^{m+n+p} B_j x_j (H_j - TS_j) + RT \sum_{j=1}^{m+n} B_j x_j (\ln B_j x_j) + RT B_o x_o \left(\ln \frac{p_T}{B_o x_o}\right) \qquad (236)$$

where

F = molar free energy
H = molar enthalpy
S = molar entropy
T = temperature
n_j = moles of exhaust specie j
B_j = maximum possible moles of specie j
x_j = ratio of actual moles of specie j to the maximum number of moles of specie j
R = universal gas constant
n_T = total gaseous moles
B_o = maximum possible total moles of gas
x_o = ratio of actual total moles of gas to the maximum number of moles of gas
p_T = total pressure
m = gaseous elements
n = gaseous molecules
p = condensed phases

3. Thermodynamic and Calculational Approach

From the basic relationship

$$dF = Vdp - SdT \qquad (237)$$

it follows that, for an ideal gas,

$$\left[\frac{\partial F}{\partial T}\right]_p = -S \qquad (238)$$

For a mixture of ideal gases, the additional restriction of constant concentration must be applied to the previous equation. This may also be shown from the definition of free energy

$$F = H - TS \tag{239}$$

Then,
$$\frac{dF}{dT} = \frac{dH}{dT} - T\frac{dS}{dT} - S\frac{dT}{dT} \tag{240}$$

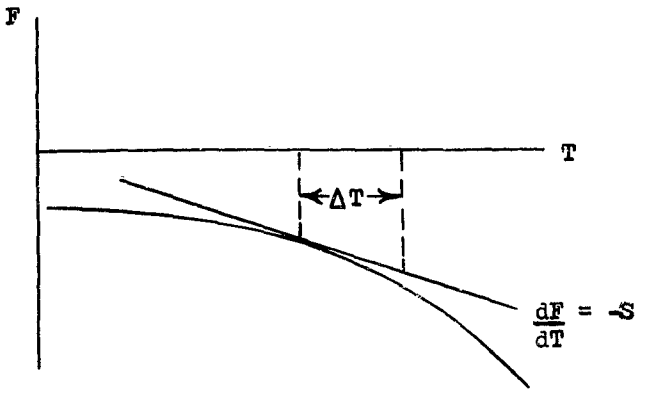
$$\frac{dF}{dT} = C_p - T\frac{dS}{dT} - S \tag{241}$$

However,
$$\frac{dS}{dT} = \frac{C_p}{T} \tag{242}$$

Therefore,
$$\frac{dF}{dT} = -S < 0 \tag{243}$$

$$\frac{d^2F}{dT^2} = -\frac{dS}{dT} = -\frac{C_p}{T} < 0 \tag{244}$$

These equations express the effect of a change in temperature on the ideal free energy of a complex mixture at constant pressure and concentration. The first derivative $\frac{dF}{dT}$ measures the slope of the free energy curve while the second derivative $\frac{d^2F}{dT^2}$ measures the curvature. Both the slope and the change in slope are always negative with the second derivative being numerically smaller than the first. Therefore, the curvature is always concave downward. The slope of the free energy curve is a good approximation to the actual curve over a fairly wide range of temperature. Furthermore, this approximation is a conservative one in that the tangent to the curve always lies above the actual curve, as illustrated below:



$$F(T + \Delta T) \leqq F(T) - S(T)\ \Delta T \tag{245}$$

$$\Delta F \leqq - S(T)\ \Delta T \tag{246}$$

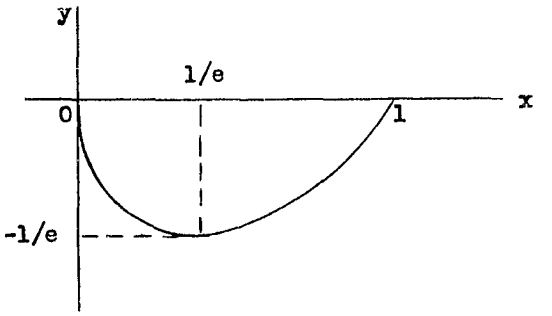
Thus, free energy may be readily estimated over small temperature intervals by the first derivative. It is important to note that these equations apply rigorously only to the ideal free energy at one atmosphere pressure. Neither the effect of mixing nor the effect of pressure is included. Whereas changes in the partial molal free energy arise from changes in temperature, changes in the entropy of mixing and pressure arise from changes in concentration.

Both of these latter quantities may be incorporated into the total free energy summation through the use of a supplemental equation of the form

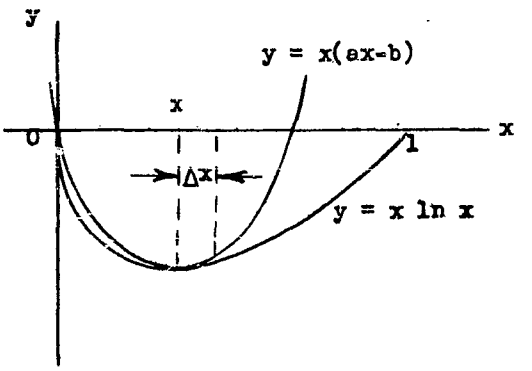
$$y = x \ln x \tag{247}$$

where y = free energy of mixing and pressure
x = concentration of the various gaseous species

For the normalized form of the equation where $0 \leqq x \leqq 1$, the absolute minimum y occurs at $x = 1/e$ and has the value $y = -1/e$, where e is the base of natural logarithms.



The slope at the y-axis is infinite while the curve intersects the x-axis at 0 and 1. Since the calculation of the x ln x function is a relatively lengthy procedure on a digital computer, Roberts has developed a quick approximation which permits a reasonable decrease in free energy for a modest calculational effort.[46] This approximation is made by constructing a parabola which is tangent to the y = x ln x curve at the initial point x and which passes through the origin, as shown below:



This is also a conservative approximation since the change in free energy is never as great on the parabola as on the x ln x curve except at the point of tangency. One such approximation is made for each specie at each trial composition. Furthermore, 100% convergence is mathematically guaranteed.

For the true free energy curve

$$y = x \ln x \tag{248}$$

and

$$\frac{dy}{dx} = \ln x + 1 \tag{249}$$

while for the parabolic approximation

$$y = x(ax - b) \tag{250}$$

and

$$dy/dx = 2ax - b \tag{251}$$

combining these into two simultaneous equations,

$$x \ln x = ax^2 - bx \tag{252}$$

$$x(\ln x + 1) = 2ax^2 - bx \tag{253}$$

the constants are found to be

$$a = \frac{1}{x} \tag{254}$$

$$b = 1 - \ln x \tag{255}$$

Using this approach, the approximate change in $y = x \ln x$ corresponding to a change in x is

$$(y + \Delta y) = (x + \Delta x) \ln (x + \Delta x) \leqq (x + \Delta x)\left[\frac{x + \Delta x}{x} - 1 + \ln x \right] \tag{256}$$

$$(y + \Delta y) \leqq (x + \Delta x) \left(\frac{\Delta x}{x} + \ln x\right) \tag{257}$$

$$\Delta y = \Delta (x \ln x) \leqq \Delta x \left[1 + \ln x + \frac{\Delta x}{x} \right] \tag{258}$$

It is important to note that x, the concentration variable, is actually the quantity $B_j x_j$ used in the program notation. Also, during the progress of a calculation, both T and x are interim numbers. The Δ values are the amounts of change employed in the next trial solution. Changes in concentration are always made for one specie at a time, choosing that specie which will reflect

the greatest change in the total free energy of the system. For each change in concentration, there is a corresponding change in temperature, and vice versa. By conducting a number of small, incremental changes, the free-energy of the system is rapidly minimized with a minimum of calculational effort.

4. Details of the Calculation Method

The calculational routine is initiated by assuming that the entire propellant composition exists as monatomic gases. This, of course, is a hypothetical situation which defines the maximum free energy and the maximum total moles of gaseous products for the system. Also, at constant enthalpy, the corresponding temperature of the monatomic gas mixture is a very low hypothetical one. In turn, the various products of combustion are introduced incrementally into the complex mixture. Each addition serves to reduce the free energy and increase the temperature of the mixture until equilibrium is attained. As shown previously, the free energy of a mixture of combustion products is

$$F = \sum_{j=1}^{m+n+p} n_j (H_j - TS_j) + RTn_T \left[\sum_{j=1}^{m+n} \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + \ln p_T \right] \qquad (259)$$

For a single gaseous specie of the mixture, the free energy is

$$F = \sum_{j=1}^{m+n} n_j (H_j - TS_j + RTn_j \ln n_j) + RT\, n_T \ln \frac{p_T}{n_T} \qquad (260)$$

where

F = free energy
H = enthalpy
S = entropy
T = temperature
n_j = moles of specie j
R = universal gas constant
p_T = total pressure
n_T = total moles of gaseous products
m = gaseous elements
n = gaseous molecules
p = condensed phases

For any incremental change in the concentration of the combustion products, there will be three contributions to the change in free energy of the mixture: (1) the free energy contributed by the formation of the new product; (2) the free energy lost by the decrease in concentration of the reactant(s); and (3) the free energy change introduced by the variation in the total number of gaseous moles. The method of handling these changes in the calculational approach may be best shown by an example. Consider the formation of nitrogen gas from its atoms:

$$2N \rightleftharpoons N_2$$

$$\Delta n_N = -2\Delta n_{N_2} \tag{261}$$

$$\Delta n_T = \Delta n_N + \Delta n_{N_2} = -\Delta n_{N_2} \tag{262}$$

A change in the number of moles of N_2 creates an inherent change in the number of moles of N. At a given temperature and concentration, the free energy of the mixture may be expressed as

$$F = n_N\left[H_N(T) - TS^{\circ}_N(T)\right] + RTn_N \ln n_N + n_{N_2}\left[H_{N_2}(T) - TS^{\circ}_{N_2}(T)\right] + RTn_{N_2} \ln n_{N_2} + \ldots + RT\, n_T \ln \frac{p_T}{n_T} \tag{263}$$

Since constant enthalpy must be maintained, any change in concentration will necessitate a change in temperature of the mixture. Over a short temperature range, $C_p\, \Delta T \cong \Delta H$.

Therefore,

$$\Delta H = 0 = \Delta n_{N_2}\left[H_{N_2}(T) - 2H_N(T)\right] + \Sigma n_j\, C_{p_j}\, \Delta T \tag{264}$$

and

$$\Delta T = -\left[\frac{H_{N_2} - 2\,H_N}{\Sigma n_j C_{p_j}}\right]^T \Delta n_{N_2} \tag{265}$$

Thus, a coefficient is obtained which relates the change in temperature of the mixture to the change in concentration of an individual specie. The incremental free energy change created by a decrease in the concentration of N is

$$\Delta F = n_N \left[H_N - TS_N\right]_T^{T+\Delta T} - 2\Delta n_{N_2}\left[H_N - TS_N\right]^{T+\Delta T} \tag{266}$$
$$+ R(T+\Delta T)\left[(n_N - 2\Delta n_{N_2}) \ln (n_N - 2\Delta n_{N_2}) - n_N \ln n_N\right] + R \cdot \Delta T\,(n_N \ln n_N)$$

This includes the ideal free energy and the free energy of mixing. Similarly, the incremental change in free energy caused by the formation of N_2 is

$$\Delta F = n_{N_2}\left[H_{N_2} - TS_{N_2}\right]_T^{T+\Delta T} + \Delta n_{N_2}\left[H_{N_2} - TS_{N_2}\right]^{T+\Delta T} \tag{267}$$
$$+ R(T+\Delta T)\left[(n_{N_2} + \Delta n_{N_2}) \ln (n_{N_2} + \Delta n_{N_2}) - n_{N_2} \ln n_{N_2}\right] + R\cdot\Delta T(n_{N_2} \ln n_{N_2})$$

Finally, the incremental change in free energy due to the variation in total moles of products is

$$\Delta F = R(T + \Delta T)\,(n_T - \Delta n_{N_2}) \ln \frac{p_T}{n_T - \Delta n_{N_2}} - RTn_T \ln \frac{p_T}{n_T} \tag{268}$$

However, this may be more conveniently re-stated as

$$\Delta F = -R(T+\Delta T)\,(\Delta n_{N_2}) \ln p_T + R\cdot\Delta T\, n_T \ln \frac{p_T}{n_T} + R(T+\Delta T)\left[n_T \ln n_T - (n_T - \Delta n_{N_2}) \ln (n_T - \Delta n_{N_2})\right] \tag{269}$$

Now, by applying the ΔF approximations previously developed, a number of coefficients may be obtained which are functions of ΔT and Δn. However, since $\Delta T = k'\Delta n$, the approximate change in free energy may be reduced to a cubic function of Δn.

First, consider the ideal contribution to free energy. From the curve of free energy versus temperature at constant concentration,

$$\Delta F = F^{\circ}(T + \Delta T) - F^{\circ}(T) \leqq -S^{\circ}(T)\ \Delta T \tag{270}$$

Therefore,

$$n_N(-S^{\circ}_N)_T\ \Delta T + n_{N_2}(-S^{\circ}_{N_2})_T\ \Delta T$$

constitutes a contribution to the total change in free energy. This contribution is the product of a constant and ΔT. Also,

$$F^{\circ}(T + \Delta T) \leqq F^{\circ}(T) - S^{\circ}(T)\ \Delta T \tag{271}$$

Therefore,

$$-2\,\Delta n_{N_2}\,(F^{\circ}_N)_T + \Delta n_{N_2}\,(F^{\circ}_{N_2})_T$$

and

$$-2\,\Delta n_{N_2}\,(-S^{\circ}_N)_T\ \Delta T + \Delta n_{N_2}\,(-S^{\circ}_{N_2})_T\ \Delta T$$

are also contributions to ΔF.

Second, the entropy of mixing will be considered. From the parabolic approximation to the function $y = x \ln x$,

$$\Delta(x \ln x) \leqq \Delta x\left[1 + \ln x + \frac{\Delta x}{x}\right] \tag{272}$$

Therefore,

$$\Delta F \leqq R(T + \Delta T)\,(-2\Delta n_{N_2})\left[1 + \ln n_N - \frac{2\,\Delta n_{N_2}}{n_N}\right] + R(n_N \ln n_N)\ \Delta T \tag{273}$$
$$+ R\,(T + \Delta T)\,(\Delta n_{N_2})\left[1 + \ln n_{N_2} + \frac{\Delta n_{N_2}}{n_{N_2}}\right] + R(n_{N_2} \ln n_{N_2})\,\Delta T$$

From this expression, the following additional contributions to the change in free energy are obtained:

(1) $R(n_N + \ln n_N)\ \Delta T + R(n_{N_2} \ln n_{N_2})\ \Delta T$

$$(2)\quad RT(-2\Delta n_{N_2})\,(1 + \ln n_N) + RT\,(\Delta n_{N_2})\,(1 + \ln n_{N_2})$$

$$(3)\quad RT(-2\Delta n_{N_2})\,\frac{(-2\Delta n_{N_2})}{n_N} + RT\,(\Delta n_{N_2})\,\frac{(\Delta n_{N_2})}{n_{N_2}}$$

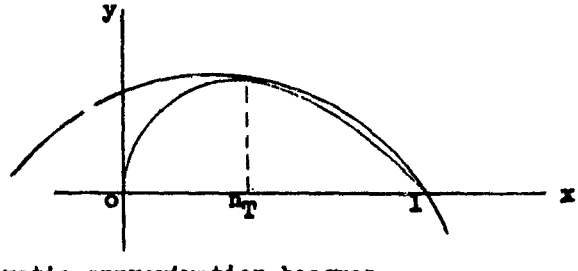
$$(4)\quad R\cdot\Delta T(-2\Delta n_{N_2})\,(1 + \ln n_N) + R\cdot\Delta T(\Delta n_{N_2})\,(1 + \ln n_{N_2})$$

$$(5)\quad R\cdot\Delta T(-2\Delta n_{N_2})\,\frac{(-2\Delta n_{N_2})}{n_N} + R\cdot\Delta T\,(\Delta n_{N_2})\,\frac{(\Delta n_{N_2})}{n_{N_2}}$$

Finally, consider the effect of a change in the total moles of gas on the free energy. This contribution contains a term of the general form $-\Delta(x \ln x)$ where $x = n_T$ and $\Delta x = -\Delta n_{N_2}$. Because of the minus sign, the same approximation used in the entropy of mixing contribution will not apply here. The desired quadratic must satisfy the requirement

$$-\Delta(x \ln x) = \Delta(-x \ln x) \leqq \text{quadratic in } \Delta x \qquad (274)$$

as shown by the illustration



This inverted quadratic approximation becomes

$$\Delta F \leqq R(T + \Delta T)\left[-(\ln n_T + 1)(\Delta n_T) + \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2}(\Delta n_T)^2\right] \qquad (275)$$

By applying L' Hospitals' principle, the coefficient of $(\Delta n_T)^2$ becomes $-1/2$ when $n_{T_{max}} = n_T$. Thus, the following contributions to free energy arise from the effect of total moles:

$$(1)\quad -RT\,(\Delta n_T) \ln p_T$$

(2) $-R \cdot \Delta T \, (\Delta n_T) \ln n_T$

(3) $+R \cdot \Delta T \, n_T \ln n_T/n_T$

(4) $-RT \, (\ln n_T + 1) \, \Delta n_T$

(5) $-R \cdot \Delta T \, (\ln n_T + 1) \Delta n_T$

(6) $$+RT \frac{(n_{T_{max}} - n_T) + n_T \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2} (\Delta n_T)^2$$

(7) $$+R \cdot \Delta T \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2} (\Delta n_T)^2$$

Now, the total incremental change in free energy, as a function of temperature and concentration may be represented by

$$\Delta F \, (T, x) \leqq \sum_j \left[A''_j \Delta T + B''_j \Delta x_j + C''_j \Delta x_j \Delta T + D''_j (\Delta x_j)^2 + E''_j (\Delta x_j)^2 \, \Delta T \right] \quad (276)$$

However, utilizing the approximation

$$T = k' \Delta x \quad (277)$$

the above equation reduces to one with only three coefficients and one unknown:

$$\Delta F \leqq \sum_j \left[A'_j \, \Delta x_j + B'_j (\Delta x_j)^2 + C'_j \, (\Delta x_j)^3 \right] \quad (278)$$

The value of Δx which minimizes ΔF is found by differentiating this equation and setting the derivative equal to zero:

$$\Delta x = \frac{-B'_j + \sqrt{(B'_j)^2 - 3 A'_j C'_j}}{3 C'_j} \quad (279)$$

Thus, a conservative approximation has been developed which can be solved directly to give Δx. Furthermore, the true change in free energy exceeds

that found by this approximate solution. In order to maintain the mass balances, the concentration of any specie cannot become negative. At the same time, the concentration cannot exceed the maximum defined by the mass balances. These two restrictions serve as limits for the values of x found from the solution of the cubic. As equilibrium is approached, the approximate solution comes closer to and finally coincides with the rigorous evaluation of composition, temperature, and free energy. In initiating the parabolic approximation, it is assumed that $x = 2/3\ x_{max}$ instead of $x = 0$ so that the constants a and b will be finite in value. The position $x = 2/3\ x_{max}$ is the point of tangency for which, on the average, the parabolic curve best approximates the $y = x \ln x$ curve. The important concept is to utilize a parabola which always lies above the $y = x \ln x$ or the $y = -x \ln x$ curves.

The summation of the various contributions to an incremental change in free energy yields, for the $2N \rightleftarrows N_2$ example, the following values for the constants of the cubic equation:

$$A' = \Sigma k' n_j (-\bar{S}^{\circ}_j)_T + \Sigma k' R (n_j \ln n_j) - 2(\bar{F}^{\circ}_N)_T + (\bar{F}^{\circ}_{N_2})_T - 2RT\ (1 + \ln n_N) + RT\ (1 + \ln n_{N_2}) - RT\ (\ln n_T + 1) - RT \ln p_T + k' R\, n_T \ln \frac{p_T}{n_T} \qquad (280)$$

$$B' = \frac{A}{n_N} RT + \frac{RT}{n_{N_2}} - 2k'(-\bar{S}^{\circ}_N)_T + k'(-\bar{S}^{\circ}_{N_2})_T - 2k'R(1 + \ln n_N) + k'R \qquad (281)$$

$$(1 + \ln n_{N_2}) - k'R(\ln n_T + 1) - k'R \ln p_T + RT \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2}$$

$$C' = \frac{Ak'R}{n_N} + \frac{k'R}{n_{N_2}} + k'R \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2} \qquad (282)$$

5. Introduction of Thermodynamic Data

Thermodynamic data for the various products of combustion are conveniently introduced in equation form as a function of temperature over a specified temperature interval. Of course, reference values of enthalpy and entropy are also introduced at a reference temperature within each interval. In order to insure an accurate fit of the thermodynamic data over the complete range from 298°K to 6000°K, several equations may be utilized, if necessary. However, in general two equations are sufficient to provide a highly accurate fit. Over the low temperature range from 298°K to about 1200°K to 1500°K, specific heat capacity data are expressed as an ascending polynomial of the form

$$C_p = a + bT + CT^2 + dT^3 + eT^4 \qquad (283)$$

From this, the enthalpy, entropy, and free energy of the individual species are evaluated as

$$H = \int C_p dT = H' + aT + \frac{bT^2}{2} + \frac{CT^3}{3} + \frac{dT^4}{4} + \frac{eT^5}{5} \qquad (284)$$

$$S^\circ = \int \frac{C_p dT}{T} = S' + a \ln T + bT + \frac{CT^2}{2} + \frac{dT^3}{3} + \frac{eT^4}{4} \qquad (285)$$

$$F^\circ = H - TS^\circ = H' - TS' + aT(1 - \ln T) - \frac{bT^2}{2} - \frac{CT^3}{6} - \frac{dT^4}{12} - \frac{eT^5}{20} \qquad (286)$$

where
- H = enthalpy at any general temperature T
- S = entropy at any general temperature T
- F = free energy at any general temperature T
- C_p = specific heat capacity at any general temperature T
- H' = reference enthalpy
- S' = reference entropy
- T = temperature x 10^{-3}
- a, b, c, d, e = empirical constants for the curve fit

Over the high temperature range extending from about 1200°K to 1500°K, the specific heat capacity data are expressed as a descending polynomial of the form

$$C_p = a + bT^{-1} + cT^{-2} + dT^{-3} + eT^{-4} \qquad (287)$$

Then, the enthalpy, entropy, and free energy equations over this interval become

$$H = \int C_p dT = H' + aT + b \ln T - \frac{c}{T} - \frac{d}{2T^2} - \frac{e}{3T^3} \qquad (288)$$

$$S^\circ = \int C_p \frac{dT}{T} = S' + a \ln T - \frac{b}{T} - \frac{c}{2T^2} - \frac{d}{3T^3} - \frac{e}{3T^4} \qquad (289)$$

$$F^\circ = H - TS^\circ = H' - TS' + (aT-b)(1-\ln T) - \frac{c}{2T} - \frac{d}{6T^2} - \frac{e}{12T^3} \qquad (290)$$

Although any reference temperature within the corresponding temperature interval may be utilized, 298°K and 3000°K, respectively, were chosen as convenient references for most species. The former is particularly desirable since it is a standard reference for many experimental data. By using the two reference points, dual integration is not necessary over both ranges of the heat capacity curve.

The functional method of introducing data into the calculation has both a thermodynamic and a programming advantage. Since the equation constants and the reference data are known, temperature and composition are the only variables involved in the calculation of enthalpy, entropy, or free energy. For a trial composition, temperature may be computed directly at either constant enthalpy or entropy. The programming advantage arises from the great saving in data storage and from the rapid solution of a polynomial equation on a high-speed digital computer. The actual storage of tables of thermodynamic data at 100°K temperature intervals would be quite cumbersome. Furthermore, the process of table look-up and interpolation is slower than the calculation of point properties from the polynomial equation.

6. Evaluation of Thermodynamic Properties and Performance Parameters

After evaluating the chamber temperature and composition by the minimization of free energy, the entropy of the system is calculated as was done in the method of equilibrium constants. Then, the exhaust temperature and composition are evaluated by minimizing the free energy of the system at constant entropy, and the exhaust enthalpy is calculated. From these data, the various performance parameters are calculated in the same manner as for the method of equilibrium constants.

CHAPTER V

THE THEORETICAL ANALYSIS PROGRAM

A Selection of Prototype Propellant Systems for Evaluation

The object of the theoretical calculation work presented in this report is to evaluate the performance of several prototype rocket fuels and oxidizers. In general, good fuels and oxidizers should possess relatively endothermic heats-of-formation and yield combustion products with large exothermic heats-of-formation. Furthermore, only the most exothermic chemical reactions are worthy of consideration for application to rocket propulsion. Since the most exothermic reactions occur between the elements in the upper-left and the upper-right corners of the periodic table, this study was confined to fuels and oxidizers consisting of the elements carbon, hydrogen, oxygen, nitrogen, chlorine, fluorine, lithium, beryllium, boron, aluminum, and magnesium. The following prototype materials were chosen for evaluation:

Fuels

Name	Formula
Liquid Hydrogen	H_2
Hydrazine	N_2H_4
Unsymmetrical Dimethyl Hydrazine	$C_2N_2H_8$
Polyethylene	CH_2
Dicyanoacetylene	C_4N_2
Pentaborane	B_5H_9
Aluminum Hydride	AlH_3
Beryllium Hydride	BeH_2
Lithium Hydride	LiH
Magnesium Hydride	MgH_2

Name	Formula
Liquid Oxygen	O_2
Liquid Fluorine	F_2
Oxygen Difluoride	OF_2
100% Hydrogen Peroxide	H_2O_2
Nitrogen Tetroxide	N_2O_4
Nitrogen Trifluoride	NF_3
Chlorine Trifluoride	ClF_3
Perchloryl Fluoride	ClO_3F
Nitronium Perchlorate	NO_2ClO_4
Ammonium Perchlorate	NH_4ClO_4

These materials were chosen in order to obtain the maximum amount of basic information for a modest calculational effort. By evaluating several fuels with a given oxidizer, a relative order-of-merit may be established for the fuels. Similarly, the evaluation of several oxidizers with each fuel reveals the relative merits of the oxidizers. Each of the previously mentioned fuels was evaluated with each of the oxidizers. While only oxygen and fluorine were considered worthy of general study as oxidizers, five light metals, in addition to carbon and hydrogen, were considered as prime fuel ingredients. The elements nitrogen and chlorine were essentially considered as carrier elements.

The study was established systematically to reveal the effects of various fundamental chemical moieties on overall performance. For example, the interactions of the fuel groups N-H, C-H, C-N-H, Al-H, B-H, Li-H, Be-H, and Mg-H are evaluated with the oxidizer groups N-F, O-F, Cl-F, Cl-O-F, N-O, Cl-O and H-O. All calculations were conducted in accordance with the assumptions and procedures discussed earlier. For each fuel-oxidizer combination, several mixture ratios were evaluated in order to define the optimum performance and provide some indication of the influence of propellant composition on performance. Although many of the fuel-oxidizer combinations in this report are not workable propellant combinations, this approach satisfies the objective of obtaining basic theoretical combustion information.

B. Thermodynamic Properties of Reactants and Products of Combustion

1. General Thermodynamic Requirements

When performance calculations are conducted rigorously as described previously in the method of equilibrium constants and the method of minimization of free energy, the accuracy of the results is governed by the accuracy of the basic thermodynamic data utilized. For reactants, only the heat-of-formation at a reference temperature must be known. However, this quantity must be known accurately because of its importance in the enthalpy balance. If either volumetric specific impulse or ideal boost velocity is to be calculated, the density of the reactants must also be known. For products of combustion, additional thermodynamic data must be available. Both the entropy and enthalpy must be known as a function of temperature in addition to the standard heat-of-formation. With these data, a consistent set of thermodynamic functions can be computed. Usually, the conventional thermodynamic functions of C_p, S, $-(F-H_{298})/T$, $H - H_{298}$, and $H-H_{298}/T$ are tabulated at temperature intervals of 100°K. Sometimes the heat-of-formation, free-energy-of-formation, and equilibrium-constant-of-formation are also included in the same tabulation.

The availability of accurate thermodynamic data for application to rocket combustion studies deserves some special comment. As shown by the performance calculations, combustion temperatures of 3000°K-4000°K are common. These obviously exceed the temperature range of experimental studies and require the use of thermodynamic data which have been computed from statistical mechanics. When the molecular structure and the basic molecular translational,

rotational, vibrational, and electronic contributions are known, the statistical mechanical approach is quite accurate. However, a fundamental problem in high temperature thermodynamics is molecular stability. New species which are insignificant or unknown at room temperatures may be quite stable in high temperature complex mixtures. An example of this phenomonen is metaboric acid, HBO_2, which replaces B_2O_3 as the dominant boron specie in the B-O-H system above 2000°K. Frequently, insufficient data are available on the high temperature decomposition and chemical equilibria of species which are quite stable at lower temperatures. This shortcoming can only be resolved by experimental research.

2. Heat-of-Formation of Reactants

The standard heats-of-formation for the reactants used in this theoretical study are, for the most part, quite accurately known. These are listed along with the densities of the reactants in Table I. Only the heats-of-formation of AlH_3 and BeH_2 are reasonably in doubt. Since these two hydrides have not been prepared in pure quantities, accurate experimental heat-of-formation data are lacking. Estimates of the ΔH_f of AlH_3 and BeH_2 vary from between +20 Kcal/mole and -15 Kcal/mole. Whereas the corresponding hydrides of lithium and magnesium are readily synthesized from the elements, attempts to prepare AlH_3 and BeH_2 in this manner have been unsuccessful. These data, along with the Al-H and Be-H bond strengths, indicate that the ΔH_f of both hydrides should be endothermic. Therefore, a ΔH_f of +10 Kcal/mole was chosen for AlH_3, and a ΔH_f of +10 Kcal/mole was also selected for BeH_2.

TABLE I

HEATS-OF-FORMATION AND DENSITIES OF REACTANTS

Reactant	Heat-of-formation Kcal/mole	Density g/cc	Ref. Temp. ^{o}K	State
H_2	-1.887	0.071	20.4	Liquid
N_2H_4	+12.05	1.004	298.16	Liquid
$C_2N_2H_8$	+12.74	0.786	298.16	Liquid
CH_2	-6.50	0.920	298.16	Solid
C_4N_2	+118.0	0.970	298.16	Liquid
B_5H_9	+7.74	0.620	298.16	Liquid
AlH_3	+10.0*	1.72*	298.16	Solid
BeH_2	+10.0*	Unknown	298.16	Solid
LiH	-21.6	0.820	298.16	Solid
MgH_2	-17.9	1.45	298.16	Solid
O_2	-3.08	1.14	90.2	Liquid
F_2	-3.47	1.51	85.2	Liquid
OF_2	+3.6	1.53	128.0	Liquid
H_2O_2	-44.84	1.443	298.16	Liquid
N_2O_4	-5.4	1.43	298.16	Liquid
NF_3	-32.2	1.532	144.0	Liquid
ClF_3	-44.4	1.810	298.16	Liquid
ClO_3F	-10.1	1.43	298.16	Liquid
NO_2ClO_4	+8.0	2.22	298.16	Solid
NH_4ClO_4	-69.42	1.96	298.16	Solid

* Estimated Values

3. Thermodynamic Properties of Combustion Products

The current status of the thermodynamic properties of combustion products varies from excellent, as in the case of hydrogen gas, to purely theoretical, as in the case of such metallic oxyhalides as AlOCl. In most cases, the properties of the dominant species are reasonably well defined for engineering applications. This is particularly true for products of combustion formed from the elements carbon, hydrogen, oxygen, nitrogen, chlorine, and fluorine. These data have been reported by Huff, et. al.,[47] Gordon[48], Stull and Sinke[49], Rossini, et. al.,[50] and others. In general, somewhat less is known about the thermodynamic properties of combustion products containing the metals lithium, boron, beryllium, magnesium, and aluminum. However, two relatively recent reports by Evans, Prosen, and Wagman provide a thorough summary of the properties of boron compounds.[51, 52] Still another recent report by Beckett, et. al., provides a summary of the known thermodynamic properties of lithium, beryllium, aluminum, and magnesium and their compounds with oxygen, hydrogen, fluorine, and chlorine.[53] Additional compilations of thermodynamic functions have been made by Gordon [54, 55], Stull and Sinke[56], Henderson, et. al.,[57, 58] and others which are applicable to the performance calculations presented in this report as well as to calculations involving other elements. All thermodynamic data used in this report are summarized in Table II, III, and IV at the end of this section. In Table II, standard values of heat-of-formation and entropy are summarized at reference temperatures. Constants for the heat capacity equation

$$C_p = a + bT + cT^2 + dT^3 + eT^4 \quad (291)$$

are presented in Table III and constants for the heat capacity equation

$$C_p = a + bT^{-1} + cT^{-2} + dT^{-3} + eT^{-4} \quad (292)$$

are presented in Table IV. These curve fits were provided by Messrs. C.B.

Henderson and R. S. Scheffee.[59] Unless otherwise specified by subscript, all species listed in Tables II, .II, and IV are gaseous molecules.

In somewhat more detail, the current status of the thermodynamic data on the metal-containing species may be summarized for various temperature ranges. From 0°K to 1000°K, experimental data are rather complete and fairly accurate for the species stable over this temperature range. Heats-of-formation and heat capacities have been measured for practically all of the significant solids and liquids. However, the chemical instability of the hydrides and the hydroxides, with the exception of LiOH, has precluded accurate measurement of their vapor pressures and heats of vaporization.[60] Low volatility of some other compounds has hindered vapor-phase studies in this temperature range.

Experimental difficulties increase in the range of 1000°-2000°K, but these are not sufficiently formidable to prevent most thermodynamic measurements. Specific heat capacity data are complete for some refractory materials, such as MgO, but usually do not extend to the melting point for substances which melt between 1000°K and 2000°K, such as Li_2O.[61] The availability of vapor-condensed phase equilibrium data for the stable species helps to compensate for lack of other data. The newer techniques of optical and mass spectrometry and molecular beams have greatly assisted in identifying the composition of high temperature gas mixtures.[62] However, more accurate analyses of such mixtures is needed. Experimental heat-of-fusion data are needed on most compounds.

Above 2000°K there are very little data on condensed phases. Specific heat capacities have been extrapolated from lower temperatures. Thermodynamic

properties of the gas species are quite accurately known for the monatomic and many of the diatomic species. However, in the polyatomic species and some of the diatomic species, molecular constant data are needed. Also, dissociation energies need refinement in most cases.[63]

A number of polyatomic gas species have been observed at low pressures by vaporization of solids and liquids in mass spectrometers. In a few cases, the electron-diffraction and infra-red spectra are also available. However, the configuration and molecular constants have been established with reliability for only a few of these species.

Basic low temperature data are available on the more significant aluminum compounds, such as Al_2O_3, $AlCl_3$, and AlF_3. At high temperatures, the existence of AlF_2 and $AlCl_2$ has been proposed on the basis of indirect evidence. Also, the oxyhalides AlOF and AlOCl and the interhalides AlF_2Cl, $AlFCl_2$, and AlFCl may be stable molecules, although no direct evidence for their existence is available. These molecules were first proposed by Gordon.[64] Their fundamental vibrations and bond distances have been estimated from values for related molecules.[65] Equilibrium studies of the Al-O system indicate that Al_2O is the predominant vapor species and that Al_2O_3 does not exist as a gas. The heat-of-formation and stability of crystalline aluminum nitride are probably the most questionable of the light metal nitrides. Experimental heats-of-formation vary between -57 and -77 Kcal/mole, with -70 ±10 Kcal/mole being the best available estimate for $AlN_{(s)}$. However, since AlN is a minor constituent in a fluorine or an oxygen atmosphere, the uncertainty in its properties is relatively insignificant in this study.

In general, data for the beryllium compounds are not as well known. Both low and high temperature heat capacity data are needed on $Be(OH)_2$, BeF_2, $BeCl_2$, BeF, and BeCl, but molecular constants are available. The mixed halide BeFCl has been proposed but not verified experimentally. Data on beryllium oxide are somewhat more complete, including the high temperature vapor phase. Gaseous polymers containing two to six BeO molecules have been identified by Chupka in the mass spectrograph.[66] Although this is of basic interest, the effect on rocket performance is not significant since the condensed phase is the predominant oxide specie. Solid BeO is more volatile in the presence of water vapor, suggesting the formation of $Be(OH)_2$. The properties of BeOH are estimated values.

The basic low and high temperature properties of the more significant magnesium compounds are fairly well defined. Some refinements would be useful in the molecular constants of the halides, and direct evidence has not been found for the existence of the mixed halides. Since magnesium oxide is an extremely high-melting compound, the gaseous oxide species are relatively unimportant in this study.

Experimental low temperature data are available on all important stable lithium compounds except LiCl. Some data are also available on these species in the high temperature range although the number of investigators has not been plentiful. Probably the most questionable data are those near the transition temperatures of LiF, LiCl, and Li_2O. The polymeric gaseous halides $(LiF)_2$, $(LiF)_3$, $(LiF)_4$, $(LiCl)_2$, and $(LiCl)_3$ have also been reported by Chupka.[67] The thermodynamic properties of these molecules need to be further refined, particularly since the lithium halides are gases at normal

rocket combustion temperatures.

The products of combustion of boron have been studied more extensively than those of either lithium, beryllium, aluminum or magnesium. However, the problem is a more complex one, particularly in the case of the boron oxides. B_2O_3, the principal stable oxide, melts and vaporizes at much lower temperatures than Al_2O_3, BeO, or MgO. This means that the vapor species play a more dominant role in the combustion of a boron-oxygen system. Also, the possible number of high temperature boron species exceeds that of lithium because of the greater valence and coordination number of boron. Probably the most controversial questions concerning the thermodynamic properties of B_2O_3 arise from the inconsistency of the molecular constant data with the thermochemical data for that molecule. Also, the structure of the crystalline state has not been absolutely resolved. The most probable sources of error in the thermochemical data are the heat capacity of the liquid and the heat-of-fusion.[68] The gaseous species H_3BO_3 and HBO_2 are significant at low and high temperatures, respectively. In fact, HBO_2 is the predominant boron species in the B-O-H system at temperatures above 2000°K. Although the heat-of-formation of HBO_2 has been questionable for some time, recent data have fairly well established a maximum ΔH_f of -140.8 Kcal/mole.[69,70] Even more recent studies by White indicate the ΔH_f of HBO_2 to be -134.5 Kcal/mole at 298°K. The data for the halides BCl, BCl_3, BF, and BF_3 are considered reliable. The existence of the subhalide BCl_2 has been suggested by the existence of the dimer B_2Cl_4. Data for BF_2 have also been estimated similarly to those for BCl_2, AlF_2, and $AlCl_2$. Direct evidence is available for the existence of BF_2Cl, $BFCl_2$, and BFCl, although the data on these

molecules need refinement.[72,73] The oxyhalides BOF and BOCl are hypothetical molecules whose properties have been estimated assuming a linear molecule.

In general, accurate heat-of-formation data are needed most for conducting theoretical performance calculations. However, another area of almost equal importance is that of high temperature properties. Both qualitative and quantitative data are needed. Experimental measurements of high temperature heat capacities and heats-of-transition are needed for solids and liquids. Although these studies may require new experimental techniques and equipment, they will undoubtedly refine the data now available. More detailed discussions of the thermodynamic properties of the reactants and products considered in this study may be found in the original literature citations listed in the footnotes and the bibliography.

In Table II, the enthalpy data at 298°K are the standard heats-of-formation of the various species, i.e. the heats-of-reaction for the formation of the species from their elements existing in their standard states. At higher temperatures, the enthalpy consists of the standard heat-of-formation at 298°K plus the heat content above that temperature. Of course, the entropy data are absolute values at a pressure of 1 atmosphere. In the two heat capacity equations, T is expressed as degrees Kelvin times 10^{-3}.

TABLE II

STANDARD VALUES OF ENTHALPY AND ENTROPY FOR PRODUCTS OF COMBUSTION

Reaction Product	ΔH_f Kcal/mole	S cal/mole/°K	Temp. °K	H Kcal/mole	S cal/mole/°K	Temp. °K
H	+52.089	27.393	298	+65.511	38.862	3000
H_2	0	31.211	298	+21.208	48.470	3000
H_2O	-57.798	45.106	298	-27.598	68.419	3000
HCl	-22.063	44.645	298	-0.198	62.364	3000
HF	-64.2	41.526	298	-43.121	58.709	3000
C(s)	0	1.361	298	+14.78	12.30	3000
C(g)	+170.89	37.762	298	+184.44	49.29	3000
CO	-26.416	47.214	298	-4.059	65.370	3000
CO_2	-94.052	51.070	298	-57.520	79.841	3000
O	+59.55	38.469	298	+73.071	50.095	3000
O_2	0	49.011	298	+23.455	67.980	3000
OH	+9.33	43.888	298	+30.786	61.376	3000
N	+113.00	36.61	298	+126.437	48.089	3000
N_2	0	45.763	298	+22.160	63.756	3000
NO	+21.60	50.339	298	+44.324	68.854	3000
F	+18.903	37.917	298	+33.641	49.791	3000
F_2	0	48.477	298	+24.192	68.436	3000
Cl	+28.942	39.457	298	+44.066	51.623	3000
Cl_2	0	53.291	298	+24.416	73.761	3000
CF	+83.0	50.889	298	+106.45	70.122	3000
CF_2	-18.0	58.254	298	+17.405	86.974	3000
CF_3	-120.0	62.352	298	-70.142	102.163	3000
CF_4	-218.0	62.635	298	-153.43	113.842	3000
CH	+143.0	42.34	298	+164.9	60.03	3000
CH_2	+66.0	44.92	298	+97.0	68.88	3000
CH_4	-17.89	44.50	298			
C_2H_2	+54.2	48.00	298	+101.0	84.08	3000
CHF_3	-162.6	62.04	298	-101.5	109.16	3000
CH_2F_2	-105.5	58.92	298	-47.56	102.26	3000
NH	+77.0	43.30	298	+98.77	60.93	3000
NH_2	+41.0	47.96	298	+71.19	71.348	3000
NH_3	-11.04	46.034	298			
CN	+94.0	48.41	298	+117.24	66.98	3000
C_2N_2	+73.8	57.91	298	+124.95	98.77	3000
HCN	+31.20	48.21	298	+66.79	75.86	3000
COF_2	-150.5	61.82	298	-101.4	100.56	3000
Al(l)				+21.330	25.217	3000
Al(g)	+77.5	39.31	298	+90.88	50.842	3000
AlH	+61.4	44.84	298	+84.79	63.842	3000
AlCl	-11.5	54.43	298	+12.90	75.120	3000
$AlCl_2$	-76.0	63.025	298	-36.671	96.914	3000
$AlCl_3$	-140.4	75.73	298	-87.61	120.086	3000
AlF	-59.2	51.450	298	-35.19	71.552	3000
AlF_2	-172.0	57.330	298	-132.874	90.768	3000

TABLE II CONTINUED

Reaction Product	ΔH_f Kcal/mole	S cal/mole/°K	Temp. °K	H Kcal/mole	S cal/mole/°K	Temp. °K
AlF_3	-283.0	66.11	298	-231.012	109.17	3000
$AlFCl_2$	-185.0	72.430	298	-132.523	116.643	3000
AlF_2Cl	-228.0	70.885	298	-176.619	114.976	3000
AlFCl	-121.0	61.962	298	-82.035	95.341	3000
AlOCl	-56.0	60.580	298	-14.818	94.216	3000
AlOF	-100.0	57.317	298	-61.677	90.055	3000
AlO	+16.8	52.16	298	+40.61	71.897	3000
Al_2O	-39.4	61.200	298	-4.160	89.710	3000
Al_2O_3(S)	-400.2	12.172	298	-339.3	69.736	2313
Al_2O_3(l)				-313.3	80.977	2313
Al_2O_2	-105.0	63.765	298	-50.56	108.54	3000
AlN(g)	+104.0	51.707	298	+128.26	71.776	3000
AlF_3(S)	-355.7	15.89	298	-346.19	34.907	727
AlN(S)	-70.0	5.0	298	-63.896	15.738	900
B(S)				+9.880	11.15	2000
B(l)				+22.630	16.47	3000
B(g)	+135.2	36.649	298	+148.62	48.121	3000
B_2(g)	+204.0	48.231	298	+227.607	67.850	3000
BH	+117	41.047	298	+139.63	59.314	3000
BN(S)	-60.3	3.37	298	-52.239	15.10	1200
BN(g)	+155.0	50.712	298	+178.169	69.616	3000
BCl	+46.23	50.944	298	+70.233	70.881	3000
BCl_2	-24.0	59.134	298	-14.807	91.104	3000
BCl_3	-97.1	69.320	298	-45.342	111.940	3000
BF	-42.87	47.892	298	-19.583	66.935	3000
BF_2	-154.0	53.235	298	-116.99	82.547	3000
BF_3	-270.0	60.71	298	-220.31	100.32	3000
BFCl	-89.0	57.376	298	-51.130	87.936	3000
BF_2Cl	-210.0	65.688	298	-159.597	106.312	3000
$BFCl_2$	-154.0	68.784	298	-102.859	110.488	3000
BOCl	-62.0	56.706	298	-24.164	87.50	3000
BOF	-118.0	54.342	298	-80.505	84.674	3000
BO	+16.0	48.609	298	+38.015	67.026	3000
B_2O_2	-105.14	57.33	298	-53.58	98.44	3000
HBO_2	-140.8	57.660	298	-94.269	93.760	3000
H_3BO_3	-238.6	68.82	298	-158.40	131.11	3000
B_2O_3(g)	-206.57	64.39	298	-145.11	111.70	3000
B_2O_3(l)	-281.65	49.38	1000			
B_2O_3(S)	-300.98	18.55	298	-294.36	33.15	600
$(HBO_2)_3$	-531.26	85.12	298	-371.76	208.82	3000
Be(S)	0	2.28	298			
Be(l)				+10.715	13.684	1556
Be(g)	+77.9	32.55	298	+91.338	44.02	3000
BeH	+76.0	42.19	298	+98.744	60.782	3000
BeCl	+13.0	51.993	298	+37.030	71.920	3000
$BeCl_2$	-84.0	57.87	298	-44.762	89.828	3000
BeF	-16.5	49.151	298	+6.963	68.399	3000
BeF_2(g)	-192.10	52.256	298	-154.65	82.294	3000

TABLE II CONTINUED

Reaction Product	ΔH_f Kcal/mole	S cal/mole/°K	Temp. °K	H Kcal/mole	S cal/mole/°K	Temp. °K
$BeF_{2(l)}$				-222.93	34.468	1076
$BeF_{2(s)}$	-241.7	9.000	298			
BeFCl	-134.0	55.960	298	-95.440	87.630	3000
$BeO_{(s)}$	-143.1	3.370	298	-111.243	28.754	2823
$BeO_{(l)}$				-94.243	34.776	2823
$BeO_{(g)}$	+30.1	47.208	298	+53.282	66.140	3000
$(BeO)_2$				-67.026	85.570	2242
$(BeO)_3$				-197.539	115.771	2242
$(BeO)_4$				-301.052	146.668	2242
$(BeO)_5$				-404.565	173.868	2242
$(BeO)_6$				-514.078	196.907	2242
$Be(OH)_2$	-159.72	54.964	298	-134.463	87.365	1500
BeOH	-28.0	54.202	298	+3.787	79.727	3000
$Be(OH)_{2(s)}$	-216.1	13.30	298			
$Be_3N_{2(s)}$	-121.47	34.67	800			
$Li_{(g)}$	+38.430	33.140	298	+51.965	44.65	3000
$Li_{(l)}$				+9.684	19.78	1600
Li_2	+50.47	47.021	298	+75.421	67.998	3000
LiH	+32.0	40.78	298	+55.53	59.97	3000
LiCl	-49.0	50.834	298	-24.623	71.191	3000
$(LiCl)_2$				-88.504	111.891	3000
$LiCl_{(l)}$	-80.34	38.074	1200			
LiF	-77.60	47.754	298	-53.33	67.674	3000
$(LiF)_2$				-176.21	96.463	3000
$(LiF)_3$				-260.66	155.421	3000
LiO	+13.8	46.65	298	+36.99	65.60	3000
$Li_2O_{(s)}$	-142.4	9.06	298			
$Li_2O_{(l)}$				-68.68	63.61	3000
$Li_2O_{(g)}$	-35.80	55.820	298	-1.19	83.430	3000
LiO_2	-63.0	54.370	298	-25.95	83.871	3000
LiOH	-53.8	53.366	298	-22.238	77.923	3000
$(LiOH)_2$				-87.76	118.619	3000
$LiF_{(s)}$	-146.3	8.57	298			
$LiF_{(l)}$				-115.7	39.54	2000
$Li_3N_{(s)}$	-47.5	8.90	298			
$Mg_{(l)}$				+7.01	18.29	1000
$Mg_{(g)}$	+35.6	35.51	298	+49.038	46.97	3000
MgH	+41	46.11	298	+64.573	65.443	3000
MgCl	+2.0	55.34	298	+28.646	76.444	3000
$MgCl_{2(g)}$	-103.7	61.65	298	-64.83	94.324	3000
$MgCl_{2(l)}$				-129.76	54.59	1000
MgF	-41.0	52.814	298	-16.862	72.948	3000
$MgF_{2(g)}$	-169.7	55.92	298	-130.66	88.344	3000
$MgF_{2(l)}$				-215.91	58.32	2000
MgFCl	-137.0	60.054	298	-97.822	93.607	3000
$MgO_{(g)}$	+13.9	50.944	298	+37.991	70.992	3000
$MgO_{(l)}$				-89.402	40.234	3073
$MgO_{(s)}$	-107.90	34.214	3073			
$MgCl_{2(s)}$	-142.06	42.00	900			

TABLE II CONTINUED

Reaction Product	ΔH_f Kcal/mole	S cal/mole/°K	Temp. °K	H Kcal/mole	S cal/mole/°K	Temp. °K
$MgF_{2(S)}$	-241.0	42.81	1500			
MgOH	-56.0	56.981	298	-23.014	83.126	3000
$Mg(OH)_{2(S)}$	-221.0	15.09	298			
$Mg_3N_{2(S)}$	-110.3	21.0	298	-95.99	48.098	823
ClF	-13.423	52.062	298	-0.8510	65.808	1500
ClO	+43.00	54.379	298	+53.501	68.217	1500

TABLE III

SUMMARY OF CONSTANTS OF THE HEAT CAPACITY EQUATION
$C_p = a + bT + CT^2 + dT^3 + eT^4$ FOR PRODUCTS OF COMBUSTION

Reaction Product	Temp. Range °K	a	b	c	d	e
H	298-1200	4.6491	2.1104	-4.9036	4.7721	-1.6529
H_2	298-1200	4.9782	12.6667	-28.6774	27.5445	-9.2560
H_2O	298-1200	7.7840	-0.4000	4.6918	-2.7618	0.5388
HCl	298-1200	5.7282	7.8535	-18.3714	18.8757	-6.6140
HF	298-1200	5.3188	11.0072	-25.9848	25.7227	-8.8189
$C_{(s)}$	298-1200	-0.8755	11.1421	-3.1995	-4.4184	2.4909
$C_{(g)}$	298-1200	5.5345	-3.5997	8.1446	-7.7652	2.6446
CO	298-1200	6.5135	2.3674	-5.4030	8.1190	-3.6364
CO_2	298-1200	4.3090	20.6041	-20.9840	11.8419	-2.7832
O	298-1200	5.5202	-1.1625	0.2062	1.0710	-0.6299
O_2	298-1200	8.1634	-10.0674	28.6774	-27.5958	9.1338
OH	298-1200	7.2173	0.3874	-3.7090	5.6460	-2.2047
N	298-1200	4.9556	0.0600	-0.0889	0.0410	0
N_2	298-1200	7.2990	-2.2393	4.0750	-0.6623	-0.6229
NO	298-1200	8.0151	-6.7019	15.9410	-12.5923	3.4646
F	298-1200	6.8092	-8.0466	16.0915	-14.8332	5.0394
F_2	298-1200	5.0585	12.5570	-18.0551	12.6196	-3.4646
Cl	298-1200	1.5072	23.2522	-49.2232	44.3739	-14.5456
Cl_2	298-1200	5.1523	17.0693	-31.3058	26.3340	-8.2644
CF	298-1200	6.7824	-0.3563	8.2324	-9.1886	3.0680
CF_2	298-1200	7.1238	10.4083	-2.9395	-3.6248	1.9745
CF_3	298-1200	1.7148	50.8439	-61.7657	36.4601	-8.5419
CF_4	298-1200	0.6148	66.6450	-77.7637	44.3853	-9.9271
CH	298-1200	7.2683	-1.8710	3.1512	-1.0671	0.02430
CH_2	298-1200	8.0892	-2.6220	9.9827	-6.3896	1.3184
CH_4	298-1200	7.3974	-6.1618	43.8496	-39.3788	11.4581
C_2H_2	298-1200	2.2834	41.8264	-59.7199	43.7790	-12.2479
CHF_3	298-1200	-0.3747	59.4746	-69.6683	43.2455	-10.9599
CH_2F_2	298-1200	3.7552	21.6690	5.1725	-17.4742	6.8712
NH	298-1200	7.0346	-0.2160	-0.6454	2.3496	-1.0510
NH_2	298-1200	8.1021	-2.5106	9.3232	-6.4932	1.6039
NH_3	298-1200	7.1234	2.3491	9.7882	-7.5632	1.7072
CN	298-1200	7.6062	-5.1455	12.8420	-10.0281	2.7218
C_2N_2	298-1200	7.5571	29.6794	-39.0639	28.2055	-8.1166
HCN	298-1200	4.6914	18.4680	-22.2652	15.6556	-4.3682
COF_2	298-1200	2.6503	39.7213	-42.3295	22.5746	-4.8420
$Al_{(g)}$	298-1200	3.9677	7.9856	-20.0784	20.3835	7.2441
$Al_{(l)}$	900-6000	7.0	0	0	0	0
AlH	298-1200	7.7836	-7.6791	21.6722	-19.2239	5.7959
AlCl	298-1200	6.4388	9.9343	-15.7794	11.5580	-3.1835
$AlCl_2$	298-1200	8.2309	25.9687	-41.3807	30.1295	-8.2564
$AlCl_3$	298-1200	10.5301	35.6821	-56.1667	40.5592	-11.0510

TABLE III CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
AlF	298-1200	5.1754	12.1638	-16.5747	10.8250	-2.7339
AlF_2	298-1200	4.9599	34.0210	-49.6949	34.0750	-8.9490
AlF_3	298-1200	5.7138	44.9180	-61.7929	40.4308	-10.2369
$AlFCl_2$	298-1200	6.7952	46.2482	-69.0741	48.0722	-12.7522
AlF_2Cl	298-1200	6.8416	43.4470	-62.1709	41.4930	-10.8748
AlFCl	298-1200	7.1218	26.3110	-38.1612	26.0522	-6.8226
AlOCl	298-1200	8.3806	19.4158	-25.4114	16.0854	-3.9854
AlOF	298-1200	5.9524	25.5204	-32.2289	19.7106	-4.7327
AlO	298-1200	4.9828	11.9091	-16.4703	11.3880	-3.1496
Al_2O	298-1200	5.4563	22.9840	-27.7457	16.2804	-3.7667
$Al_2O_3(S)$	298-1200	-6.5714	134.3794	-203.2832	144.0387	-38.7424
$Al_2O_3(S)$	2100-6000	31.15	2.0	0	0	0
$Al_2O_3(l)$	298-1200	7.7923	41.8087	-57.9975	38.2374	-9.7448
Al_2O_2	298-1200	5.8327	11.4582	-17.5701	12.4443	-3.3414
AlN(g)	298-900	5.47	7.80	0	0	0
AlN(S)	298-727	2.580	86.775	-157.717	145.5	-48.5
$AlF_3(S)$	727-2000	20.93	1.50	0	0	0
$AlF_3(S)$	2100-6000	7.5	0	0	0	0
B(l)	298-1200	3.4917	9.8630	-23.0913	22.6147	-7.8740
B(g)	298-1200	5.8345	5.7108	-2.4451	-1.7599	1.2598
$B_2(g)$	298-1200	7.4053	-3.2771	7.1383	-4.0601	0.6299
BH	298-1200	1.5198	27.8125	-26.4121	14.4284	-3.6331
BN(S)	298-1200	7.1326	-3.5555	14.0143	-13.0869	4.1677
BN(g)	298-1200	5.2489	11.3558	-14.8233	9.2787	-2.2540
BCl	298-1200	4.9226	32.5208	-46.0491	30.9468	-8.0194
BCl_2	298-1200	6.5126	43.1581	-60.1744	39.7437	-10.1276
BCl_3	298-1200	5.3144	8.3476	-11.7021	9.9308	-3.4646
BF	298-1200	6.1558	7.3366	12.9662	-20.8438	7.8372
BF_2	298-1200	3.6440	39.0299	-42.9112	23.7218	-5.3543
BF_3	298-1200	3.0732	32.6145	-40.5830	24.7328	-5.9538
BFCl	298-1200	13.3393	-8.0392	47.1216	-51.4582	17.4848
BF_2Cl	298-1200	5.9286	40.4030	-52.1268	32.6017	-7.9951
$BFCl_2$	298-1200	6.1872	22.5827	-29.6029	19.9190	-5.3220
BOCl	298-1200	7.7388	10.6700	-3.9988	-2.2705	1.5553
BOF	298-1200	7.9062	-7.6457	19.9985	-17.5116	5.3543
BO	298-1200	10.1212	19.6261	-19.6396	11.6047	-3.0012
B_2O_2	298-1200	4.7597	24.2014	-19.4200	8.2347	-1.4398
HBO_2	298-1200	0.1952	79.1232	-91.5570	55.9425	-13.7120
H_3BO_3	298-1200	5.4370	39.1950	-34.4995	15.0008	-2.5699
$B_2O_3(g)$	298-600	-52.30	488.83	-1190.0	1016.67	0
$B_2O_3(S)$	298-1200	-1.2880	161.8829	-189.244	111.294	-25.9599
$(HBO_2)_3$	298.1700	4.13	2.4	0	0	0
Be(S)	1400-6000	7.5	0	0	0	0
Be(l)	298-2500	4.97	0	0	0	0
Be(g)	298-1200	10.6340	-22.5709	47.4823	-38.7665	11.2880
BeH						

TABLE III CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
BeCl	298-1200	5.2314	11.4345	-14.9863	9.4369	-2.3086
$BeCl_2$	298-1200	5.1303	31.6832	-44.6868	29.9397	-7.7400
BeF	298-1200	6.1152	3.3155	0.9714	3.0498	1.1968
$BeF_{2(g)}$	298-1200	2.4903	31.1361	-34.9557	17.2050	-4.1859
$BeF_{2(l)}$	1000-6000	21.0	0	0	0	0
$BeF_{2(s)}$	298-1200	8.4	12.0	0	0	0
BeFCl	298-1200	5.6566	26.5295	-35.2020	22.7686	-5.7716
$BeO_{(s)}$	298-1200	-5.6027	61.5775	-93.2205	68.0057	-18.8518
$BeO_{(l)}$	2700-6000	14.5	0	0	0	0
$BeO_{(g)}$	298-1200	7.0077	-2.8128	12.7681	12.5039	3.9368
$Be(OH)_2$	298-1200	-0.6491	79.4228	-119.3368	86.4588	-23.7485
BeOH	298-1200	7.4132	-0.5027	14.1321	-14.6854	4.7205
$BeO_{(s)}$	1200-3000	11.93	0.91	0	0	0
$Be_3N_{2(s)}$	298-800	7.32	30.8	0	0	0
$Li_{(g)}$	298-1200	4.97	0	0	0	0
$Li_{(l)}$	500-6000	6.87	0	0	0	0
Li_2	298-1200	7.3496	6.8209	-10.6540	7.9135	-2.1993
LiH	298-1200	6.6048	-0.7687	10.0114	-10.8285	3.5662
LiCl	298-1200	5.6195	11.9363	-18.0048	12.6189	-3.3657
LiF	298-1200	5.2328	10.6854	-12.9571	7.5804	-1.7254
LiO	298-1200	6.9059	-1.8393	10.5388	-10.6287	3.3779
$Li_2O_{(s)}$	298-1900	2.4011	51.2102	-62.7011	38.2906	-8.5721
$Li_2O_{(l)}$	1500-6000	24.0	0	0	0	0
$Li_2O_{(g)}$	298-1200	6.1995	9.1561	1.7129	-7.6438	3.1166
LiO_2	298-1200	2.8280	29.2237	-33.5974	19.6045	-4.6172
LiOH	298-1200	8.3729	-6.3251	23.2359	-20.5663	6.1118
$LiF_{(s)}$	298-1200	2.1602	43.3753	-72.9975	58.1838	-16.4581
$LiF_{(l)}$	1000-6000	15.5	0	0	0	0
$LiCl_{(l)}$	880-1200	17.0691	-1.52	0	0	0
$Li_3N_{(s)}$	298-800	11.73	23.0	0	0	0
$Mg_{(l)}$	900-6000	8.1	0	0	0	0
$Mg_{(g)}$	298-2500	4.97	0	0	0	0
MgH	298-1200	6.9688	-3.2669	14.7073	-14.4920	4.6051
MgCl	298-1200	6.5499	9.5397	-15.1524	11.1001	-3.0559
$MgCl_{2(g)}$	298-1200	8.1795	26.3921	-42.2976	30.9229	-8.4994
$MgCl_{2(l)}$	900-6000	22.1	0	0	0	0
MgF	298-1200	5.4028	12.1908	-17.5182	11.8730	-3.0802
$MgF_{2(g)}$	298-1200	4.1208	38.3454	-57.5026	40.1424	-10.6744
$MgF_{2(l)}$	1400-6000	22.6	0	0	0	0
MgFCl	298-1200	5.8100	33.7002	-52.0243	37.0813	-10.0122
$MgO_{(g)}$	298-1200	5.2592	12.0747	-16.6978	11.0012	-2.7946
$MgO_{(l)}$	2900-6000	14.5	0	0	0	0
MgOH	298-1200	5.8757	13.4434	-13.5188	7.2214	-1.5067
$MgO_{(s)}$	300-3200	9.965	1.805	0	0	0

TABLE III CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
$MgF_2(s)$	400-2000	16.47	2.76	0	0	0
$Mg_3N_2(s)$	298-823	20.77	11.20	0	0	0
$Mg_3N_2(s)$	823-1061	20.07	10.66	0	0	0
$Mg_3N_2(s)$	1061-2000	28.5	0	0	0	0
ClF	298-1200	5.5350	10.5214	-13.6836	8.2632	-1.8898
ClO	298-1200	-2.0832	6.0494	3.7874	-2.3555	0.5893

TABLE IV

SUMMARY OF CONSTANTS OF THE HEAT CAPACITY EQUATION
$C_p = a + bT^{-1} + cT^{-2} + dT^{-3} + eT^{-4}$ FOR PRODUCTS OF COMBUSTION

Reaction Product	Temp. Range °K	a	b	c	d	e
H	1200-6000	4.9680	0	0	0	0
H_2	1200-6000	13.1615	-27.4278	67.2718	-84.8607	40.7688
H_2O	1200-6000	13.7762	1.8181	-19.5586	21.5310	-7.7672
HCl	1200-6000	10.2217	-7.2070	15.6488	-22.0974	11.6068
HF	1200-6000	12.3357	-25.0605	67.8036	-91.7611	45.9920
$C_{(s)}$	1200-6000	8.9014	-14.7665	31.8293	-33.9478	13.2068
$C_{(g)}$	1200-6000	5.7187	0.3176	-13.1090	27.1718	-16.0
CO	1200-6000	8.9548	3.1902	-17.8004	28.4934	-16.0
CO_2	1200-6000	17.0619	-10.1588	-17.6949	-18.8447	7.2457
O	1200-6000	6.7126	-13.5630	39.3302	-49.8513	23.2136
O_2	1200-6000	11.0432	-3.3193	-9.4192	22.2363	-12.6224
OH	1200-6000	11.1146	-12.8166	27.9832	-36.0147	17.8456
N	1200-6000	11.2577	-52.8970	162.330	-214.4616	102.7204
N_2	1200-6000	9.4233	-1.7978	0.1459	0.8427	1.0156
NO	1200-6000	10.1998	-8.4006	23.0720	-31.8463	15.8143
F	1200-6000	4.9810	0.3996	-1.3628	2.3392	-1.3058
F_2	1200-6000	8.8708	0.8054	-3.4224	5.1525	-2.9017
Cl	1200-6000	5.1251	-1.7062	7.2114	-10.6191	5.6584
Cl_2	1200-6000	11.0049	-12.3026	33.9264	-43.7925	21.0372
CF	1200-6000	9.7813	-3.6223	7.1708	-8.0166	3.2911
CF_2	1200-6000	13.9133	-0.03111	-1.0264	-0.1186	0.2110
CF_3	1200-6000	23.5138	-20.5833	52.6576	-66.2369	30.0422
CF_4	1200-6000	30.2094	-21.8359	47.4496	-52.9712	21.6034
CH	1200-6000	10.5378	-8.2322	16.2034	-20.1049	9.2827
CH_2	1200-6000	13.8598	0.5278	-9.6784	7.0023	-1.3080
C_2H_2	1200-6000	21.0765	-2.7760	2.0961	-17.1159	13.3333
CHF_3	1200-6000	25.8030	0.3565	-8.0184	4.2406	-0.6329
CH_2F_2	1200-6000	25.7758	0.5723	-12.1526	6.1841	-0.2954
NH	1200-6000	10.5927	-8.4438	15.7380	-19.0571	8.8608
NH_2	1200-6000	13.8508	0.8784	-13.6628	12.3590	-3.3755
CN	1200-6000	9.4034	25.5485	-119.9354	177.2701	-86.6245
C_2N_2	1200-6000	21.3002	-4.0233	8.6897	-15.9300	8.4388
HCN	1200-6000	18.0749	-15.9472	31.9731	-39.9297	18.4810
COF_2	1200-6000	19.8930	-0.2882	-1.4691	-1.6824	1.3924
$Al_{(g)}$	1200-6000	6.7710	-16.8320	56.1522	-79.2737	40.0435
AlH	1200-6000	11.1719	-11.7417	27.5952	-32.2290	13.8397
AlCl	1200-6000	10.4069	-7.7297	18.7755	-21.3683	9.0717
$AlCl_2$	1200-6000	14.9053	-0.01523	-0.1658	-0.07478	0.04219
$AlCl_3$	1200-6000	19.8693	0.01952	-0.3761	0.04007	0
AlF	1200-6000	5.1754	12.1638	-16.5747	10.8250	-2.7339
AlF_2	1200-6000	14.9017	0.0238	-0.6166	0.1412	-0.042

TABLE IV CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
AlF_3	1200-6000	19.8763	-0.0514	-0.7156	-0.2812	0.2110
$AlFCl_2$	1200-6000	19.8743	-0.0300	-0.4986	-0.1797	0.1266
AlF_2Cl	1200-6000	19.8738	-0.0247	-0.6365	-0.1499	0.1266
AlFCl	1200-6000	14.9100	-0.06719	-0.1884	-0.3579	0.2110
AlOCl	1200-6000	14.9088	-0.05508	-0.3275	-0.3052	0.2110
AlOF	1200-6000	14.9030	0.0087	-0.7949	0.0626	0.0422
AlO	1200-6000	8.6384	3.3156	-12.9668	19.9806	-11.0265
Al_2O	1200-6000	13.9092	0.01136	-0.8344	0.07978	0.04219
$Al_2O_3(S)$	1200-2500	55.0332	-84.0657	105.1027	-47.4432	0
Al_2O_2	1200-6000	20.8688	-0.03878	-0.6914	-0.2064	0.1688
AlN(g)	1200-6000	8.9423	0.001028	-0.1281	0.008015	0
AlN(S)	900-3000	14.699	0	-1.789	0	0
B(S)	1000-2400	10.3983	-7.0902	-4.2064	15.8978	-9.3332
B(g)	1200-6000	5.3886	-4.5609	16.9404	-26.4531	14.5085
B_2(g)	1200-6000	9.1384	-1.4373	3.0706	-3.0243	0.7254
BH	1200-6000	8.7146	2.4833	-11.2827	15.2569	-7.8346
BN(S)	1200-6000	18.0317	-37.9094	95.3357	-111.5386	47.6000
BN(g)	1200-6000	9.9021	-5.0205	11.3351	-13.5906	5.8650
BCl	1200-6000	10.2413	-6.8557	16.4790	-18.9494	8.0591
BCl_2	1200-6000	14.9077	-0.0398	-0.5047	-0.1671	0.1266
BCl_3	1200-6000	19.8782	-0.0711	-0.5586	-0.3812	0.2532
BF	1200-6000	8.7610	1.9896	-8.2963	12.1788	-6.6739
BF_2	1200-6000	14.9054	-0.0149	-1.6857	0.0081	0.2532
BF_3	1200-6000	19.7823	0.9185	-5.3913	5.1252	-2.4664
BFCl	1200-6000	14.9062	-0.0224	-1.1104	-0.0553	0.1688
BF_2Cl	1200-6000	19.8719	-0.0004	-1.6333	0.0604	0.1688
$BFCl_2$	1200-6000	19.8794	-0.0826	-0.8952	-0.4174	0.3376
BOCl	1200-6000	14.9077	-0.0334	-1.4348	0.0375	0.2954
BOF	1200-6000	14.9050	-0.0029	-1.8188	0.2612	0.2532
BO	1200-6000	10.2272	-9.1175	25.9717	-36.2764	18.1357
B_2O_2	1200-6000	20.8674	-0.0048	-3.1009	0.5032	0.4641
HBO_2	1200-6000	4.7597	24.2014	19.4200	8.2347	-1.4398
H_3BO_3	1200-6000	37.6781	1.1163	-20.0353	14.5691	-3.2911
B_2O_3(g)	1200-6000	25.8298	0.0601	-4.6868	0.9570	0.4219
B_2O_3(l)	600-6000	30.5	0	0	0	0
B_2O_3(gl)	600-6000	30.5	0	0	0	0
$(HBO_2)_3$	1200-6000	67.4341	1.7731	-28.7114	22.4454	-6.2447
Be(g)	2500-6000	21.9304	-148.4244	435.4418	-428.4375	5.00
BeH	1200-6000	10.9483	-10.5468	24.1330	-28.6829	12.4894
BeCl	1200-6000	10.2809	-7.0561	16.9462	-19.4619	8.2700
$BeCl_2$	1200-6000	14.9066	-0.0294	-0.5268	-0.1476	0.1266
BeF	1200-6000	10.5587	-10.5803	28.9426	-36.5533	16.6245
BeF_2(g)	1200-6000	14.9061	-0.0226	-1.3434	-0.0556	0.2110
BeFCl	1200-6000	14.9098	-0.0631	-0.6087	-0.3033	0.2532
BeO(g)	1200-6000	9.9108	-5.0763	11.5275	-13.7951	5.9494

TABLE IV CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
$(BeO)_2$	1000-6000	19.981	0	-2.207	0	0
$(BeO)_3$	1000-6000	31.957	0	-3.278	0	0
$(BeO)_4$	1000-6000	43.870	0	-3.083	0	0
$(BeO)_5$	1000-6000	55.846	0	-4.154	0	0
$(BeO)_6$	1000-6000	67.760	0	-3.959	0	0
$Be(OH)_2$	1200-6000	26.7677	0.8694	-14.3231	12.1060	-3.2489
BeOH	1200-6000	13.8695	0.6035	-9.5250	8.8324	-2.7004
$Be(OH)_{2(S)}$	298-6000	35.211	0	-1.903	0	0
$Be_3N_{2(S)}$	800-2600	36.753	0	-3.067	0	0
Li_2	1200-6000	13.6444	-24.7845	60.3401	-68.3563	28.9873
LiH	1200-6000	11.8739	-15.4597	36.9991	-42.6350	18.1856
LiCl	1200-6000	8.9450	-0.0290	-0.0397	-0.1542	0.0844
$(LiCl)_2$	1000-6000	19.969	0	-1.969	0	0
$LiF_{(g)}$	1200-6000	10.8294	-9.9162	23.8040	-27.1839	11.5190
$(LiF)_2$	1000-6000	19.969	0	-1.969	0	0
$(LiF)_3$	1000-6000	31.788	0	-1.788	0	0
LiO	1200-6000	8.9422	0.0040	-0.7480	0.0737	0.0844
$Li_2O_{(g)}$	1200-6000	13.9102	0.0039	-1.7148	0.1367	0.2110
LiO_2	1200-6000	14.9121	-0.0823	-1.5936	-0.2421	0.4641
LiOH	1200-6000	13.8676	0.6242	-9.9390	8.8958	-2.6160
$(LiOH)_2$	1000-6000	31.735	0	-2.735	0	0
$LiCl_{(l)}$	1200-6000	15.2	0	0	0	0
$Mg_{(g)}$	2500-6000	25.8927	-188.3282	566.1888	-566.0000	0
MgH	1200-6000	11.8517	-15.3516	36.6664	-42.3675	18.1013
MgCl	1200-6000	10.5230	-8.3132	20.1329	-22.8263	9.6624
$MgCl_{2(g)}$	1200-6000	14.9119	-0.0885	0.1132	-0.4842	0.2532
MgF	1200-6000	10.2757	-7.0273	16.9432	-19.3802	8.2278
$MgF_{2(g)}$	1200-6000	14.9101	-0.0675	-0.2527	-0.3625	0.2110
MgFCl	1200-6000	14.9049	-0.0114	-0.3259	-0.0553	0.0422
$MgO_{(g)}$	1200-6000	10.3480	-7.4032	17.8101	-20.3834	8.6498
MgOH	1200-6000	13.8733	0.5641	-8.8582	8.6828	-2.7426
$MgCl_{2(S)}$	298-1100	19.917	0	-0.258	0	0
$Mg(OH)_{2(S)}$	298-6000	39.391	-13.946	2.293	0	0
ClF	1200-6000	20.7734	-97.8828	295.5712	-385.2596	182.2271
ClO	1200-6000	135.5942	-750.9014	1852.353	-2111.363	899.1561
$Li_{(g)}$	1200-6000	15.6816	-81.3779	231.0344	-287.9056	132.0276

CHAPTER VI

RESULTS

A. Summary of the Results

The performance of 100 prototype propellant systems has been evaluated, with each of the ten selected fuels being considered in combination with each of the ten oxidizers. All calculations were made at a combustion pressure of 1000 psi expanding to exhaust pressures of 14.696 psi (1 atmosphere), 2.0 psi, and 0.2 psi. The latter exhaust conditions were chosen to simulate high altitude operation where large nozzle area area ratios are desirable. The temperature, enthalpy, entropy, heat capacity, and molecular composition of the combustion products were determined for the chamber and each exhaust condition. Then, assuming shifting chemical equilibrium accompanied by complete phase equilibrium, the following performance parameters were evaluated:

(1) Specific impulse.
(2) Specific heat capacity ratio.
(3) Volumetric specific impulse.
(4) Thrust coefficient.
(5) Nozzle area ratio.

Also, the following parameters were evaluated for the condition of complete frozen equilibrium:

(1) Specific impulse.
(2) Characteristic exhaust velocity.
(3) Thrust coefficient.
(4) Nozzle area ratio.

Since the prime purpose of this study was to evaluate the chemical performance of prototype propellant systems, the shifting specific impulse has been considered the most important single parameter. As shown earlier, this represents the maximum energy attainable from a chemical propulsion

system. This, and some other significant parameters, have been plotted in a series of three graphs for each propellant system. The first presents both the shifting and frozen specific impulse as a function of the propellant composition for each of the three exhaust pressures. The second presents the corresponding exhaust temperatures at each exhaust pressure. Finally, the third graph presents the chamber temperature, the chamber molecular weight, and the characteristic exhaust velocity as a function of the propellant composition. These graphs constitute Appendix C. Unfortunately, the volume of output information from the computer was much too large to be incorporated in its entirety into this report. Two pages of output were obtained for each chemical formulation considered. However, since the complete output contains additional data which was not plotted, including the molecular composition, the complete output is presented for one fuel-to-oxidizer ratio of each propellant system. This constitutes Appendix D. The molecular composition is of particular importance since it indicates the relative concentrations of the various combustion products as well as those which were considered in making the calculations. It should be pointed out that 298°K constitutes a minimum temperature limit in the calculations. During the frozen flow expansion to 0.2 psi, the temperature dropped to this point in a few instances. In these cases, the true frozen exhaust temperature lies somewhere below 298°K. There is no maximum temperature limit to the calculations. A linear heat capacity is automatically assumed above the maximum temperature for which thermodynamic data are provided, if this temperature should be exceeded.

In addition to the compilation of data in Appendices C and D, the maximum shifting specific impulses of the various systems are summarized in six tables within this chapter. Each of the various oxidizers is listed, in order of its performance, with each of the fuels in Tables V, VI, and VII. These are for exhaust pressures of 14.7 psi, 2.0 psi, and 0.2 psi respectively. Conversely, in Tables VIII, IX, and X, the various fuels are tabulated in order of their performance with each oxidizer. The combustion temperature at the point of maximum specific impulse is also listed. These tables provide a concise presentation of the relative energy available from the various systems. Following these tables is a brief discussion of the more significant findings of this study. The discussion is subdivided by fuels.

Table V

Summary of Maximum Shifting Specific Impulse
pc = 1000 psi
P_e = 14.696 psi

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^oK
H_2	OF_2	85.5	411	3591
H_2	F_2	89	410	3964
H_2	O_2	78	391	2769
H_2	NF_3	93	351	3876
H_2	NO_2ClO_4	83	349	2713
H_2	ClO_3F	84	344	2744
H_2	N_2O_4	84	342	2660
H_2	H_2O_2	88	322	2404
H_2	ClF_3	92	318	3403
H_2	NH_4ClO_4	91	287	2448
N_2H_4	F_2	69	363	4688
N_2H_4	OF_2	60	345	4037
N_2H_4	NF_3	73	322	4242
N_2H_4	O_2	48	313	3409
N_2H_4	NO_2ClO_4	56	295	3363
N_2H_4	ClO_3F	59.5	295	3466
N_2H_4	ClF_3	73	293	3882
N_2H_4	N_2O_4	57	291	3257
N_2H_4	H_2O_2	67	286	2923
N_2H_4	NH_4ClO_4	73	265	2969
CH_2	OF_2	79	350	4650
CH_2	F_2	72.5	325	4382
CH_2	O_2	73	300	3683
CH_2	NF_3	78	287	3781
CH_2	ClO_3F	81	280	3722
CH_2	NO_2ClO_4	79	278	3586
CH_2	H_2O_2	86.5	277	2999
CH_2	N_2O_4	80	276	3444
CH_2	ClF_3	77	257	3541
CH_2	NH_4ClO_4	90.5	252	3016

Table V Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
UDMH	OF_2	72	351	4460
UDMH	F_2	71	344	4342
UDMH	O_2	63	310	3614
UDMH	NF_3	76	309	3964
UDMH	ClO_3F	73	290	3666
UDMH	NO_2ClO_4	70	289	3540
UDMH	N_2O_4	72	286	3429
UDMH	H_2O_2	81	283	3008
UDMH	ClF_3	75	280	3794
UDMH	NH_4ClO_4	85	259	3038
C_4N_2	O_2	49	302	4816
C_4N_2	N_2O_4	61	282	4224
C_4N_2	H_2O_2	75	280	3320
C_4N_2	OF_2	68	278	4061
C_4N_2	NO_2ClO_4	61	276	4272
C_4N_2	NH_4ClO_4	80	258	3333
C_4N_2	ClO_3F	62	255	3708
C_4N_2	F_2	85	253	3891
C_4N_2	NF_3	85	232	3680
C_4N_2	ClF_3	87	203	3404
B_5H_9	OF_2	80	367	5169
B_5H_9	F_2	82	360	5101
B_5H_9	O_2	70	327	4518
B_5H_9	NF_3	87	326	4809
B_5H_9	H_2O_2	73	316	3400
B_5H_9	ClO_3F	79	306	4447
B_5H_9	N_2O_4	77	306	4266
B_5H_9	NO_2ClO_4	78	302	4432
B_5H_9	ClF_3	88	290	4487
B_5H_9	NH_4ClO_4	82	285	3484
MgH_2	F2	72	329	4963
MgH_2	OF_2	79	305	4516
MgH_2	NF_3	78	302	4620
MgH_2	H_2O_2	39	280	3073
MgH_2	ClF_3	78	275	4465
MgH_2	O_2	31	270	3076
MgH_2	NH_4ClO_4	50	266	3073
MgH_2	N_2O_4	40	265	3073
MgH_2	NO_2ClO_4	38	263	3114
MgH_2	ClO_3F	46	260	3237

Table V Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^{o}K
AlH_3	F_2	73.5	353	5317
AlH_3	OF_2	59	333	4406
AlH_3	H_2O_2	48	326	3923
AlH_3	NF_3	78	323	4956
AlH_3	O_2	42	318	4299
AlH_3	N_2O_4	52	308	4226
AlH_3	NO_2ClO_4	49	305	4175
AlH_3	NH_4ClO_4	58	302	3837
AlH_3	ClO_3F	50	301	4029
AlH_3	ClF_3	77	291	4593
BeH_2	F_2	80.5	395	5331
BeH_2	OF_2	67	383	4347
BeH_2	H_2O_2	56.5	375	3574
BeH_2	O_2	54.5	371	4138
BeH_2	NF_3	81.5	359	4731
BeH_2	N_2O_4	50	351	3403
BeH_2	NO_2ClO_4	55	346	3394
BeH_2	NH_4ClO_4	62	340	3283
BeH_2	ClO_3F	68	339	4173
BeH_2	ClF_3	81.5	329	4500
LiH	F_2	82	363	4886
LiH	OF_2	77	337	4093
LiH	NF_3	85.5	319	4384
LiH	ClF_3	84	293	4109
LiH	ClO_3F	76	272	3351
LiH	O_2	66	263	3309
LiH	H_2O_2	81	262	2711
LiH	NO_2ClO_4	73	258	3292
LiH	NH_4ClO_4	85	250	2754
LiH	N_2O_4	74	250	3171

Table VI

Summary of Maximum Shifting Specific Impulse
pc = 1000 psi
p_e = 2.0 psi

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
H_2	OF_2	87	458	3756
H_2	F_2	92	457	4462
H_2	O_2	82	437	3182
H_2	NF_3	94.5	390	4212
H_2	NO_2ClO_4	86	389	3080
H_2	ClO_3F	87	383	3273
H_2	N_2O_4	86	381	2891
H_2	H_2O_2	91	359	2740
H_2	ClF_3	93.5	352	3690
H_2	NH_4ClO_4	92.5	319	2660
N_2H_4	F_2	69	408	4688
N_2H_4	OF_2	63	392	4100
N_2H_4	NF_3	73	357	4242
N_2H_4	O_2	49	355	3425
N_2H_4	NO_2ClO_4	58	333	3375
N_2H_4	ClO_3F	61	333	3478
N_2H_4	N_2O_4	59	329	3262
N_2H_4	ClF_3	73	325	3882
N_2H_4	H_2O_2	68	323	2916
N_2H_4	NH_4ClO_4	73	297	2969
CH_2	OF_2	79	393	4650
CH_2	F_2	72.5	371	4382
CH_2	O_2	73	344	3683
CH_2	NF_3	78	326	3781
CH_2	ClO_3F	82	319	3734
CH_2	NO_2ClO_4	81	318	3603
CH_2	N_2O_4	82	316	3453
CH_2	H_2O_2	88	315	2979
CH_2	ClF_3	77	291	3541
CH_2	NH_4ClO_4	91	287	3001

Table VI Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
UDMH	OF_2	75	400	4519
UDMH	F_2	71	393	4342
UDMH	O_2	65	354	3633
UDMH	NF_3	76	348	3964
UDMH	ClO_3F	75	329	3686
UDMH	NO_2ClO_4	73	328	3567
UDMH	N_2O_4	74	325	3433
UDMH	H_2O_2	81	321	3008
UDMH	ClF_3	75	314	3794
UDMH	NH_4ClO_4	86	293	3026
C_4N_2	O_2	52	342	4609
C_4N_2	N_2O_4	64	320	4127
C_4N_2	OF_2	68	320	4061
C_4N_2	H_2O_2	75	319	3320
C_4N_2	NO_2ClO_4	64	313	4168
C_4N_2	NH_4ClO_4	83	293	3264
C_4N_2	F_2	85	292	3891
C_4N_2	ClO_3F	62	289	3708
C_4N_2	NF_3	85	269	3680
C_4N_2	ClF_3	87	235	3404
B_5H_9	OF_2	80	422	5169
B_5H_9	F_2	84	413	5165
B_5H_9	O_2	70	379	4518
B_5H_9	NF_3	88	374	4841
B_5H_9	H_2O_2	73	361	3400
B_5H_9	ClO_3F	79	353	4447
B_5H_9	N_2O_4	79	353	4388
B_5H_9	NO_2ClO_4	79	350	4502
B_5H_9	ClF_3	88	333	4487
B_5H_9	NH_4ClO_4	73	330	3000
MgH_2	F_2	74	379	4991
MgH_2	OF_2	69	352	4404
MgH_2	NF_3	78	346	4620
MgH_2	H_2O_2	42	327	3073
MgH_2	O_2	33	316	3216
MgH_2	ClF_3	78	315	4465
MgH_2	NH_4ClO_4	50	311	3073
MgH_2	N_2O_4	44	310	3265
MgH_2	NO_2ClO_4	40	308	3124
MgH_2	ClO_3F	49	305	3390

Table VI Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Second	Tc, ^{o}K
AlH_3	F_2	75	405	5346
AlH_3	OF_2	62	386	4447
AlH_3	H_2O_2	48	378	3923
AlH_3	O_2	44	371	4299
AlH_3	NF_3	81	370	5006
AlH_3	N_2O_4	52	358	4226
AlH_3	NO_2ClO_4	51	355	4252
AlH_3	NH_4ClO_4	58	350	3837
AlH_3	ClO_3F	55	350	4204
AlH_3	ClF_3	80	333	4693
BeH_2	F_2	80.5	453	5331
BeH_2	OF_2	67	445	4347
BeH_2	H_2O_2	58	442	3708
BeH_2	O_2	53	436	4004
BeH_2	NF_3	81.5	413	4731
BeH_2	N_2O_4	50	411	3403
BeH_2	NO_2ClO_4	61	406	3866
BeH_2	NH_4ClO_4	62	398	3283
BeH_2	ClO_3F	68	396	4173
BeH_2	ClF_3	81.5	378	4500
LiH	F_2	82	410	4886
LiH	OF_2	77	386	4093
LiH	NF_3	85.5	360	4384
LiH	ClF_3	84	330	4109
LiH	ClO_3F	76	312	3351
LiH	O_2	66	306	3309
LiH	H_2O_2	81	304	2711
LiH	NO_2ClO_4	73	299	3292
LiH	NH_4ClO_4	85	289	2754
LiH	N_2O_4	74	290	3171

Table VII

Summary of Maximum Shifting Specific Impulse
pc = 1000 psi
p_e = 0.2 psi

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
H_2	OF_2	91	491	4149
H_2	F_2	94	489	4809
H_2	O_2	84	470	3374
H_2	NO_2ClO_4	87.5	416	3259
H_2	NF_3	94.5	413	4212
H_2	ClO_3F	90	409	3502
H_2	N_2O_4	89	408	3254
H_2	H_2O_2	92.5	385	2912
H_2	ClF_3	95	373	3985
H_2	NH_4ClO_4	94	340	2883
N_2H_4	F_2	69	436	4688
N_2H_4	OF_2	63	424	4100
N_2H_4	O_2	49	384	3425
N_2H_4	NF_3	73	379	4242
N_2H_4	NO_2ClO_4	58	359	3375
N_2H_4	ClO_3F	61	358	3478
N_2H_4	N_2O_4	59	354	3262
N_2H_4	H_2O_2	68	348	2916
N_2H_4	ClF_3	73	345	3882
N_2H_4	NH_4ClO_4	73	318	2969
CH_2	OF_2	79	420	4650
CH_2	F_2	74	405	4405
CH_2	O_2	75	379	3699
CH_2	NF_3	78	352	3781
CH_2	NO_2ClO_4	82.5	349	3587
CH_2	ClO_3F	85	347	3700
CH_2	N_2O_4	82	345	3453
CH_2	H_2O_2	88	344	2979
CH_2	ClF_3	77	315	3541
CH_2	NH_4ClO_4	91	309	3001

Table VII Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^{o}K
UDMH	OF_2	78	435	4510
UDMH	F_2	71	426	4342
UDMH	O_2	68	388	3626
UDMH	NF_3	76	373	3964
UDMH	ClO_3F	77	359	3678
UDMH	NO_2ClO_4	73	358	3567
UDMH	N_2O_4	74	354	3433
UDMH	H_2O_2	82	349	2992
UDMH	ClF_3	75	337	3794
UDMH	NH_4ClO_4	86	316	3026
C_4N_2	O_2	55	374	4475
C_4N_2	OF_2	65	355	4112
C_4N_2	N_2O_4	67	350	4034
C_4N_2	H_2O_2	78	350	3257
C_4N_2	NO_2ClO_4	67	342	4073
C_4N_2	F_2	85	325	3891
C_4N_2	NH_4ClO_4	83	319	3264
C_4N_2	ClO_3F	68	316	3488
C_4N_2	NF_3	85	301	3680
C_4N_2	ClF_3	87	261	3404
B_5H_9	OF_2	81.5	466	5215
B_5H_9	F_2	84	460	5165
B_5H_9	O_2	72	421	4620
B_5H_9	NF_3	89	413	4854
B_5H_9	H_2O_2	73	399	3400
B_5H_9	N_2O_4	79	391	4388
B_5H_9	ClO_3F	79	390	4447
B_5H_9	NO_2ClO_4	79	389	4502
B_5H_9	ClF_3	89	368	4543
B_5H_9	NH_4ClO_4	73	370	3000
MgH_2	F_2	74	420	4991
MgH_2	OF_2	65	394	4337
MgH_2	NF_3	78	380	4620
MgH_2	H_2O_2	42	368	3073
MgH_2	O_2	33	357	3216
MgH_2	N_2O_4	44	349	3265
MgH_2	NH_4ClO_4	53	348	3080
MgH_2	ClF_3	78	347	4465
MgH_2	NO_2ClO_4	43	346	3288
MgH_2	ClO_3F	49	343	3390

Table VII Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
AlH_3	F_2	77	447	5368
AlH_3	OF_2	62	431	4447
AlH_3	H_2O_2	48	424	3923
AlH_3	O_2	44	416	4374
AlH_3	NF_3	81	407	5006
AlH_3	N_2O_4	54	401	4292
AlH_3	NO_2ClO_4	51	397	4252
AlH_3	NH_4ClO_4	58	393	3837
AlH_3	ClO_3F	55	390	4204
AlH_3	ClF_3	80	367	4693
BeH_2	F_2	79	501	5194
BeH_2	H_2O_2	61	498	3884
BeH_2	OF_2	70	497	4527
BeH_2	O_2	53	492	4004
BeH_2	N_2O_4	52	462	3446
BeH_2	NF_3	81.5	456	4731
BeH_2	NO_2ClO_4	64	456	4132
BeH_2	NH_4ClO_4	62	446	3283
BeH_2	ClO_3F	68	446	4173
BeH_2	ClF_3	81.5	418	4500
LiH	F_2	82	445	4886
LiH	OF_2	77	424	4093
LiH	NF_3	85.5	392	4384
LiH	ClF_3	84	360	4109
LiH	ClO_3F	76	345	3351
LiH	O_2	66	342	3309
LiH	H_2O_2	81	341	2711
LiH	NO_2ClO_4	73	333	3292
LiH	NH_4ClO_4	63.5	326	2292
LiH	N_2O_4	74	325	3171

Table VIII

Summary of Maximum Shifting Specific Impulse
p_c = 1000 psi
p_e = 14.696 psi

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
F_2	H_2	89	410	3964
F_2	BeH_2	80.5	395	5331
F_2	LiH	82	363	4886
F_2	N_2H_4	69	363	4688
F_2	B_5H_9	82	360	5101
F_2	AlH_3	73.5	353	5317
F_2	UDMH	71	344	4342
F_2	MgH_2	72	329	4963
F_2	CH_2	72.5	325	4382
F_2	C_4N_2	85	253	3891
O_2	H_2	78	391	2769
O_2	BeH_2	54.5	371	4138
O_2	B_5H_9	70	327	4518
O_2	AlH_3	42	318	4299
O_2	N_2H_4	48	313	3409
O_2	UDMH	63	310	3614
O_2	C_4N_2	49	302	4816
O_2	CH_2	73	300	3683
O_2	MgH_2	31	270	3076
O_2	LiH	66	263	3309
OF_2	H_2	85.5	411	3591
OF_2	BeH_2	67	383	4347
OF_2	B_5H_9	80	367	5169
OF_2	UDMH	72	351	4460
OF_2	CH_2	79	350	4650
OF_2	N_2H_4	60	345	4037
OF_2	LiH	77	337	4093
OF_2	AlH_3	59	333	4297
OF_2	MgH_2	79	305	4516
OF_2	C_4N_2	68	278	4061

Table VIII Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^{o}K
H_2O_2	BeH_2	56.5	375	3574
H_2O_2	AlH_3	48	326	3923
H_2O_2	H_2	88	322	2404
H_2O_2	B_5H_9	73	316	3400
H_2O_2	N_2H_4	67	286	2923
H_2O_2	UDMH	81	283	3008
H_2O_2	MgH_2	39	280	3073
H_2O_2	C_4N_2	75	280	3320
H_2O_2	CH_2	86.5	277	2999
H_2O_2	LiH	81	262	2711
N_2O_4	BeH_2	50	351	3403
N_2O_4	H_2	84	342	2660
N_2O_4	AlH_3	52	308	4226
N_2O_4	B_5H_9	77	306	4266
N_2O_4	N_2H_4	57	291	3257
N_2O_4	UDMH	72	286	3429
N_2O_4	C_4N_2	61	282	4224
N_2O_4	CH_2	80	276	3444
N_2O_4	MgH_2	40	265	3073
N_2O_4	LiH	74	250	3171
NF_3	BeH_2	81.5	359	4731
NF_3	H_2	93	351	3876
NF_3	B_5H_9	87	326	4809
NF_3	AlH_3	78	323	4956
NF_3	N_2H_4	73	322	4242
NF_3	LiH	85.5	319	4384
NF_3	UDMH	76	309	3964
NF_3	MgH_2	78	302	4620
NF_3	CH_2	78	287	3781
NF_3	C_4N_2	85	232	3680
ClF_3	BeH_2	81.5	329	4500
ClF_3	H_2	92	318	3403
ClF_3	LiH	84	293	4109
ClF_3	N_2H_4	73	293	3882
ClF_3	AlH_3	77	291	4593
ClF_3	B_5H_9	88	290	4487
ClF_3	UDMH	75	280	3794
ClF_3	MgH_2	78	275	4465
ClF_3	CH_2	77	257	3541
ClF_3	C_4N_2	87	203	3404

Table VIII Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^{o}K
ClO_3F	H_2	84	344	2744
ClO_3F	BeH_2	68	339	4173
ClO_3F	B_5H_9	79	306	4447
ClO_3F	AlH_3	50	301	4029
ClO_3F	N_2H_4	59.5	295	3466
ClO_3F	CH_2	81	280	3722
ClO_3F	LiH	76	272	3351
ClO_3F	MgH_2	46	260	3237
ClO_3F	C_4N_2	62	255	3708
NO_2ClO_4	H_2	83	349	2713
NO_2ClO_4	BeH_2	55	346	3394
NO_2ClO_4	AlH_3	49	305	4175
NO_2ClO_4	B_5H_9	78	302	4432
NO_2ClO_4	N_2H_4	56	295	3363
NO_2ClO_4	UDMH	70	289	3540
NO_2ClO_4	CH_2	79	278	3586
NO_2ClO_4	C_4N_2	61	276	4272
NO_2ClO_4	MgH_2	38	263	3114
NO_2ClO_4	LiH	73	258	3292
NH_4ClO_4	BeH_2	62	340	3283
NH_4ClO_4	AlH_3	58	302	3837
NH_4ClO_4	H_2	91	287	2448
NH_4ClO_4	B_5H_9	82	285	3484
NH_4ClO_4	MgH_2	50	266	3073
NH_4ClO_4	N_2H_4	73	265	2969
NH_4ClO_4	UDMH	85	259	3038
NH_4ClO_4	C_4N_2	80	258	3333
NH_4ClO_4	CH_2	90.5	252	3016
NH_4ClO_4	LiH	82	249	2687

Table IX

Summary of Maximum Shifting Specific Impulse
P_c = 1000 psi
P_e = 2.0 psi

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
F_2	H_2	92	457	4462
F_2	BeH_2	80.5	453	5331
F_2	B_5H_9	84	413	5165
F_2	LiH	82	410	4886
F_2	N_2H_4	64	408	4688
F_2	AlH_3	75	405	5346
F_2	UDMH	71	393	4342
F_2	MgH_2	74	379	4991
F_2	CH_2	72.5	371	4382
F_2	C_4N_2	85	292	3891
O_2	H_2	82	437	3182
O_2	BeH_2	53	436	4004
O_2	B_5H_9	70	379	4518
O_2	AlH_3	44	371	4299
O_2	N_2H_4	49	355	3425
O_2	UDMH	65	354	3633
O_2	CH_2	73	344	3683
O_2	C_4N_2	52	342	4609
O_2	MgH_2	33	316	3216
O_2	LiH	66	306	3309
OF_2	H_2	87	458	3756
OF_2	BeH_2	67	445	4347
OF_2	B_5H_9	80	422	5169
OF_2	UDMH	75	400	4519
OF_2	CH_2	79	393	4650
OF_2	N_2H_4	63	392	4100
OF_2	LiH	77	386	4093
OF_2	AlH_3	62	386	4447
OF_2	MgH_2	69	352	4404
OF_2	C_4N_2	68	320	4061

Table IX Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^{o}K
H_2O_2	BeH_2	58	442	3708
H_2O_2	AlH_3	48	378	3923
H_2O_2	B_5H_9	73	361	3400
H_2O_2	H_2	91	359	2740
H_2O_2	MgH_2	42	327	3073
H_2O_2	N_2H_4	68	323	2916
H_2O_2	UDMH	81	321	3008
H_2O_2	C_4N_2	75	319	3320
H_2O_2	CH_2	88	315	2979
H_2O_2	LiH	81	304	2711
N_2O_4	BeH_2	50	411	3403
N_2O_4	H_2	86	381	2891
N_2O_4	AlH_3	52	358	4226
N_2O_4	B_5H_9	79	353	4388
N_2O_4	N_2H_4	59	329	3262
N_2O_4	UDMH	74	325	3433
N_2O_4	C_4N_2	64	320	4127
N_2O_4	CH_2	82	316	3453
N_2O_4	MgH_2	44	310	3265
N_2O_4	LiH	74	290	3171
NF_3	BeH_2	81.5	413	4731
NF_3	H_2	94.5	390	4212
NF_3	B_5H_9	88	374	4841
NF_3	AlH_3	81	370	5006
NF_3	LiH	85.5	360	4384
NF_3	N_2H_4	73	357	4242
NF_3	UDMH	76	348	3964
NF_3	MgH_2	78	346	4620
NF_3	CH_2	78	326	3781
NF_3	C_4N_2	85	269	3680
ClF_3	BeH_2	81.5	378	4500
ClF_3	H_2	93.5	352	3690
ClF_3	B_5H_9	88	333	4487
ClF_3	LiH	84	330	4109
ClF_3	AlH_3	80	333	4693
ClF_3	N_2H_4	73	325	3882
ClF_3	MgH_2	78	315	4465
ClF_3	UDMH	75	314	3794
ClF_3	CH_2	77	291	3541
ClF_3	C_4N_2	87	235	3404

Table IX Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^{o}K
ClO_3F	BeH_2	68	396	4173
ClO_3F	H_2	87	383	3273
ClO_3F	B_5H_9	79	353	4447
ClO_3F	AlH_3	55	350	4204
ClO_3F	N_2H_4	61	333	3478
ClO_3F	UDMH	75	329	3686
ClO_3F	CH_2	82	319	3734
ClO_3F	LiH	76	312	3351
ClO_3F	MgH_2	49	305	3390
ClO_3F	C_4N_2	62	289	3708
NO_2ClO_4	BeH_2	61	406	3866
NO_2ClO_4	H_2	86	389	3080
NO_2ClO_4	AlH_3	51	355	4252
NO_2ClO_4	B_5H_9	79	350	4502
NO_2ClO_4	N_2H_4	58	333	3375
NO_2ClO_4	UDMH	73	328	3567
NO_2ClO_4	CH_2	81	318	3603
NO_2ClO_4	C_4N_2	64	313	4168
NO_2ClO_4	MgH_2	40	308	3124
NO_2ClO_4	LiH	73	299	3292
NH_4ClO_4	BeH_2	62	398	3283
NH_4ClO_4	AlH_3	58	350	3837
NH_4ClO_4	B_5H_9	73	330	3000
NH_4ClO_4	H_2	92.5	319	2660
NH_4ClO_4	MgH_2	50	311	3073
NH_4ClO_4	N_2H_4	73	297	2969
NH_4ClO_4	UDMH	86	293	3026
NH_4ClO_4	C_4N_2	83	293	3264
NH_4ClO_4	LiH	82	288	2687
NH_4ClO_4	CH_2	91	287	3001

Table X

Summary of Maximum Shifting Specific Impulse
p_c = 1000 psi
p_e = 0.2 psi

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^{o}K
F_2	BeH_2	79	501	5194
F_2	F_2	94	489	4809
F_2	B_5H_9	84	460	5165
F_2	AlH_3	77	447	5368
F_2	LiH	82	445	4886
F_2	N_2H_4	69	436	4688
F_2	UDMH	71	426	4342
F_2	MgH_2	74	420	4991
F_2	CH_2	74	405	4405
F_2	C_4N_2	85	325	3891
O_2	BeH_2	53	492	4004
O_2	H_2	84	470	3374
O_2	B_5H_9	72	421	4620
O_2	AlH_3	44	416	4374
O_2	UDMH	68	388	3626
O_2	N_2H_4	49	384	3425
O_2	CH_2	75	379	3699
O_2	C_4N_2	55	374	4475
O_2	MgH_2	33	357	3216
O_2	LiH	66	342	3309
OF_2	BeH_2	70	497	4527
OF_2	H_2	91	491	4149
OF_2	B_5H_9	81.5	466	5215
OF_2	UDMH	78	435	4510
OF_2	AlH_3	62	431	4447
OF_2	N_2H_4	63	424	4100
OF_2	LiH	77	424	4093
OF_2	CH_2	79	420	4650
OF_2	MgH_2	65	394	4337
OF_2	C_4N_2	65	355	4112

Table X Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, ^{o}K
H_2O_2	BeH_2	61	498	3884
H_2O_2	AlH_3	48	424	3923
H_2O_2	B_5H_9	73	399	3400
H_2O_2	H_2	92.5	385	2912
H_2O_2	MgH_2	42	368	3073
H_2O_2	C_4N_2	78	350	3257
H_2O_2	UDMH	82	349	2992
H_2O_2	N_2H_4	68	348	2916
H_2O_2	CH_2	88	344	2979
H_2O_2	LiH	81	341	2711
N_2O_4	BeH_2	52	462	3446
N_2O_4	H_2	89	408	3254
N_2O_4	AlH_3	54	401	4292
N_2O_4	B_5H_9	79	391	4388
N_2O_4	N_2H_4	59	354	3262
N_2O_4	UDMH	74	354	3433
N_2O_4	C_4N_2	67	350	4034
N_2O_4	MgH_2	44	349	3265
N_2O_4	CH_2	88	344	2979
N_2O_4	LiH	74	325	3171
NF_3	BeH_2	81.5	456	4731
NF_3	H_2	94.5	413	4212
NF_3	B_5H_9	89	413	4854
NF_3	AlH_3	81	407	5006
NF_3	LiH	85.5	392	4384
NF_3	MgH_2	78	380	4620
NF_3	N_2H_4	73	379	4242
NF_3	UDMH	76	373	3964
NF_3	CH_2	78	352	3781
NF_3	C_4N_2	85	301	3680
ClF_3	BeH_2	81.5	418	4500
ClF_3	H_2	95	373	3985
ClF_3	B_5H_9	89	368	4543
ClF_3	AlH_3	80	367	4693
ClF_3	LiH	84	360	4109
ClF_3	MgH_2	78	347	4465
ClF_3	N_2H_4	73	345	2969
ClF_3	UDMH	75	337	3794
ClF_3	CH_2	77	315	3541
ClF_3	C_4N_2	87	261	3404

Table X Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
ClO_3F	BeH_2	68	446	4173
ClO_3F	H_2	90	409	3502
ClO_3F	AlH_3	55	390	4204
ClO_3F	B_5H_9	79	390	4447
ClO_3F	UDMH	77	359	3678
ClO_3F	N_2H_4	61	358	3478
ClO_3F	CH_2	85	347	3700
ClO_3F	LiH	76	345	3351
ClO_3F	MgH_2	49	343	3390
ClO_3F	C_4N_2	68	316	3488
NO_2ClO_4	BeH_2	64	456	4132
NO_2ClO_4	H_2	87.5	416	3259
NO_2ClO_4	AlH_3	51	397	4252
NO_2ClO_4	B_5H_9	79	389	4502
NO_2ClO_4	N_2H_4	58	359	3375
NO_2ClO_4	UDMH	73	358	3567
NO_2ClO_4	CH_2	82.5	349	3587
NO_2ClO_4	MgH_2	43	346	3288
NO_2ClO_4	C_4N_2	67	342	4073
NO_2ClO_4	LiH	73	333	3292
NH_4ClO_4	BeH_2	62	446	3283
NH_4ClO_4	AlH_3	58	393	3837
NH_4ClO_4	B_5H_9	73	370	3000
NH_4ClO_4	MgH_2	53	348	3080
NH_4ClO_4	H_2	94	340	2883
NH_4ClO_4	LiH	62	326	2227
NH_4ClO_4	C_4N_2	83	319	3264
NH_4ClO_4	N_2H_4	73	318	2969
NH_4ClO_4	UDMH	86	316	3026
NH_4ClO_4	CH_2	91	309	3001

B. Discussion of the Results

1. Liquid Hydrogen Systems

Both liquid fluorine and liquid oxygen difluoride were found to be excellent oxidizers for liquid hydrogen, with the latter yielding slightly higher maximum performance. On the fuel-rich side of maximum performance, oxygen difluoride is the superior oxidizer. However, the performance drops - off more gradually on the oxidizer-rich side using liquid fluorine. Combustion temperatures are comparable in both systems up to the point of maximum specific impulse. Beyond that, on the oxidizer-rich side, the H_2-F_2 system burns with the hotter flame. The prime energy source is the formation of HF, with the formation of H_2O also contributing in the H_2-OF_2 system. It is interesting to note that the maximum performance occurs on the fuel-rich side of stoichiometric combustion, indicating the value of hydrogen gas as a working fluid. In fact, dissociation is relatively slight in both systems on the fuel-rich side of peak performance, causing only a slight difference in the frozen and shifting specific impulse. However, as the systems become oxidizer-rich, the degree of chamber dissociation increases rapidly, and the spread between frozen and shifting performance increases accordingly.

Liquid oxygen rates closely behind oxygen difluoride and liquid fluorine as an energetic oxidizer for liquid hydrogen. Again, the maximum performance occurs on the fuel-rich side of stoichiometric combustion. Of course, the principal source of energy is the formation of water. Dissociation, and the corresponding spread between shifting and frozen impulse, increases

as the system becomes oxidizer-rich. The most significant difference between the H_2-O_2 system and previous two is the lower combustion temperature of H_2-O_2. Although somewhat higher performance may be achieved by oxidizing hydrogen to HF rather than to H_2O, a considerably hotter flame must be tolerated. This characteristic is also displayed by the other less-energetic oxidizers, in which nitrogen and chlorine serve as carrier atoms for oxygen and fluorine.

Next in order of performance are NF_3, NO_2ClO_4, ClO_3F, and N_2O_4. These four oxidizers are closely grouped, yielding maximum specific impulses of 351, 349, 344, and 341 seconds respectively at an exhaust pressure of one atmosphere. Furthermore, the shifting specific impulse spread is narrowed to five seconds at an exhaust pressure of 0.2 psi. The halogens, chlorine and fluorine, appear as HCl and HF in the products of combustion. Both constitute energy sources, although HCl is considerably less valuable in this respect. Also, its higher molecular weight makes it relatively less desirable as a working fluid. In each system, the peak performance still occurs on the fuel-rich side of stoichiometric combustion. This further illustrates the value of only partially oxidizing the hydrogen in order to obtain the maximum useful energy. In the H_2-NO_2ClO_4 and the H_2-N_2O_4 systems, most of the nitrogen appears as N_2 in the combustion products. However, upon reacting fuel-rich, considerable amounts of NH_3 are formed at the lower exhaust pressures. The lower pressures, coupled with the corresponding lower temperatures, promote the formation of this larger molecule. In each case, the spread between frozen and shifting specific impulse is considerably greater on the oxidizer-rich side of the performance

curve. As before, this is attributed to the greater degree of dissociation at the higher combustion temperatures.

Hydrogen peroxide and chlorine trifluoride constitute the next oxidizer performance plateau. Chemically, the H_2-H_2O_2 system differs from the H_2-O_2 system only in that the oxygen is partially reacted with hydrogen in H_2O_2. Whereas the heat-of-formation of liquid oxygen is -3.08 Kcal/mole at its boiling point, that of H_2O_2 is -44.84 Kcal/mole at 298°K. This means that a substantial amount of useful energy has been lost in H_2O_2. The loss in shifting specific impulse is 69 seconds at an exhaust pressure of 1 atmosphere, 78 seconds at 2.0 psi, and 85 seconds at 0.2 psi. Similarly, ClF_3 differs from NF_3 in that chlorine has replaced nitrogen as a carrier for fluorine. The more exothermic heat-of-formation for ClF_3 indicates that the Cl-F bond is stronger, and therefore less desirable in a propellant ingredient. The loss in maximum specific impulse is 33 seconds when exhausting to one atmosphere, 38 seconds at 2.0 psi, and 40 seconds at 0.2 psi. The lower molecular weight of nitrogen also contributes to these performance spreads.

Ammonium perchlorate was found to be the least energetic oxidizer for liquid hydrogen. This was to be expected in view of its relatively exothermic heat-of-formation of -69.42 Kcal/mole and the presence of both nitrogen and chlorine as carrier elements. The formation of H_2O and HCl constitute the principal energy sources. On the other hand, H_2 and N_2 are the principal unreacted working fluids. However, again large concentrations of NH_3 are obtained at the sub-atmospheric exhaust pressures when the stoichiometry is fuel-rich. The ClO_4 moiety is common to both ammonium

perchlorate and nitronium perchlorate. However, the marked superiority of NO_2ClO_4 as an oxidizer is quite apparent from the performance curves. This stems from the substantially more endothermic heat-of-formation of NO_2ClO_4 as well as the greater quantity of available oxygen. Ammonium perchlorate, like hydrogen peroxide, may be thought of as low-energy monopropellant since both hydrogen and oxygen are available in the same molecule for subsequent chemical reaction.

2. Hydrazine Systems

Using hydrazine as the rocket fuel, liquid fluorine is the most energetic oxidizer. Although N_2H_4 has an endothermic heat-of-formation, there is a substantial drop in performance caused by the introduction of nitrogen as a carrier element. Whereas the H_2-F_2 system yields a maximum Isp of 410 seconds at pc/pe = 68, the N_2H_4-F_2 system yields only 363 seconds. Chemically, the N_2H_4-F_2 system is comparable to the H_2-NF_3 system. Of these, the N_2H_4-F_2 system is superior because of the endothermic heat-of-formation of hydrazine. This points out the desirability of utilizing the most endothermic reactants for propellant ingredients, providing other considerations are equal. Furthermore, the endothermic heat-of-formation of hydrazine causes a higher flame temperature than using liquid hydrogen as the fuel. Subsequently, dissociation is greater and the spread between frozen and shifting Isp is greater, on a percentage basis. These generalizations apply to the use of each oxidizer with hydrazine.

Oxygen difluoride was found to be the second most energetic oxidizer for use with hydrazine. The principal exhaust products for this system are HF, H_2O, H_2, and N_2. Next in order of performance are nitrogen trifluoride

and liquid oxygen. Like the H_2-NF_3 and the N_2H_4-F_2 systems, the N_2H_4-NF_3 system is composed of only nitrogen, hydrogen, and fluorine. However, in this latter system nitrogen serves as a carrier for both hydrogen and fluorine. Consequently, the performance is lower. The still lower performance of N_2H_4-O_2, relative to N_2H_4-NF_3, indicates that the presence of nitrogen in the fuel is more detrimental when oxidizing with oxygen than when utilizing fluorine. This trend is maintained with the other oxidizers considered. Both ClO_3F and ClF_3, the other fluorine-containing oxidizers, ranked relatively more potent with hydrazine than with liquid hydrogen although the absolute performances were lower. Very little ammonia was present in the combustion products of the hydrazine-oxygen system, even on the fuel-rich side, despite the presence of large quantities of nitrogen and hydrogen gases. This was due to the higher exhaust temperatures in this system. In general, NH_3 is a significant exhaust specie only below 600°K at a pressure of 2.0 psi and only below 500°K at a pressure of 0.2 psi.

Perchloryl fluoride and nitronium perchlorate yielded equivalent performances with hydrazine. The presence of fluorine in ClO_3F offset the more endothermic heat-of-formation of NO_2ClO_4. With liquid hydrogen, the latter oxidizer was superior by 5-7 seconds. Furthermore, the presence of fluorine in ClO_3F accounted for a slightly higher combustion temperature, again offsetting the higher heat-of-formation of NO_2ClO_4. Neither system was very highly dissociated, even on the oxygen-rich sides. The maximum combustion temperatures occurred near the stoichiometry of maximum specific impulse.

Closely following perchloryl fluoride and nitronium perchlorate in order of performance are chlorine trifluoride, nitrogen tetroxide, and hydrogen peroxide respectively. The most noticeable contrast in the performance curves of the three systems is the sharp drop-off on the oxidizer-rich side of the ClF_3 system. In general, this is typical of the behavior of ClF_3 systems and, to a lesser extent, NF_3 systems. However, this is more pronounced with some of the other fuels, as will be shown later. Ammonium perchlorate is the least energetic oxidizer, for the same reasons cited previously.

3. Polyethylene Systems

Polyethylene, with the empirical formula $(CH_2)_x$, was chosen as the prototype fuel to represent the hydrocarbon family. Having the highest H/C ratio of any of the aliphatic hydrocarbons, CH_2 represents the maximum energy source from this family. Furthermore, its stoichiometry corresponds to that of diethylcyclohexane, $C_{10}H_{20}$, although the performance of the latter is somewhat less because of its slightly more exothermic heat-of-formation.

Oxygen difluoride was found to be the best oxidizer for CH_2. One of the prime reasons for this is the ideal stoichiometry for the formation of HF and CO as products of combustion. At the point of maximum specific impulse, the HF is slightly dissociated into H, F, and H_2 because of the high combustion temperature. In the CH_2-OF_2 system, greater performance is obtained by forming the maximum amount of HF and CO than by under-oxidizing in order to obtain hydrogen. By under-oxidizing, large quantities of solid carbon are formed in the exhaust. Over-oxidizing tends to promote

the formation of carbon dioxide as well as allowing F and F_2 to emerge uncombined. The spread between frozen and shifting impulse reaches a maximum at the point of maximum performance.

Next in order of performance is liquid fluorine. In this case, HF alone constitutes energy source with all the carbon emerging as the unreacted solid element. This further emphasizes the value of HF as a product of combustion. On the oxidizer-rich side of the system, solid carbon is still the predominant carbon-containing specie. Only small quantities of fluorocarbons were present in the exhaust. Liquid oxygen, the next best oxidizer, is distinctly inferior to either OF_2 or F_2. In the CH_2-O_2 system, the predominant chemical equilibrium is the water-gas shift reaction. During expansion, some of the carbon monoxide and water react to form carbon dioxide and hydrogen. Under-oxidizing reduces performance because CO and CO_2 do not supply sufficient energy to the low molecular weight hydrogen gas. On the other hand, over-oxidizing lowers performance because too much CO_2 and H_2O are present. Thus, more energy may be obtained from a hydrocarbon by its combustion with a combination of oxygen and fluorine than with either oxygen or fluorine alone.

Nitrogen trifluoride, perchloryl fluoride, nitronium perchlorate, hydrogen peroxide, and nitrogen tetroxide are closely grouped in the next energy level. At pc/pe = 68 the performance spread for this group is 11 seconds while at pc/pe = 5000 it is only 7 seconds. In view of this relatively small spread in specific impulse, the considerably higher density of NO_2ClO_4 makes it the best of the group for overall missile performance. Chemically, the ClO_3F-CH_2 system is the most complex with HF, HCl, H_2O, CO_2,

and CO all contributing useful energy. Completing the ranking of the oxidizers are ClF_3 and NH_4ClO_4. Maximum performance occurs in the ClF_3-CH_2 system near the point of maximum formation of HF and HCl. However, the large quantity of unreacted carbon makes the system unattractive from an energy standpoint.

With the exception of OF_2, every oxidizer behaves poorer with CH_2 than with N_2H_4. Of course, the performance is still lower than when reacting each oxidizer with liquid hydrogen. Thus, carbon appears less desirable than either hydrogen or nitrogen as a propellant ingredient, from the energy viewpoint. Also, oxygen appears to be essential for the energetic oxidation of carbon.

4. UDMH Systems

The use of unsymmetrical dimethyl hydrazine as a fuel introduces carbon, nitrogen, and hydrogen simultaneously into a propellant system. Although two of hydrazine's four hydrogen atoms are replaced by methyl groups in UDMH, there is less than 1 Kcal difference in the heat-of-formation of the two molecules. Thus, the relative performances of hydrazine and UDMH provide a good measure of the effect of carbon on performance.

Again, OF_2 is the best oxidizer with F_2 following closely. Liquid oxygen ranks third, but considerably below the first two. In fact, the UDMH-O_2 system exceeds the UDMH-NF_3 system by only one second at pc/pe = 68. However, at pc/pe = 5000 this spread is 15 seconds. This further shows that the presence of nitrogen is more detrimental to the C-H-O system than to the C-H-F system. In general, the same comments made previously on stoichiometry and reaction products apply here. In a C-H-O-N system, maximum performance

usually lies somewhere between balancing the reactants to CO and H_2O and to CO_2 and H_2O. In a C-H-F system, the greatest energy release occurs when all the hydrogen and fluorine combine to form HF.

The other oxidizers, in order of their performance with UDMH, are perchloryl fluoride, nitronium perchlorate, nitrogen tetroxide, hydrogen peroxide, chlorine trifluoride, and ammonium perchlorate. It is interesting to note that the performance of the various UDMH systems is only 3-6 seconds lower than that of corresponding hydrazine systems at pc/pe = 68 for any oxidizer containing oxygen. At pc/pe=5000, the difference is even less. In fact, the performance of UDMH-O_2 exceeds that of N_2H_4-O_2 at pc/pe = 5000. The same holds when NF_3, F_2, and ClF_3 are the oxidizers. Although the I_{sp} spread between UDMH and hydrazine varies from 13-19 seconds at pc/pe = 68, the variation is only 6-10 seconds at pc/pe = 5000. Chamber temperatures are slightly higher when UDMH is reacted with oxygen-containing oxidizers than when hydrazine is the fuel. The opposite is true when fluorine is the sole oxidizer. Although the presence of carbon in UDMH does not appreciably reduce the performance below that attainable from hydrazine, two compensating factors must be considered. One is the small change in heat-of-formation of the fuel. Usually, the addition of alkyl groups to a fuel makes its heat-of-formation more exothermic. The second factor is the greater percentage of hydrogen in UDMH. This tends to offset the deleterious effects of carbon.

In the UDMH-F_2, UDMH-NF_3, and UDMH-ClF_3 systems, practically all of the carbon emerged as the unreacted solid element. Even when operating oxidizer-rich, only small concentrations of fluorocarbons appeared. Of these, CF_4 was the predominant one. This increased in concentration as both temperature

and pressure decreased, but was always appreciably less than the concentration of solid carbon. The fluorocarbons appear to be very poor products of combustion, both as an energy source and as a working fluid.

5. Dicyanoacetylene Systems

Dicyanoacetylene constitutes a unique prototype fuel in that it has an unusually endothermic heat-of-formation and is composed of only carbon and nitrogen. Thus, eight of the ten C_4N_2 systems are void of hydrogen. With O_2, H_2O_2, N_2O_4, NO_2ClO_4, and NH_4ClO_4, the performance of C_4N_2 was found comparable to that of CH_2. However, the combustion temperatures were considerably hotter because of the relatively slight dissociation of the combustion products. When hydrogen was absent, CO and N_2 were the principal combustion products, and the maximum specific impulse occurred when reacting slightly oxygen-rich of this stoichiometry. The carbon nitrides CN and C_2N_2 were formed in only minor concentrations, being practically nonexistent except on the fuel-rich side of the C_4N_2-N_2O_4 system.

The presence of fluorine in these hydrogen-free systems caused a marked drop in performance. This was true even for CF_2 and ClO_3F in which oxygen also is present. Using F_2, NF_3, and ClF_3 as oxidizers, the fluorocarbons were the principal energy sources. In the chamber CF_3 was most predominant while CF_4 became increasingly more important as the temperature and pressure were reduced. Although combustion temperatures in excess of 3000°K were obtained, the performance was very poor. Thus, the C_4N_2 series emphasizes that oxygen is essential for the energetic oxidation of carbon and that a large endothermic heat-of-formation cannot surpass the value of hydrogen in a propellant formulation.

6. Pentaborane Systems

Pentaborane, one of five light metal hydrides selected for this study, represents the boron hydride family. Both oxygen difluoride and liquid fluorine were found to be excellent oxidizers for pentaborane. The former system yields a specific impulse of 367 seconds at an exhaust pressure of one atmosphere while the latter yields 360 seconds under the same conditions. However, the performance of the OF_2 - B_5H_9 system is contingent upon the formation of BOF as a product of combustion. Although this oxyhalide has never been isolated, the trimer has been synthesized and its heat-of-formation evaluated. Because of its relatively simple structure, the probability of BOF occurring in a high temperature equilibruim mixture is good. A heat-of-formation of -150 Kcal/mole at 298°K was used in this study. If BOF is not considered as a product of combustion, the maximum specific impulse of the OF_2-B_5H_9 drops to 350 seconds. This peak occurs at 77% by weight oxidizer and still constitutes a very energetic system. Both oxygen difluoride and liquid fluorine produce combustion temperatures in excess of 5000°K at their points of maximum specific impulse. Because of these high temperatures, both systems are highly dissociated. For the F_2-B_5H_9 system, HF and BF are the principal species in the chamber. During expansion through the nozzle, BF_3 and H_2 also become major products of combustion. This is particularly true at the sub-atmospheric exhaust pressures.

For the OF_2-B_5H_9 system, BOF and HF are the principal combustion products, with hydrogen gas increasing in concentration during expansion.

Both liquid oxygen and nitrogen trifluoride are also good oxidizers for pentaborane. Closely following is hydrogen peroxide. Although somewhat less energetic, the H_2O_2-B_5H_9 system has a combustion temperature approximately 1100°K less than that of O_2-B_5H_9 and approximately 1400°K less than that of NF_3-B_5H_9. The combustion products of the latter system were essentially the same as those of the F_2-B_5H_9 system, except nitrogen gas was also present. Metaboric acid, HBO_2, was the principal boron-containing specie not only in the O_2-B_5H_9 and H_2O_2-B_5H_9 systems but also in the others containing boron, oxygen, and hydrogen in the absence of fluorine. Liquid boric oxide becomes a major specie only when operating fuel-rich at lower temperatures.

Nitrogen tetroxide, perchloryl fluoride, and nitronuim perchlorate constitute the next performance plateau with chlorine trifluoride and ammonuim perchlorate being the least energetic. Despite the strong affinity of boron for fluorine, chlorine trifluoride is not a particularly potent oxidizer for the boron hydrides. This constitutes still further evidence of the undesirability of the Cl-F bond in propellant ingredients relative to the N-F or O-F bond. The oxidizers N_2O_4, NO_2ClO_4, and NH_4ClO_4 possess gradually-sloping performance curves on the fuel-rich side of maximum performance. This may be attributed to the formation of crystalline boron nitride and liquid boric oxide under these conditions.

When oxidizing pentaborane with F_2, NF_3, or ClF_3, the maximum specific impulse occurs near the stoichiometry for which all the boron and fluorine exist as BF_3. When oxygen is the only oxidizer, the stoichiometric reaction of all the boron and oxygen to HBO_2 will define the peak performance very

closely. In the OF_2-B_5H_9 system, maximum performance occurs near the point of stoichiometric reaction to HF and BOF.

Whereas fluorine has a very strong affinity for boron, that of chlorine is not as great. Large concentrations of the boron chlorides are rare, with hydrogen chloride being formed in preference. Also, the boron interhalides are not formed in large quantities relative to the boron fluorides.

7. Aluminum Hydride Systems

In general, the performance of aluminum hydride with the various oxidizers closely parallels that of pentaborane. The most noticeable differences are OF_2, O_2, H_2O_2, and NH_4ClO_4. Whereas the first two oxidizers are superior with pentaborane, the latter two yields higher performances with AlH_3. Combustion temperatures are also comparable, with those for the AlH_3 systems tending to be slightly higher.

The principal energy source of the aluminum-oxygen systems is condensed Al_2O_3, which has a highly exothermic heat-of-formation. Hydrogen gas is the main constituent of the working fluid. Using O_2, H_2O_2, N_2O_4, and NH_4ClO_4 as oxidizers for AlH_3, the maximum specific impulse occurs near the stoichiometry for which all the aluminum and oxygen react to Al_2O_3. The peak performance of the NO_2ClO_4-AlH_3 system is defined by reacting stoichiometrically to Al_2O_3 and AlCl.

Using fluorine as the oxidizer for aluminum, the point of maximum performance is more difficult to predict. With F_2, NF_3, and ClF_3, the peak performance occurs between reacting to AlF_3 and AlF_3 plus HF. The reaction products are usually highly dissociated, with AlF, AlF_2, and AlF_3

all existing in appreciable quantities. The first of these predominates in the chamber while the last is most significant at exhaust conditions. Of course, HF also exists in large concentrations, particularly in the c... ber. During expansion, the quantity of HF decreases in favor of AlF_3. In the AlH_3-ClF_3 system, the aluminum chlorides and mixed halides are formed. The oxyhalide AlOF is a minor specie and does not possess the same importance of its boron counterpart, BOF.

As in the case of boron, fluorine appears superior to oxygen as an oxidizer for aluminum. Liquid fluorine ranks as the best oxidizer for aluminum hydride, followed by OF_2, H_2O_2, NF_3, and O_2. Closely grouped behind these oxidizers are N_2O_4, NO_2ClO_4, ClO_3F, and NH_4ClO_4. It is interesting to note that ammonium perchlorate is almost as good an oxidizer as nitronium perchlorate and nitrogen tetroxide with AlH_3. This is probably due, in part, to the relatively small quantities of hydrogen available for working fluid in the latter two systems. Since Al_2O_3 is a relatively large molecule with a molecular weight of 102, a considerable amount of low molecular weight gas must accompany its formation to obtain high performance. Thus, if another source of working fluid, such as H_2 or N_2H_4, were added to the AlH_3-N_2O_4 and AlH_3-NO_2ClO_4 systems, the performance could probably be increased. The fact that hydrogen peroxide excels over liquid oxygen as an oxidizer for AlH_3 further emphasizes the importance of having large quantities of working fluid to accompany the formation of highly exothermic condensed phases, such as Al_2O_3.

The spread between frozen and shifting specific impulse is considerably greater in the aluminum-fluorine systems than in the aluminum-

oxygen systems. Upon expanding to sub-atmospheric exhaust pressures, this spread becomes greater.

8. Beryllium Hydride Systems

Beryllium hydride was found to be an extremely energetic fuel. Only liquid hydrogen yielded greater performance at pc/pe = 68 with the oxidizers F_2, O_2, OF_2, and NO_2ClO_4. However, at pc/pe = 5000 beryllium hydride was the most energetic fuel in every case. Under these conditions the BeH_2-F_2 system yielded a maximum specific impulse of 501 seconds, exceeding that of the H_2-F_2 system by 12 seconds.

Using fluorine as the oxidizer for beryllium hydride, the principal combustion products are BeF_2 and H_2. Because of the high combustion temperatures, a significant degree of dissociation exists in the chamber. Hydrogen atoms, beryllium gas, and hydrogen fluoride are each present in fairly large amounts. Upon expansion, these shift to form BeF_2 and H_2, releasing considerable energy in the process. The maximum performance occurs near the point at which all beryllium and fluorine react to form BeF_2. Liquid fluorine, nitrogen trifluoride, and chlorine trifluoride each follow this pattern.

With oxygen as the oxidizer for beryllium hydride, the principal combustion products are condensed beryllium oxide and hydrogen. As in the case of the aluminum-oxygen system, large quantities of working fluid must accompany the formation of the highly exothermic BeO in order to realize the optimum performance. This is illustrated by the fact that hydrogen peroxide yields greater performance than liquid oxygen with beryllium hydride, and ammonium perchlorate is almost as energetic as

nitronium perchlorate. In the beryllium-oxygen system, the maximum specific impulse was found to occur on the fuel-rich side of stoichiometric combustion to BeO. This varied from 5% by weight oxidizer in the case of the BeH_2-H_2O_2 system to 18% in the case of the BeH_2-N_2O_4 system. The beryllium systems are different from the other metal hydride systems in that fairly significant quantities of the metallic gas exists at the point of maximum specific impulse. Like hydrogen gas, the beryllium gas serves as additional working fluid to which the energy of formation of BeO may be transferred. Furthermore, when nitrogen was present in the oxidizer, significant quantities of solid beryllium nitride were present at the point of maximum specific impulse. The affinity of beryllium for chlorine was also found to be quite high. In the chamber, BeCl replaces HCl as the predominant chloride, particularly at high temperatures. In the exhaust, $BeCl_2$ is the principal chloride. The gaseous polymers of the beryllium oxide were found to exist in relatively small quantities, having only a very slight, if not negligible, influence on performance. The principal beryllium-oxygen gas specie is beryllium hydroxide, BeOH. Another feature of the beryllium systems is the relatively higher performance available upon expanding to low pressures. The gain in performance over the other light metal systems is greater at the lower exhaust pressures.

Like the other chemical systems studied, the spread between frozen and shifting specific impulse is considerably greater when carrier elements, such as nitrogen and chlorine, are not present. The spread varies from as much as 40 seconds in the BeH_2-F_2 system to as little as 10 seconds in the BeH_2-NH_4ClO_4 system.

9. Lithium Hydride Systems

Lithium hydride was found to be considerably more energetic with fluorine than with oxygen. In fact, liquid fluorine, oxygen difluoride, nitrogen tetroxide, and chlorine trifluoride all yielded substantially higher performance with lithium hydride than did any of the all-oxygen oxidizers. Combustion temperatures ranged between 4000°K and 5000°K. The spread in performance was relatively small for liquid oxygen, hydrogen peroxide, nitronium perchlorate, ammonium perchlorate, and nitrogen tetroxide, varying from 263 to 250 seconds at pc/pe = 68.

The maximum specific impulse of the LiH-F_2 and LiH-NF_3 systems occurs near the point of stoichiometric combustion to LiF and HF. However, peak performance for the interhalide ClF_3 is defined by stoichiometric combustion to HF, LiF, and LiCl. The affinity of chlorine for lithium appears stronger than for any of the other light metals. Lithium chloride is the principal chlorine-containing specie in the products of combustion. Both LiF and HF are highly exothermic energy sources as well as fairly low molecular weight working fluids. The dimer and trimer of lithium fluoride become significant exhaust species at low pressures and temperatures. Although their concentrations are negligible in the combustion chamber, these polymers may constitute more than 50% of the lithium fluoride at the sub-atmospheric exhaust conditions. The dimer of lithium chloride was found to be considerably less significant.

For the oxygen-containing oxidizers, maximum performance usually occurs near the point of stoichiometric combustion to Li_2O and H_2O.

One exception is hydrogen peroxide, for which the peak is very close to stoichiometric combustion to LiOH and H_2O. In all of these systems, lithium hydroxide is the principal lithium-containing gas specie. Liquid lithium oxide and water are the other major products of combustion. Upon reacting fuel-rich, considerable quantities of hydrogen gas are also evolved. This accounts for the gradual slope of the performance curves over the fuel-rich composition range. Once again H_2O_2 and NH_4ClO_4, with relatively exothermic heats-of-formation, yield almost as much performance as their more oxygen-rich counterparts, O_2 and NO_2ClO_4. Again this points out the necessity for a low molecular weight working fluid to accompany the formation of an exothermic condensed phase, such as liquid lithium oxide. Although lithium hydride is competitive with pentaborane, aluminum hydride and hydrazine when reacted with F_2, NF_3, and ClF_3, it is quite inferior with the oxygen-containing oxidizers.

10. Magnesium Hydride Systems

Magnesium hydride was found to be somewhat like lithium hydride in that superior performance is obtained by oxidizing with fluorine. However, this effect is not as pronounced as with lithium hydride. Although liquid fluorine yielded the greatest performance with magnesium hydride, this was not exceptionally energetic. At $p_c/p_e = 68$, a maximum specific impulse of 329 seconds was obtained. This occurred near the point of stoichiometric combustion to MgF_2 and HF. The same held for the NF_3-MgH_2 system. With chlorine trifluoride, maximum performance was achieved by reacting to HF, HCl, and MgF_2.

Hydrogen peroxide yielded the best performance of the oxygen-containing oxidizers. Closely grouped behind were O_2, NH_4ClO_4, N_2O_4 and NO_2ClO_4 respectively. Again, the lack of low molecular weight working fluid limited the usefulness of O_2 and NO_2ClO_4. Condensed magnesium oxide, hydrogen gas, water, and magnesium hydroxide constituted the principal combustion products. The first two are particularly predominant over the entire range of combustion stoichiometry. As in the case of lithium and beryllium, the predominant gas metal-oxygen specie was the metallic hydroxide. One outstanding characteristic of the magnesium-oxygen systems is the very gradual slope of the performance curves over relatively wide ranges of composition.

11. General Conclusions

Of the non-metallic fuels, liquid hydroger was found to yield the greatest performance with each of the ten oxidizers. This was to be expected because of the energetic reactions of hydrogen with both oxygen and fluorine. In most cases, the remaining order of performance was hydrazine, UDMH, polyethylene, and dicyanoacetylene. From this, it may be concluded that the N-H bond is more desirable than the C-H bond in a rocket fuel. Most important of all is that the hydrogen content of the fuel be high. Even the presence of a highly endothermic reactant, such as dicyanoacetylene, cannot overcome the value of hydrogen as in ingredient element. Of the metallic fuels, beryllium hydride was clearly superior, both with fluorine and oxygen as oxidizers. Pentaborane and aluminum hydride were found to be highly energetic with both oxygen and fluorine. Lithium appears to be a desirable fuel ingredient if oxidized

with fluorine. However, neither lithium nor magnesium yields high performance if combined with oxygen.

Both fluorine and oxygen difluoride were found to be highly energetic oxidizers. Thus, it may be concluded that fluorine or mixtures of fluorine and oxygen yield greater performance than oxygen alone. An exception occurs when the carbon-to-hydrogen ratio of the ingredients is large. With both metallic and non-metallic fuels, the performance of oxygen difluoride exceeded that of nitrogen trifluoride which, in turn, surpassed that of chlorine trifluoride. These data indicate that O-F bonding, N-F bonding, and Cl-F bonding are preferred in that order.

The relative ranking of the propellant systems at an exhaust pressure of one atmosphere was not always the same at the lower exit pressures. For example, although BeH_2 was the most energetic fuel in six of the ten cases at pc/pe = 68, it excelled in all ten cases at pc/pe = 5000. In general, expansion to sub-atmospheric pressures yielded relatively more performance for the metallic fuels. Any similar changes in the ranking of the oxidizers was not as sharply pronounced.

APPENDICES

APPENDIX A

SAMPLE CALCULATION USING THE METHOD OF EQUILIBRIUM CONSTANTS

1. Statement of the Problem

Ingredient	Weight %	Moles/100 gm Propellant	MW	ΔH_{f298} Kcal/mole	ρ g/cc
NH_4ClO_4	62	0.5277	117.497	-69.42	1.95
Al	23	0.8528	26.97	0	2.7
$(CH_2)_x$	15	1.0694	14.026	0	0.78

Chamber Pressure = 1000 PSIA

Exhaust Pressure = 14.7 PSIA

Density of Propellant = 1.7715 g/cc

Heat-of-Formation of Propellant = -36.633 Kcal/100 gm

Concentration of Ingredients per 100 gm propellant:

C = 1.0694 gm-atoms

H = 4.2496 gm-atoms

O = 2.1107 gm-atoms

N = 0.5277 gm-atoms

Cl = 0.5277 gm-atoms

Al = 0.8528 gm-atoms

2. Mass Balances and Chemical Equilibrium

In solving this problem on a high-speed digital computer, all products of combustion which could exist would be considered until proven to exist in negligible quantities. However, this rigorous approach is not feasible when using a desk calculator. Therefore, the following species are selected for consideration in this sample calculation: H, Cl, Al(g), CO, CO_2, H_2O, H_2,

HCl, N_2, AlO, Al_2O, AlCl, $AlCl_3$, $Al_2O_{3(s)}$, and $Al_2O_{3(l)}$. Since, in all probability, aluminum oxide will exist in only one condensed phase in the chamber and one condensed phase at the nozzle exit, this propellant system can be solved by 14 simultaneous equations.

The mass balances are:

$$\Sigma H = 4.2496 = n_H + 2n_{H_2} + 2n_{H_2O} + n_{HCl}$$

$$\Sigma C = 1.0694 = n_{CO} + n_{CO_2}$$

$$\Sigma N = 0.5277 = 2n_{N_2}$$

$$\Sigma Cl = 0.5277 = n_{Cl} + n_{HCl} + 3n_{AlCl_3} + n_{AlCl}$$

$$\Sigma Al = 0.8528 = n_{Al(g)} + n_{AlO} + 2n_{Al_2O} + n_{AlCl} + n_{AlCl_3} + 2n_{Al_2O_{3(l)}} + 2n_{Al_2O_{3(s)}}$$

$$\Sigma O = 2.1107 = n_{CO} + 2n_{CO_2} + n_{H_2O} + n_{AlO} + n_{Al_2O} + 3n_{Al_2O_{3(l)}} + 3n_{Al_2O_{3(s)}}$$

The equations of chemical equilibria may be written as:

a. $CO + H_2O \rightleftharpoons CO_2 + H_2$ $\qquad \Delta n = 0$

$$K_{p_1} = \frac{P_{CO_2} \cdot P_{H_2}}{P_{CO} \cdot P_{H_2O}} = \frac{n_{CO_2} \cdot n_{H_2}}{n_{CO} \cdot n_{H_2O}}$$

b. $1/2\ H_2 \rightleftharpoons H$ $\qquad \Delta n = 1/2$

$$K_{p_2} = \frac{P_H}{P_{H_2}^{1/2}} = \frac{n_H}{n_{H_2}^{1/2}} \left[\frac{P_T}{n_T}\right]^{1/2}$$

c. $HCl \rightleftharpoons Cl + 1/2H_2$ $\qquad \Delta n = 1/2$

$$K_{p_3} = \frac{P_{Cl} \cdot P_{H_2}^{1/2}}{P_{HCl}} = \frac{n_{Cl} \cdot n_{H_2}^{1/2}}{n_{HCl}} \left[\frac{P_T}{n_T}\right]^{1/2}$$

d. $1/2\ Al_2O_{3(l)} + 1/2\ CO \rightleftharpoons AlO_{(g)} + 1/2\ CO_2$ $\quad \Delta n = 1$

$$K_{p_4} = \frac{P_{AlO} \cdot P_{CO_2}^{1/2}}{P_{CO}^{1/2}} = \frac{n_{AlO} \cdot n_{CO_2}^{1/2}}{n_{CO}^{1/2}} \left[\frac{P_T}{n_T}\right]^1$$

e. $2AlO + CO \rightleftharpoons Al_2O_{(g)} + CO_2$ $\quad \Delta n = 1$

$$K_{p_5} = \frac{P_{Al_2O} \cdot P_{CO_2}}{P_{AlO}^2 \cdot P_{CO}} = \frac{n_{Al_2O} \cdot n_{CO_2}}{n_{AlO}^2 \cdot n_{CO}} \cdot \frac{n_T}{P_T}$$

f. $AlO + CO \rightleftharpoons Al_{(g)} + CO_2$ $\quad \Delta n = 0$

$$K_{p_6} = \frac{P_{Al} \cdot P_{CO_2}}{P_{AlO} \cdot P_{CO}} = \frac{n_{Al} \cdot n_{CO_2}}{n_{AlO} \cdot n_{CO}}$$

g. $Al + 3Cl \rightleftharpoons AlCl_3$ $\quad \Delta n = -3$

$$K_{p_7} = \frac{P_{AlCl_3}}{P_{Al} \cdot P_{Cl}^3} = \frac{n_{AlCl_3}}{n_{Al} \cdot n_{Cl}^3} \left[\frac{n_T}{P_T}\right]^3$$

h. $AlCl \rightleftharpoons Al + Cl$ $\quad \Delta n = 1$

$$K_{p_8} = \frac{P_{Al} \cdot P_{Cl}}{P_{AlCl}} = \frac{n_{Al} \cdot n_{Cl}}{n_{AlCl}} \cdot \frac{P_T}{n_T}$$

3. Chamber Composition Iteration

At an assumed combustion temperature, the chamber composition is calculated. Although general methods of iteration utilizing general equations of equilibrium and matrix techniques are preferred for use on computers, algebraic routines are faster for desk calculator solutions. Therefore, this illustrative example will be solved using trial-and-error algebraic iteration.

An initial combustion temperature of 3500°K is assumed. At 3500°K, the equilibrium constants for the previously chosen equilibrium reactions are:

$$K_1 = K_W = 0.1248$$

$$K_2 = K_H = 0.5888$$

$$K_3 = K_{HCl} = 0.3937$$

$$K_4 = K_{AlO} = 0.04746$$

$$K_5 = K_{Al_2O} = 0.1722$$

$$K_6 = K_{Al} = 0.01564$$

$$K_7 = K_{AlCl_3} = 1.177$$

$$K_8 = K_{AlCl} = 0.1145$$

An initial estimate of n_T, the total moles of gaseous products, is

$$n_T = 1/2(\Sigma Cl + \Sigma H + 2\Sigma C + \Sigma Al + \Sigma N)$$

$$n_T = 4.1483 \text{ moles}$$

Also, the initial estimate of n_{H_2} is

$$n_{H_2} = 0.45\ (\Sigma H - \Sigma Cl + 3\Sigma Al - \Sigma O + \Sigma C)$$

$$n_{H_2} = 2.3576$$

Then,

$$\frac{n_T}{p_T} = \frac{4.1483 \text{ moles}}{1000 \text{ PSI} \times 1 \text{ atm}/14.7 \text{ PSI}} = 0.061004$$

$$\left[\frac{n_T}{p_T}\right]^{1/2} = 0.2470 \qquad \left[\frac{p_T}{n_T}\right]^{1/2} = 4.0486$$

Evaluating H,

$$n_H = K_2\ (n_{H_2}{}^{1/2})\left(\frac{n_T}{p_T}\right)^{1/2} = (0.5888)\ (1.5354)\ (0.2470) = 0.2233$$

Evaluating HCl and Cl,

$$\Sigma Cl = 0.5277 = n_{Cl} + n_{HCl} + 3n_{AlCl_3} + n_{AlCl}$$

Initially, assume that all chlorine exists as HCl or Cl.

$$\frac{n_{HCl}}{n_{Cl}} = \frac{(n_{H_2}^{1/2})}{K_3}\left(\frac{p_T}{n_T}\right)^{1/2} = \frac{1.5354}{0.3937}(4.0486) = 15.7892$$

$$n_{Cl} = \frac{\Sigma Cl}{\left(\frac{n_{HCl}}{n_{Cl}} + 1\right)} = \frac{0.5277}{16.7892} = 0.0314$$

$$n_{HCl} = 0.4963$$

Evaluating H_2O,

$$\Sigma H = 4.2496 = n_H + 2n_{H_2} + 2n_{H_2O} + n_{HCl}$$

$$n_{H_2O} = 1/2\ (\Sigma H - 2n_{H_2} - n_H - n_{HCl}) = -0.5926$$

However, it would be physically impossible to have a negative quantity of water present. This means that the original estimates of n_T and n_{H_2}, especially the latter, were too large. Assume a 5% smaller n_T and a 20% smaller n_{H_2} and re-calculate.

Let $n_T = (4.1483)\ (0.95) = 3.9409$ moles

$n_{H_2} = (2.3576)\ (0.80) = 1.8861$ moles

$$\frac{n_T}{p_T} = \frac{3.9409}{68\ \text{atm}} = 0.057954$$

$$\left[\frac{n_T}{p_T}\right]^{1/2} = 0.24074 \qquad \left[\frac{p_T}{n_T}\right]^{1/2} = 4.1538$$

Re-evaluating H,

$$n_H = K_2\ (n_{H_2}^{1/2})\left[\frac{n_T}{p_T}\right]^{1/2} = (0.5888)\ (1.3734)\ (0.24074) = 0.1947$$

Re-evaluating HCl and Cl,

$$\frac{n_{HCl}}{n_{Cl}} = \frac{n_{H_2}^{1/2}}{K_3}\left[\frac{p_T}{n_T}\right]^{1/2} = \frac{1.3734}{0.3937}(4.1538) = 14.4903$$

$$n_{Cl} = \frac{\Sigma Cl}{\left(\frac{n_{HCl}}{n_{Cl}} + 1\right)} = \frac{0.5277}{15.4903} = 0.0341$$

$n_{HCl} = 0.4936$

Re-evaluating H_2O,

$$n_{H_2O} = 1/2\ (\Sigma H - 2n_{H_2} - n_H - n_{HCl}) = -0.1055$$

Again, this is a physical impossibility. This time n_{H_2} will be assumed 10% smaller than before while n_T remains 3.9409 moles.

$$n_{H_2} = (1.8861)\ (0.90) = 1.6975 \qquad n_{H_2}^{1/2} = 1.3029$$

Re-evaluating H,

$$n_H = K_2\ (n_{H_2}^{1/2}) \left(\frac{n_T}{p_T}\right)^{1/2} = (0.5888)\ (1.3029)\ (0.24074) = 0.1849$$

Re-evaluating HCl and Cl,

$$\frac{n_{HCl}}{n_{Cl}} = \frac{1.3029}{0.3937}\ (4.1538) = 13.7464$$

$$n_{Cl} = \frac{0.5277}{14.7464} = 0.0358 \qquad n_{HCl} = 0.4919$$

Re-evaluating H_2O,

$$n_{H_2O} = 1/2\ (\Sigma H - 2n_{H_2} - n_H - n_{HCl}) = 0.0889$$

Since water is now present in realistic quantities, the iteration my be continued to other species.

Evaluating CO and CO_2,

$$\frac{n_{CO_2}}{n_{CO}} = K_1 \frac{n_{H_2O}}{n_{H_2}} = 0.1248\ \frac{0.0889}{1.6975} = 0.0065359$$

$$\frac{n_{CO_2}}{1.0694 - n_{CO_2}} = 0.0065359$$

$$n_{CO_2} = 0.00694 \text{ and } n_{CO} = 1.0625$$

Evaluating AlO,

$$n_{AlO} = K_4\left[\frac{n_{CO}}{n_{CO_2}}\right]^{1/2}\left[\frac{n_T}{p_T}\right]^1 = \left[\frac{1.0625}{0.00694}\right]^{1/2} (.04746)\ (.057954) = 0.03403$$

Evaluating Al_2O,

$$n_{Al_2O} = (n_{AlO})^2\ (K_5)\ \frac{n_{CO}}{n_{CO_2}} \cdot \frac{p_T}{n_T} = (.03403)^2\ (.1722)\ (153.10)\ (17.255) = 0.5269$$

However, this is another physical impossibility since $2n_{Al_2O} \geq Al$. The concentrations of AlO and Al_2O are greatly affected by the ratio $\frac{n_{CO}}{n_{CO_2}}$. Therefore, this ratio will be introduced as a third unknown variable to facilitate rapid convergance of the aluminum balance. Next, assume

$$\frac{n_{CO}}{n_{CO_2}} = 75. \qquad \left[\frac{n_{CO}}{n_{CO_2}}\right]^{1/2} = 8.66.$$

Re-evaluating AlO,

$$n_{AlO} = K_4\left[\frac{n_{CO}}{n_{CO_2}}\right]^{1/2}\left[\frac{n_T}{p_T}\right]^1 = (.04746)\ (8.66)\ (.057954) = 0.02382$$

Re-evaluating Al_2O,

$$n_{Al_2O} = K_5\ (n_{AlO})^2\ \frac{n_{CO}}{n_{CO_2}} \cdot \frac{p_T}{n_T} = (.1722)\ (.02382)^2 (75.0)\ (17.255) = 0.1264$$

Then, other species are:

$$n_{Al} = (n_{AlO})\ (K_6)\ \frac{n_{CO}}{n_{CO_2}} = (.02382)\ (.01564)\ (75.0) = 0.02794$$

$$n_{AlCl} = \frac{n_{Al} \cdot n_{Cl}}{K_8}\ \frac{p_T}{n_T} = \frac{(.02794)\ (.0358)}{0.1145}\ (17.255) = 0.1507$$

$$n_{AlCl_3} = (n_{Al})\ (n_{Cl})^3\ (K_7)\left[\frac{p_T}{n_T}\right]^3$$

$$n_{AlCl_3} = (.02794)\ (3.58 \times 10^{-2})^3\ (1.177)\ (.17255 \times 10^2)^3 = 0.00775$$

Re-evaluating H_2O, CO, and CO_2,

$$\frac{n_{H_2}}{n_{H_2O}} = K_1 \frac{n_{CO}}{n_{CO_2}} = (0.1248)\ (75) = 9.360$$

If $n_{H_2} = 1.6975$, then $n_{H_2O} = 0.1814$.

$$\frac{n_{CO}}{n_{CO_2}} = \frac{n_{CO}}{1.0694 - n_{CO}} = 75$$

$$n_{CO} = 1.0553$$

$$n_{CO_2} = 0.0141$$

Re-evaluating HCl and Cl,

$$n_{HCl} = \Sigma H - 2n_{H_2} - n_H - 2n_{H_2O} = 0.3069$$

$$n_{Cl} = \frac{\Sigma Cl - n_{AlCl} - 3n_{AlCl_3}}{\frac{n_{HCl}}{n_{Cl}} + 1} = \frac{0.35375}{15.4903} = 0.0228$$

The other species are:

$$n_{AlCl} = \frac{n_{Al} \cdot n_{Cl}}{K_8} \cdot \frac{p_T}{n_T} = \frac{(.02794)\ (.0228)}{0.1145}\ (17.255) = 0.0960$$

$$n_{AlCl} = 0.0960$$

$$n_{AlCl_3} = (.02794)\ (2.28 \times 10^{-2})^3\ (1.177)\ (.17255 \times 10^2)^3 = 0.0020$$

$$n_{Al_2O_{3(l)}} = 1/2\ (\Sigma Al - n_{Al(g)} - n_{AlO} - 2n_{Al_2O} - n_{AlCl} - n_{AlCl_3}) = 0.2252$$

Checking by oxygen balance,

$$\Sigma O = n_{CO} + 2n_{CO_2} + n_{H_2O} + n_{AlO} + n_{Al_2O} + 3n_{Al_2O_{3(l)}}$$

$$\Sigma O = 2.1107 \cong 2.0907$$

Checking by total moles balance,

$$n_T = n_{H_2} + n_H + n_{HCl} + n_{CO} + n_{CO_2} + n_{H_2O} + n_{Cl} + n_{AlO} + n_{Al_2O} + n_{Al} + n_{AlCl_3} + n_{N_2} + n_{AlCl}$$

$n_T = 3.9409 \cong 4.0029$

Checking by chlorine balance,

$\Sigma Cl = n_{Cl} + n_{HCl} + n_{AlCl} + 3n_{AlCl_3}$

$\Sigma Cl = 0.5277 \neq 0.4317$

None of the preceding three material balances is completely satisfied. However, it is highly improbable that the correct combustion temperature was guessed. Therefore, an enthalpy balance will be made to determine the degree of error in the assumed combustion temperature. Of course, in a high speed digital computer, new values of n_T, n_{H_2}, n_{CO}/n_{CO_2} would be assumed until the material balances each converged.

4. Enthalpy Balance at 3500°K

Specie	n_j	H^T_{298}	$n_j H_j$	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_j}$
H_2	1.6975	25.702		0	
H	0.1849	15.906		+52.089	
H_2O	0.1814	36.933		-57.798	
CO	1.0553	26.821		-26.416	
CO_2	0.0141	44.003		-94.052	
HCl	0.3069	26.347		-22.063	
Cl	0.0228	16.359		+28.942	
AlO	0.0238	28.400		+16.9	
Al_2O	0.1264	44.080		-39.4	
$Al_{(g)}$	0.0279	15.946		+77.4	
AlCl	0.0960	28.414		-50.0	
$AlCl_3$	0.0020	62.700		-137.7	
$Al_2O_{3(l)}$	0.2252	131.410		-373.09	
N_2	0.2639	26.605		0	
			136.818		-127.681

$$-(\Sigma n_j H_j)_p = \Delta H_R = (\Sigma n_j \Delta H_{f_j})_p - (\Sigma n_j \Delta H_{f_j})_r$$

$$-136.818 \stackrel{?}{=} -127.681 + 36.633$$

$$-136.818 \neq -91.048$$

Thus, the enthalpy balance is not satisfied. Since the assumed temperature was too high, a combustion temperature of 3100°K will be assumed.

5. Chamber Composition Iteration at 3100°K

$K_1 = K_W = 0.1349$

$K_2 = K_H = 0.2121$

$K_3 = K_{HCl} = 0.1453$

$K_4 = K_{AlO} = 3.618 \times 10^{-3}$

$K_5 = K_{Al_2O} = 1.241$

$K_6 = K_{Al} = 1.441 \times 10^{-2}$

$K_7 = K_{AlCl_3} = 336.2$

$K_8 = K_{AlCl} = 1.421 \times 10^{-2}$

Assume $n_T = 3.8600$ moles

$n_{H_2} = 1.8410$ moles

$n_{CO}/n_{CO_2} = 220$

Then, $n_T/p_T = 0.056764$

$p_T/n_T = 17.6166$

$(n_T/p_T)^{1/2} = 0.23825$

$(p_T/n_T)^{1/2} = 4.1972$

The chamber composition then becomes:

$n_{N_2} = 0.2639$

$n_{CO} = 1.0646$

$n_{CO_2} = 0.0048$

$$n_H = (K_2)(n_{H_2}{}^{1/2})\left[\frac{n_T}{p_T}\right]^{1/2} = (.2121)(1.3568)(.23825) = 0.0686$$

$$\frac{n_{H_2}}{n_{H_2O}} = K_1 \frac{n_{CO}}{n_{CO_2}} = (.1349)(220) = 29.678$$

$$n_{H_2O} = 0.0620$$

$$n_{HCl} = \Sigma Cl - 2n_{H_2} - 2n_{H_2O} - n_H = 0.3750$$

$$\frac{n_{HCl}}{n_{Cl}} = \frac{n_{H_2}^{1/2}}{K_3}\left[\frac{p_T}{n_T}\right]^{1/2} = \frac{(1.3568)}{(.1453)} \quad (4.1972) = 39.193$$

$$n_{Cl} = 0.009578$$

$$n_{AlO} = \left(\frac{n_{CO}}{n_{CO_2}}\right)^{1/2} (K_4)\,\frac{n_T}{p_T} = (14.8324)\ (.003618)\ (.056764) = 0.0030$$

$$n_{Al_2O} = (K_5)\ (n_{AlO})^2\ \frac{n_{CO}}{n_{CO_2}} \cdot \frac{p_T}{n_T} = (1.241)\ (.003046)^2\ (220)\ (17.6166) = 0.0446$$

$$n_{Al} = (K_6)\ (n_{AlO})\ \frac{n_{CO}}{n_{CO_2}} = (.01441)\ (.003046)\ (220) = 0.0097$$

$$n_{AlCl} = \frac{(n_{Al})\ (n_{Cl})}{K_8}\ \frac{p_T}{n_T} = \frac{(.009656)\ (.009578)}{(.01421} \quad (17.6166) = 0.1147$$

$$n_{AlCl_3} = (K_7)\ (n_{Al})\ (n_{Cl})^3 \left[\frac{p_T}{n_T}\right]^3 = 0.0156$$

$$n_{Al_2O_{3(l)}} = 1/2\ (\Sigma Al - n_{AlO} - 2n_{Al_2O} - n_{Al} - n_{AlCl} - n_{AlCl_3}) = 0.3103$$

Checking oxygen balance,

$$\Sigma O = 2.1107 \cong 2.1147$$

Checking chlorine balance,

$$\Sigma Cl = 0.5277 \cong 0.5461$$ (Satisfactory checks)

Checking total moles balance,

$$n_T = 3.8771 \cong 3.8600$$

6. **Enthalpy Balance at 3100°K**

Specie	n_j	H^T_{298}	$n_j H_j$	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_{j298}}$
H_2	1.8410	22.210	40.889	0	0
H	0.0686	13.919	0.955	+52.089	+3.573
H_2O	0.0620	31.530	1.955	-57.798	-3.583
CO	1.0646	23.246	24.748	-26.416	-28.122
CO_2	0.0048	38.021	0.183	-94.052	-0.451
HCl	0.3750	22.756	8.534	-22.063	-8.274
Cl	0.0096	14.529	0.139	+28.942	+0.278
AlO	0.0030	24.726	0.074	+16.9	+0.051
Al_2O	0.0446	38.51	1.718	-39.4	-1.757
Al	0.0097	13.957	0.135	+77.4	+0.751
AlCl	0.1147	24.838	2.849	-50.0	-5.735
$AlCl_3$	0.0156	54.78	0.855	-137.7	-2.148
$Al_2O_{3(l)}$	0.3103	115.78	35.927	-373.09	-115.780
N_2	0.2639	23.046	6.082	0	0
	3.8771		125.043		-161.197

$$-(\Sigma n_j H_j)_p = \Delta H_R = (\Sigma n_j \Delta H_{f_{j298}})_p - (\Sigma n_j \Delta H_{f_{j298}})_R$$

$$-125.043 \stackrel{?}{=} -161.197 + 36.633$$

$$-125.043 \cong -124.564$$

Thus, the enthalpy balance is satisfied.

7. Calculation of Chamber Entropy and Heat Capacity

Specie	n_j	S	$n_j S_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$	C_p	$n_j C_{p_j}$
H_2	1.8410	48.761	89.769	0.474	-0.747	-0.354	8.912	16.407
H	0.0686	39.025	2.677	0.018	-4.017	-0.072	4.968	0.341
H_2O	0.0620	68.856	4.269	0.016	-4.135	-0.066	13.374	0.829
CO	1.0646	65.662	69.904	0.275	-1.291	-0.355	8.910	9.486
CO_2	0.0048	80.328	0.386	0.001	-6.908	-0.007	14.902	0.072
HCl	0.3750	62.656	23.446	0.097	-2.333	0.226	8.929	3.348
Cl	0.0096	51.788	0.497	0.002	-6.215	-0.012	5.030	0.048
AlO	0.0030	72.164	0.216	0.001	-6.908	-0.007	9.165	0.027
Al_2O	0.0446	96.100	4.286	0.012	-4.423	-0.053	13.90	0.620
$Al_{(g)}$	0.0097	51.005	0.495	0.002	-6.215	-0.012	4.970	0.048
AlCl	0.1147	74.994	8.602	0.030	-3.507	-0.105	9.086	1.042
$AlCl_3$	0.0156	119.40	1.863	0.004	-5.521	-0.022	19.84	0.310
$Al_2O_{3(l)}$	0.3103	92.22	28.616	-----	------	------	38.15	11.838
N_2	0.2639	64.046	16.902	0.068	-2.688	-0.183	8.868	2.340
	3.8771		251.978			-1.474		46.756

$$S_c = \Sigma n_j S_j - n_T \cdot R \cdot \Sigma \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T \cdot R \cdot \ln P_c$$

$$S_c = \Sigma n_j S_j - R \cdot n_T \left(\Sigma \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + \ln P_c \right)$$

$$S_c = 251.978 - 7.704 \, (-1.474 + 4.220)$$

$$S_c = 251.978 - 21.155$$

$$S_c = 230.823$$

$$\text{Mean Molecular Weight} = \frac{100 \text{ gm propellant}}{3.8771 \text{ moles of gas}} = 25.79$$

8. Exhaust Composition Iteration

At an assumed exhaust temperature, the exhaust composition is calculated. Assume the exhaust temperature is 2150°K. Since this is below the melting point of Al_2O_3, the species AlO, Al_2O, $Al_{(g)}$, and $Al_2O_{3(l)}$ will be neglected in the exhaust composition. Also, the concentrations of Cl and AlCl will be small in comparison to those of HCl and $AlCl_3$. Therefore, the following species will be considered: CO, CO_2, H_2O, H_2, HCl, H, N_2, $AlCl_3$, and $Al_2O_{3(s)}$. The new mass balances become:

$$\Sigma H = 4.2496 = 2n_{H_2} + 2n_{H_2O} + n_{HCl} + n_H$$

$$\Sigma C = 1.0694 = n_{CO} + n_{CO_2}$$

$$\Sigma N = 0.5277 = 2n_{N_2}$$

$$\Sigma Cl = 0.5277 = n_{HCl} + 3n_{AlCl_3}$$

$$\Sigma Al = 0.8528 = 2n_{Al_2O_{3(s)}} + n_{AlCl_3}$$

$$\Sigma O = 2.1107 = n_{CO} + 2n_{CO_2} + n_{H_2O} + 3n_{Al_2O_{3(s)}}$$

Necessary equilibria are:

a. $CO + H_2O \rightleftharpoons CO_2 + H_2$ $\qquad \Delta n = 0$

$$K_{p_1} = \frac{p_{CO_2} \cdot p_{H_2}}{p_{CO} \cdot p_{H_2O}} = \frac{n_{CO_2} \cdot n_{H_2}}{n_{CO} \cdot n_{H_2O}}$$

b. $1/2\ H_2 \rightleftharpoons H$ $\qquad \Delta n = 1/2$

$$K_{p_2} = \frac{p_H}{p_{H_2}^{1/2}} = \frac{n_H}{n_{H_2}^{1/2}} \left[\frac{p_T}{n_T}\right]^{1/2}$$

$K_1 = K_W = 0.19786$

$K_2 = K_H = 0.004366$

Assume $n_T = 3.6400$ moles

Then, $n_T/p_T = 3.6400$

$(n_T/p_T)^{1/2} = 1.9079$

$n_{H_2} = 2.0950$ moles

$n_{CO} = 1.0693$

$n_{CO_2} = 0.0001$

$n_{N_2} = 0.2639$

$$\frac{n_{H_2}}{n_{H_2O}} = K_1 \frac{n_{CO}}{n_{CO_2}} = 1978.6$$

$n_{H_2O} = 0.0011$

$$n_H = (K_2)\,(n_{H_2}{}^{1/2}) \left[\frac{n_T}{p_T}\right]^{1/2} = 0.0121$$

$n_{HCl} = \Sigma Cl - 2n_{H_2} - 2n_{H_2O} - n_H = 0.0453$

$n_{Al_2O_3(s)} = 1/3\,(\Sigma O - n_{CC} - 2n_{CO_2} - n_{H_2O}) = 0.3467$

$n_{AlCl_3} = \Sigma Al - 2n_{Al_2O_3(s)} = 0.1594$

Checking chlorine balance

$\Sigma Cl = 0.5277 \cong 0.5235$ (Satisfactory Check)

Checking total moles

$n_T = 3.6462 \cong 3.6400$

9. Entropy Balance at 2150°K

Constituent	n_j	S	$n_j S_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$
H_2	2.0950	45.213	94.721	0.576	-0.552	-0.318
H	0.0121	37.206	0.450	0.003	-5.809	-0.017
H_2O	0.0011	64.121	0.071	0.000	------	------
CO	1.0693	62.434	66.671	0.293	-1.228	-0.360
CO_2	0.0001	74.939	0.007	0.000	------	------
HCl	0.0453	59.446	2.693	0.012	-4.423	-0.053
$AlCl_3$	0.1594	112.11	17.870	0.044	-3.124	-0.137
$Al_2O_3(s)$	0.3467	67.763	23.493	-----	------	------
N_2	0.2639	60.836	16.055	0.072	-2.631	-0.189
	3.6462		222.121	1.000		-1.074

$$S_e = \Sigma n_j S_j - R \cdot n_T \left(\Sigma \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + \ln P_e \right)$$

$$S_e = 222.121 + (1.074)\ (7.245)$$

$$S_e = 222.121 + 7.781$$

$$S_e = 229.902$$

$S_e = 229.902 \cong 230.823 = S_c$ (Satisfactory check)

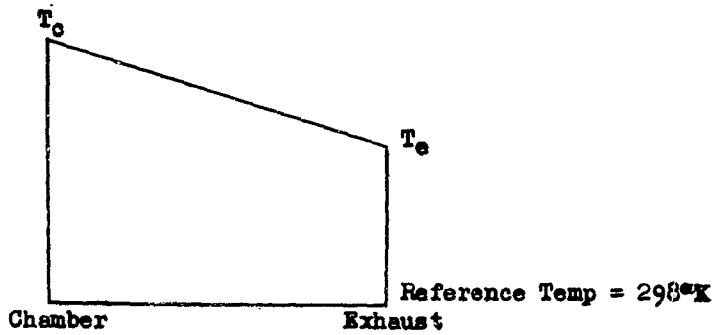
10. Calculation of Exhaust Enthalpy, Heat Capacity, and Heat-of-Formation at 2150°K

Specie	n_j	H^T_{298}	$n_j H_j$	C_p	$n_j C_{p_j}$	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_{j298}}$
H_2	2.0950	13.896	29.112	8.315	17.420	0	0
H	0.0121	9.200	0.111	4.968	0.060	+52.089	+0.630
H_2O	0.0011	19.222	0.021	12.435	0.014	-57.798	-0.064
CO	1.0693	14.866	15.896	8.713	9.317	-26.416	-28.247
CO_2	0.0001	24.027	0.002	14.518	0.001	-94.052	-0.009
HCl	0.0453	12.710	0.576	8.537	0.387	-22.063	-0.999
$AlCl_3$	0.1594	35.93	5.727	19.80	3.156	-137.7	-21.949
$Al_2O_{3(s)}$	0.3467	55.29	19.169	33.80	11.718	-400.4	-138.819
N_2	0.2639	14.711	3.882	8.653	2.284	0	0
	3.6462		74.496		44.357		-189.457

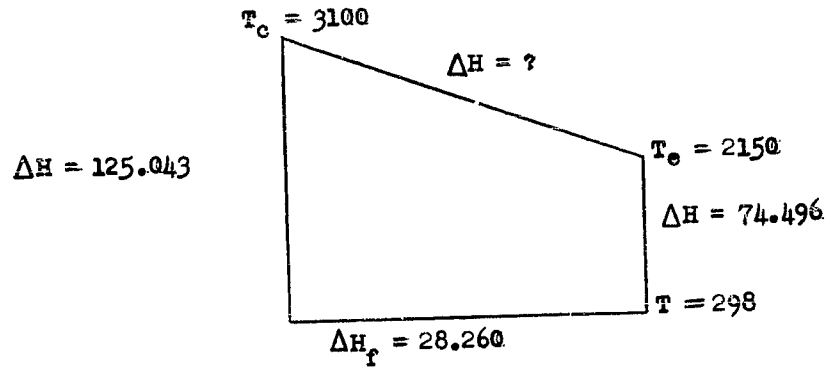
Mean Molecular Weight = $\frac{100 \text{ gm propellant}}{3.6462 \text{ moles of gas}} = 27.43$

11. Overall Enthalpy Balance

Since absolute quantities of enthalpy cannot be assigned, the overall enthalpy balance must be calculated for the complete path followed in the rocket motor:



$$\Sigma n_j H_{j298}^{T_e} + \Delta H_{T_c}^{T_e} + \Sigma n_j H_{jT_e}^{298} + (\Sigma n_j \Delta H_{f_j})_e - (\Sigma n_j \Delta H_{f_j})_c = 0$$



$$125.043 - \Delta H_{T_e}^{T_c} - 74.496 * 28.260 = 0$$

$$\Delta H_{T_e}^{T_c} = 78.807 \text{ Kcal/100 gm}$$

12. Summery of Chamber Conditions

Pressure = 1000 PSIA

Temperature = 3100°K

Enthalpy = 125.043 Kcal/100 gm propellant

Entropy = 230.823 calories/100 gm - °K

Heat Capacity = 46.756 calories /100 gm - °K

Moles of Gas = 3.8771 moles/100 gm

Total Moles = 4.1874 moles/100 gm

Mean Molecular Weight = 25.79 gm/mole

Gas Composition, moles/100 gm propellant

H_2 = 1.8410

H = 0.0686

H_2O = 0.0620

CO = 1.0646

CO_2 = 0.0043

$HCl = 0.3750$

$Cl = 0.0096$

$AlO = 0.0030$

$Al_2O = 0.0446$

$Al_{(g)} = 0.0097$

$AlCl = 0.1147$

$AlCl_3 = 0.0156$

$Al_2O_{3(l)} = 0.3103$

$N_2 = 0.2639$

13. Summary of Exhaust Conditions

Pressure = 14.7 PSIA

Temperature = 2150°K

Enthalpy = 74.496 Kcal/100 gm propellant

Entropy = 229.902 calories/100 gm - °K

Heat Capacity = 44.357 calories/100 gm - °K

Moles of Gas = 3.6462 moles/100 gm

Total moles = 3.9929 moles/100 gm

Mean Molecular Weight = 27.43 gm/mole

Gas Composition, moles/100 gm propellant

$H_2 = 2.0950$

$H = 0.0121$

$H_2O = 0.0011$

$CO = 1.0693$

$CO_2 = 0.0001$

$HCl = 0.0453$

$AlCl_3 = 0.1594$

$Al_2O_{3(s)} = 0.3467$

$N_2 = 0.2639$

14. Calculation of Rocket Performance Parameters

a. $Isp = 9.330\sqrt{H_c - H_e} = 9.330\sqrt{788.07}$

$Isp = (9.330)(28.071)$

$Isp = 261.9$ seconds

b. $Ivsp = \rho \cdot Isp = 1.7715 \frac{gm}{cc} \cdot \frac{1\ lb}{453.6\ gm} \cdot \frac{1\ cc}{0.06102\ in.^3} (261.9\ sec)$

$Ivsp = 16.75$ lb-sec/in.^{3}

c. $u_e = Isp \cdot g = (261.9\ seconds)(32.2\ ft/sec^2)$

$u_e = 8433$ ft/sec

d. $\frac{k-1}{k} = \frac{\ln \frac{T_c}{T_e}}{\ln \frac{P_c}{P_e}} = \frac{\ln \frac{3100}{2150}}{\ln 68} = \frac{\ln 1.442}{\ln 68} = 0.0868$

$\overline{k} = 1.096$

e. $C_F = \sqrt{\frac{4k^2}{k^2-1}\left[\frac{2}{k+1}\right]^{\frac{2}{k-1}}\left[1 - \frac{T_e}{T_c}\right]}$

$C_F = \sqrt{(23.44)(0.953)^{20.39}(0.312)} = \sqrt{(7.313)(0.373)}$

$C_F = 1.652$

f. $\frac{A_e}{A_t} = \frac{k}{C_F}\left[\frac{2}{k+1}\right]^{\frac{k+1}{k-1}}\left[\frac{P_c}{P_e}\right]^{1/k}$

$\frac{A_e}{A_t} = \frac{1.096}{1.652}(0.953)^{21.39}(68)^{0.911} = (.665)(.357)(46.7)$

$\frac{A_e}{A_t} = 11.09$

g. $c^* = \frac{u_e}{C_F} = \frac{8433}{1.652} = 5100$

$c^* = 5100$ ft/sec

h. $\left(\frac{C_p}{C_v}\right)_{chamber} = k = \frac{C_p}{C_p - n_T \cdot R} = \frac{46.756}{46.756 - (3.8771)(1.987)}$

$k = 1.199$

i. $\frac{p_e A_e}{\dot{m}} = \frac{1}{a} \cdot n_T \left(\frac{T_c}{Isp}\right)_{shifting} = \frac{1}{1.15667} (3.6462) \frac{2150}{261.9}$

$\frac{p_e A_e}{\dot{m}} = 25.9$

j. $g/c^* = a^{1/2}\left[\frac{k}{n_T T_c}\right]^{1/2} \left[\frac{2}{k+1}\right]^{\frac{k+1}{2(k-1)}}$

$g/c^* = 1.074\left[\frac{1.199}{(3.8771)(3100)}\right]^{1/2} \left[\frac{2}{2.199}\right]^{\frac{2.199}{0.398}}$

$g/c^* = (1.074)(0.01)(0.587) = 0.00631$

$c^* = \frac{g}{0.00631} = 5100$ ft/sec

k. $C_F = \frac{Isp \cdot g}{c^*} = \frac{(261.9)(32.2)}{5100}$

$C_F = 1.655$

l. $\frac{A_e}{A^*} = \frac{g}{c^*} \cdot \frac{p_c}{p_e} \cdot \frac{p_e A_e}{\dot{m}} = \frac{32.2}{5100} \cdot \frac{1000}{14.7} (25.9)$

$\frac{A_e}{A^*} = 11.12$

m. Ideal boost velocity data are evaluated as follows:

$$V_b = Isp \cdot g \cdot \ln \left[\frac{W_M}{W_M - W_p} \right] = Isp \cdot g \cdot \ln \left[1 + \frac{\rho}{W_f / V_p} \right]$$

W_f = mass of missile hardware

V_p = volume of propellant

ρ = density of propellant

W_M = total mass of missile

W_p = mass of propellant

$\frac{W_p}{W_M}$	$\frac{W_M}{W_M - W_p}$	$\ln \frac{W_M}{W_M - W_p}$	V_b
0.95	20	3.00	25,300
0.90	10	2.30	19,400
0.85	6.67	1.90	16,020
0.80	5.0	1.61	13,580
0.70	3.33	1.20	10,110
0.50	2.0	0.69	5,820

$\frac{W_f}{V_p}$	$\frac{\rho}{W_f / V_p}$	$1 + \frac{\rho}{W_f / V_p}$	$\ln \left[1 + \frac{\rho}{W_f / V_p} \right]$	V_b
25	4.422	5.422	1.690	14,250
60	1.842	2.842	1.040	8,770
100	1.005	2.005	0.693	5,840

APPENDIX B

SAMPLE CALCULATION USING THE METHOD OF MINIMIZATION OF FREE ENERGY

1. Statement of the Problem

Ingredient	Weight %	Moles/100 gm Propellant	MW	ΔH_{f298} Kcal/mole	gm/cc
N_2H_4	58.207	1.8162	32	+12.05	1.004
N_2O_4	41.793	0.4542	92	-5.4	1.43

Chamber Pressure = 500 PSIA

Exhaust Pressure = 14.7PSIA

Density of Propellant = 1.148 g/cc

Heat-of-Formation of Propellant = +19.44 Kcal/100 gm

Concentration of Ingredients per 100 gm Propellant:

H = 7.2648 gm-atoms

N = 4.5408 gm-atoms

O = 1.8168 gm-atoms

2. Mass Balance

In solving this problem on a high speed digital computer, all products of combustion which could exist would be considered until proven to be present in negligible quantities. However, such a rigorous approach is beyond the scope and feasibility of this sample calculation. In this example, the purpose is solely to demonstrate the calculation method. Therefore, the products-of-combustion will be limited to the following species: H_2, H_2O, N_2, H, N, OH, and O. The mass balances are:

$$\Sigma H = 7.2648 = 2n_{H_2} + 2n_{H_2O} + n_{OH} + n_H$$

$$\Sigma N = 4.5408 = 2n_{N_2} + n_N$$

$$\Sigma O = 1.8168 = n_{H_2O} + n_{OH} + n_O$$

3. Initial Conditions

Initially, in a general solution, it is assumed that the only products of combustion are the elemental gas species. At 298°K, the properties of N, H, and O are:

Specie	C_p	ΔH_f
N	4.97 cal/deg-mole	+113.0 Kcal/mole
H	4.968 cal/deg-mole	+52.09 Kcal/mole
O	5.24 cal/deg-mole	+59.55 Kcal/mole

From these data, an enthalpy balance is made with ΔT the variable:

$$-\Sigma(n_j H_j)_{products} = (\Sigma n_j \Delta H_{f_{j298}})_{products} - (\Sigma n_j \Delta H_{f_{j298}})_{reactants}$$

$$(\Sigma n_j \Delta H_{f_{j298}})_{reactants} = (\Sigma n_j \Delta H_{f_{j298}})_{products} + (\Sigma n_j C_{p_{j298}} \Delta T)_{products}$$

Specie	n_j	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_j}$	C_{p_j}	$n_j C_{p_j}$
N	4.5408	+113.0	+513.0	4.97	22.5
H	7.2648	+52.09	+377.5	4.968	36.1
O	1.8168	+59.55	+108.0	5.24	9.5
	13.6224		+998.5		68.1

+19,440 calories/100 gm = 998,500 + 68.1 ΔT

ΔT = -14,400°K

This, of course, is a hypothetical temperature corresponding to the existence of species N, H, and O at the constant enthalpy of the propellant. Whenever

the hypothetical temperature of the mixture falls below 298°K, thermodynamic data at 298°K are used for the various product species until the trial temperature raises above that value.

Each of the various products of combustion will now be examined, one by one, to determine which specie will cause the greatest reduction in total free energy of the system if introduced as a constituent. Species are examined and introduced one at a time.

4. Formation of N_2

Nitrogen gas is introduced into the system by formation from nitrogen atoms:

$$2N \rightleftharpoons N_2$$

$$2\Delta n_{N_2} = -\Delta n_N$$

The formation of N_2 will cause both a temperature and concentration change. At a given temperature, this relationship is

$$-\Delta T = \frac{H_{N_2} - 2H_N}{\sum n_j C_{p_j}} \Delta n_{N_2}$$

or $$-\Delta T = k' \Delta n_{N_2}$$

where $$k' = \frac{H_{N_2} - 2H_N}{\sum n_j C_{p_j}}$$

When the temperature of the mixture is a hypothetical value below 298°K, k' is considered zero and the above relationship loses significance. However, when the temperature rises above 298°K, the above expression is used to relate ΔT and Δn.

At 298°K, the ideal entropy and free energy of N and N_2 are:

$S_N^\circ = 36.61$ cal/deg-mole

$S_{N_2}^\circ = 45.77$ cal/deg-mole

$F_N^\circ = H - TS^\circ = +113.0 - 10.90 = +102.1$ Kcal/mole

$F_{N_2}^\circ = H - TS^\circ = 0 - 13.65 = -13.65$ Kcal/mole

For the general case, the approximate quantity of N_2 which should be introduced in order to minimize the free energy of the system is defined by the equation

$$\Delta F \leq A' \Delta n_{N_2} + B' (\Delta n_{N_2})^2 + C' (\Delta n_{N_2})^3$$

where A' = cal/mole $= k' n_N (-S_N^\circ)_T + k' n_{N_2} (-S_{N_2}^\circ)_T + k' n_H (-S_H^\circ)_T + k' n_0 (-S_0^\circ)_T - 2(F_N^\circ)_T + (F_{N_2}^\circ)_T - 2RT (1 + \ln n_N) + RT (1 + \ln n_{N_2}) + k'R (n_N \ln n_N) + k'R (n_{N_2} \ln n_{N_2}) + k'R (n_H \ln n_H) + k'R (n_0 \ln n_0) - RT (\ln n_T + 1) - RT \ln p_T + k'R \cdot n_T \ln p_T/n_T$

$$B' = \text{cal/(mole)}^2 = \frac{4RT}{n_N} + \frac{RT}{n_{N_2}} - 2k' (-S_N^\circ)_T + k' (-S_{N_2}^\circ)_T - 2k'R (1 + \ln n_N) + k'R (1 + \ln n_{N_2}) - k'R (\ln n_T + 1) - k'R \ln p_T + RT \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2}$$

$$C' = \text{cal/(mole)}^3 = \frac{4k'R}{n_N} + \frac{k'R}{n_{N_2}} + k'R \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2}$$

Then, $\Delta n_{N_2} = \frac{-B' + \sqrt{(B')^2 - 3A'C'}}{3C'}$

However, k' will be zero at first corresponding to the low hypothetical temperature. Under this condition, the general cubic equation reduces to a quadratic. Furthermore, n_{N_2} is initially zero. Some finite value of n_{N_2} must be assigned, however, in order to avoid infinite contributions to the coefficients A', B', C'. For the general case, 2/3 of the maximum allowable concentration is chosen as the initial quantity to be introduced. This value corresponds to the point of tangency at which, on the average, the $y = ax^2 - bx$ curve approximates the $y = x \ln x$ curve. Thus, the coefficients are evaluated as:

$A' = -2(102,100) + (-13,650) - 2(1.987)(298)(1 + \ln 4.5408) + (1.987)(298)(1 + \ln 1.5136) - (1.987)(298)(\ln 13.6224 + 1) - (1.987)(298)(\ln 34.0)$

$A' = -204,200 - 13,650 - 2976 + 837 - 2139 - 2089$

$A' = -224,217$

$$B' = \frac{4(1.987)(298)}{4.5408} + \frac{(1.987)(298)}{1.5136} + (1.987)(298)(-0.5)$$

$B' = 616.7$

$C' = 0$

In this case,

$$\Delta F^{\ddagger} \leqq A' (\Delta n_{N_2}) + B' (\Delta n_{N_2})^2$$

$$\Delta F \leqq -224,217 (\Delta n_{N_2}) + 616.7 (\Delta n_{N_2})^2$$

Differentiating and setting the derivative equal to zero,

$$0 = -224,217 + 1233.4 \Delta n_{N_2}$$

$$\Delta n_{N_2} = 181.8$$

However, according to the mass balance limitation, a maximum of 2.2704 moles of N_2 can be formed.

Therefore, since 181.8 exceeds 2.2704, all nitrogen should exist

as N_2. If all N were transformed into N_2, the total change in ideal free energy of the system at 298°K would be:

$$\Delta F = 2.2704\ (-13.65) - 4.5408\ (+102.1)$$

$$\Delta F = -494.0 \text{ Kcal}$$

5. Formation of H_2

Consider the introduction of hydrogen gas into the system by formation from hydrogen atoms:

$$2H \rightleftharpoons H_2$$

$$2\Delta n_{H_2} = -\Delta n_H$$

The relationship between temperature and concentration changes is

$$-\Delta T = \frac{H_{H_2} - 2H_H}{\sum n_j C_{p_j}} \Delta n_{N_2}$$

At 298°K, the ideal entropy and free energy of H and H_2 are:

$S^{\circ}_H = 27.39$ cal/deg-mole

$S^{\circ}_{H_2} = 31.21$ cal/deg-mole

$F^{\circ}_H = H - TS^{\circ} = +52.09 - 8.17 = +43.92$ Kcal/mole

$F^{\circ}_{H_2} = H - TS^{\circ} = 0 - 9.30 = -9.30$ Kcal/mole

Proceeding as before,

$$A' = -2(F^{\circ}_H)_T + (F^{\circ}_{H_2})_T - 2RT\ (1 + \ln n_H) + RT\ (1 + \ln n_{H_2}) - RT\ (\ln n_T + 1)$$

$$- RT \ln p_T$$

$$A' = -103.783$$

$$B' + \frac{4RT}{n_H} + \frac{RT}{n_{H_2}} + RT \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2}$$

$B' = 274.4$

$C' = 0$

Then, $548.8\ \Delta n_{H_2} - 103.783 = 0$

$$\Delta n_{H_2} = 189.1$$

However, according to the mass balance limitations, a maximum of 3.6324 moles of H_2 can be formed. Therefore, since 189.1 exceeds 3.6324, all hydrogen should exist as H_2 in preference to existing as H. For this case, the change in ideal free energy of the system at 298°K would be:

$$\Delta F = 3.6324\ (-9.30) - 7.2648\ (43.92)$$

$$\Delta F = -352.8 \text{ Kcal}$$

6. Formation of H_2O

Next, consider the formation of water from hydrogen and oxygen:

$$2H + O \rightleftharpoons H_2O$$

$$\Delta n_{H_2O} = -\Delta n_O - 2\Delta n_H$$

From the oxygen balance, a maximum of 1.8168 moles of water could be formed. From the hydrogen balance, a maximum of 3.6324 moles of water could be formed. Hence, the oxygen balance is the restricting one. The general relationship between ΔT and Δn_{H_2O} is

$$-\Delta T = \frac{H_{H_2O} \quad H_O - 2H_H}{\Sigma n_j C_{p_j}} \Delta n_{H_2O}$$

At 298°K, the ideal entropy and free energy of H, O, and H_2O are:

$S_H^\circ = 27.39$ cal/deg-mole

$S_0^\circ = 38.47$ cal/deg-mole

$S_{H_2O}^\circ = 45.11$ cal/deg-mole

$F_H^\circ = H - TS^\circ = +43.92$ Kcal/mole

$F_0^\circ = H - TS^\circ = +48.07$ Kcal/mole

$F_{H_2O}^\circ = H = TS^\circ = -71.21$ Kcal/mole

In this case, the respective constants to the cubic equation are:

$$A' = -2(F_H^\circ)_T - (F_0^\circ)_T + (F_{H_2O}^\circ)_T - 2RT\,(1 + \ln n_H) - RT\,(1 + \ln n_0) + RT\,(1 + \ln n_{H_2O}) - RT\,(\ln n_T + 1) - RT \ln p_T$$

$$A' = -215,119$$

$$B' = \frac{4RT}{n_H} + \frac{RT}{n_0} + \frac{RT}{n_{H_2O}} - RT\,\frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2}$$

$$B' = 844.7$$

$$C' = 0$$

Then, $1689.4\ \Delta n_{H_2O} - 215,119 = 0$

$$\Delta n_{H_2O} = 127.3$$

However, a maximum of 1.8168 moles of water can exist. Since Δn_{H_2O} exceeds this value, all oxygen should exist as water in preference to oxygen atoms. Furthermore, 3.6324 moles of hydrogen should also be combined. The ideal free energy change accompanying this concentration change is

$$\Delta F = 1.8168(-71.21) - 1.8168(+48.07) - 3.6336(+43.92)$$

$$\Delta F = -375.9 \text{ Kcal}$$

7. Introduction of Major Species

In a general computer solution, all other species, including OH, would be evaluated in the same manner. In fact, the existence of H_2, N_2, and H_2O as the predominant species could be reasoned from intuition in this relatively simple example. Nevertheless, the preceding procedure was followed to demonstrate the fundamental approach. Since the greatest single reduction in free energy occurs by transforming N to N_2, the first new trial composition will be:

N_2 = 2.2704 moles

O = 1.8168 moles

H = 7.2648 moles

Specie	n_j	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_j}$	$c_{p_{j298}}$	$n_j c_{p_j}$
N_2	2.2704	0	0	6.96	15.8
H	7.2648	+52.09	+377.5	4.968	36.1
O	1.8168	+59.55	+108.0	5.24	9.5
			+485.5		61.4

$$19.440 = 485.500 + 61.4\ \Delta T$$

$$\Delta T = -7580^{\circ}K$$

Since the introduction of N_2 was not sufficient to raise the temperature of the mixture to a realistic value, water will also be introduced:

Specie	n_j	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_j}$	$c_{p_{j298}}$	$n_j c_{p_j}$
N_2	2.2704	0	0	6.96	15.8
H_2O	1.8168	-57.79	-105.0	8.03	14.6
H	3.6336	+52.09	+189.0	4.968	18.0
			+ 84.0		48.4

$$+19.440 = +84.000 + 48.4\ \Delta T$$

$$\Delta T = -1330^{\circ}K$$

Next, let the rest of the H be introduced as H_2.

Specie	n_j	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_j}$	$c_{p_{j298}}$	$n_j c_{p_j}$
N_2	2.2704	0	0	6.96	15.8
H_2O	1.8168	-57.79	-105.0	8.03	14.6
H_2	1.8168	0	0	6.89	12.5
	5.9040		-105.0		42.9

$$+19,440 = -105,000 + 42.9\ \Delta T$$

$$\Delta T = 2900°K$$

This corresponds to $T_c = 3198°K$. However, the heat capacity data used in obtaining this temperature were extrapolated over a wide range. An enthalpy balance is therefore needed to adjust to the corresponding chamber temperature. At 2700°K,

$$(\Sigma n_j \Delta H_{f_{j298}})_{\text{reactants}} - (\Sigma n_j \Delta H_{f_{j298}})_{\text{products}} = -(\Sigma n_j H_j)^{T}_{298\ \text{products}}$$

$$+ 124.44 \cong 125.3$$

and the enthalpy balance is essentially satisfied. Actually, by extrapolation $T_c = 2687°K$. The free energy of the system at 2700°K is

Specie	n_j	H_j	$n_j H_j$	S°_j	$n_j S^\circ_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$	c_{p_j}	$n_j c_{p_j}$
N_2	2.2704	+19.52	44.32	62.51	141.9	0.384	-0.957	-0.367	8.80	20.0
H_2O	1.8168	-31.81	-57.79	66.44	120.7	0.308	-1.178	-0.363	12.72	23.1
H_2	1.8168	+18.59	33.77	47.23	85.8	0.308	-1.178	-0.363	8.73	15.9
	5.9040		+20.30		348.4	1.000		-1.093		59.0

$$F = \Sigma n_j H_j - T \Sigma n_j S_j + RTn_T \left[\sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} \right] + RTn_T \ln p_T$$

$$F = +20,300 - (2700)(348.4) + (1.987)(2700)(5.9040)(3.526 - 1.093)$$

$$F = +20,300 - 940,080 + 77,065$$

$$F = -842,715 \text{ calories/100 gm propellant}$$

8. Introduction of Minor Species

At 2700°K, some dissociation will be present. Therefore, the species N, H, O, and OH will be re-introduced. First, atomic hydrogen will be considered. Its concentration may be approximated from the decomposition of hydrogen gas by the reaction

$$H_2 \rightleftarrows 2H$$

$$2\Delta n_{H_2} = \Delta n_H$$

$$\Delta n_T = +1/2 \Delta n_H$$

At constant enthalpy, the formation of H will cause both a temperature and a concentration change. The enthalpy balance becomes

$$\Delta H = 0 = \Delta n_H (H_H - 1/2\ H_{H_2}) + \Sigma n_j c_{p_j} \Delta T$$

$$-\Delta T = \frac{H_H - 1/2\ H_{H_2}}{\Sigma n_j c_{p_j}} \Delta n_H$$

At 2700°K,

$$-\Delta T = \frac{64.02 - 9.30}{59.0} \Delta n_H$$

$$\Delta T = -0.928\ \Delta n_H$$

$S^\circ_{H_2} = 47.23$ cal/deg-mole

$S^\circ_H = 38.34$ cal/deg-mole

$F^\circ_{H_2} = H - TS^\circ = 18.59 - (2700)(.94723) = -109.6$ Kcal/mole

$F^\circ_H = H - TS^\circ = 64.02 - (2700)(.03834) = -39.4$ Kcal/mole

Thus, at this point, the species H_2, N_2, H_2O, and H are present as products of combustion. The constants for the cubic equation become

$$A' = k'n_{H_2}\left(-S^{\circ}_{H_2}\right)_T + k'n_H\left(-S^{\circ}_H\right)_T + k'n_{N_2}\left(-S^{\circ}_{N_2}\right)_T + k'n_{H2O}\left(-S^{\circ}_{H2O}\right)_T - 1/2 \left(F^{\circ}_{H_2}\right)_T + \left(F^{\circ}_H\right)_T - 1/2\ RT\ (1 + \ln n_{H_2}) + RT\ (1 + \ln n_H) + k'R\ (n_{H_2} \ln n_{H_2}) + k'R\ (n_H \ln n_H) + k'R\ (n_{N_2} \ln n_{N_2}) + k'R\ (n_{H2O} \ln n_{H_2O}) - 1/2\ RT\ (\ln n_T + 1) + 1/2\ RT \ln p_T + k'R\ n_T \ln \frac{p_T}{n_T}$$

$$B' = \frac{RT}{4n_{H_2}} + \frac{RT}{n_H} - 1/2\ k'\left(-S^{\circ}_{H_2}\right)_T + k'\left(-S^{\circ}_H\right)_T - 1/2\ k'R\ (1 + \ln n_{H_2}) + k'R\ (1 + \ln n_H) - 1/2\ k'R\ (\ln n_T + 1) + RT\ \frac{(n_{T\ max} - n_T) + n_{Tmax} \ln \frac{n_T}{n_{Tmax}}}{4\ (n_{Tmax} - n_T)^2} + 1/2\ k'R \ln p_T$$

$$C' = \frac{k'R}{4n_{H_2}} + \frac{k'R}{n_H} + k'R\ \frac{(n_{Tmax} - n_T) + n_{Tmax} \ln \frac{n_T}{n_{Tmax}}}{4(n_{Tmax} - n_T)^2}$$

Some finite value of n_H must be initially assigned. Although 2/3 of the maximum allowable concentration would be initially assumed for the general case, the first estimate for this sample problem was made from equilibrium data:

$$n_H = K_p \left(n_{H_2}^{1/2}\right) \left(\frac{n_T}{p_T}\right)^{1/2} = (0.05669)\ (1.3440)\ \left(\frac{5.9040}{34.0}\right)^{1/2} = 0.0316$$

Evaluating the constants,

$A' = (-0.928)\ (1.8168)\ (-47.55) + (-0.928)(0.0316)\ (-38.34) + (-0.928)\ (2.2704)\ (-62.84) + (-0.928)\ (1.8168)\ (-66.92) - 1/2\ (-109.6) + (-39.4) - 1/2\ (1.987)\ (2700)\ (1.599) + (1.987)\ (2700)\ (-2.45) + (-0.928)\ (1.987)\ (1.081) + (-0.928)\ (1.987)\ (.109) + (-0.928)\ (1.987)\ (1.861) + (-0.928)\ (1.987)\ (1.081) - 1/2\ (1.987)\ (2700)\ (2.775) + 1/2\ (1.987)\ (2700)\ (3.526) + (-0.928)\ (1.987)\ (5.9040)\ (1.750)$

$$A' = 80.17 + 1.12 + 132.40 + 112.83 + 54.800 - 39.400 - 4289.2 - 13,143.6$$

$$- 1.99 - 0.2 - 3.43 - 1.99 - 7443.8 + 9.458.3 - 19.05$$

$$A' = + 281.56$$

$$B' = \frac{(1.987)(2700)}{4(1.8168)} + \frac{(1.987)(2700)}{0.0316} - 1/2(-0.928)(-47.55) + (-0.928)$$

$$(-38.34) - 1/2(-0.928)(1.987)(1.599) + (0.928)(1.987)(-2.45)$$

$$+ (1.987)(2700)\frac{(13.6224) - 5.9040) + 13.6224 \ln \frac{5.9040}{13.6224}}{(13.6224 - 5.9040)^2} + 1/2(-0.928)$$

$$(1.987)(3.526) - 1/2(-0.928)(1.987)(2.775)$$

$$B' = 738.23 + 169,773.3 - 21.61 + 35.58 + 1.47 + 4.52 - 2.56 - 82.30 - 3.25$$

$$B' = +170,443.4$$

$$C' = \frac{(-0.928)(1.987)}{4(1.8168)} + \frac{(-0.928)(1.987)}{0.0316} + (-0.928)(1.987)(-0.06137)$$

$$C' = -0.2537 - 58.3525 + 0.0283$$

$$C' = -58.578$$

The change in concentration of hydrogen atoms is evaluated as:

$$\Delta n_H = \frac{-B' + \sqrt{(B')^2 - 3A'C'}}{3C'}$$

$$\Delta n_H = \frac{-170,443.4 + \sqrt{29,051,003,083.23}}{-175.734}$$

$$\Delta n_H = -0.0114 \text{ moles}$$

Thus, the new concentration of H is

$$n_H = 0.0316 - 0.0114 = 0.0202 \text{ moles}$$

By continuing the iteration until all species have been re-introduced and the free energy of the system has been minimized, the gas composition is found to be:

n_{N_2} = 2.2704 moles

n_{H_2O} = 1.8112

n_{H_2} = 1.8051

n_H = 0.0266

n_{OH} = 0.0056

n_O = 0.0000

n_N = 0.0000

9. Enthalpy Balance at 2650°K

Specie	n_j	ΔH_{298}^{2650}	$n_j H_j$	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_j}$
N_2	2.2704	19.08	43.319	0	0
H_2O	1.8112	25.35	45.914	-57.798	-104.684
H_2	1.8051	18.155	32.772	0	0
H	0.0266	11.68	0.311	+52.089	+1.386
OH	0.0056	18.35	0.103	+ 9.33	+0.052
	5.9189		122.419		-103.246

$-(\Sigma n_j H_j)_p = (\Sigma n_j \Delta H_{f_{j298}})_p - (\Sigma n_j \Delta H_{f_{j298}})_r$

$-122.419 = -103.246 - 19.44$

$-122.419 \cong -122.686$

Thus, the enthalpy balance is satisfied at 2650°K.

10. Calculation of Chamber Entropy, Heat Capacity, and Free Energy

Specie	n_j	S	$n_j S_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$	c_p	$n_j c_{p_j}$
N_2	2.2704	62.68	142.31	0.384	-0.947	-0.367	8.79	19.957
H_2O	1.8112	66.68	120.77	0.306	-1.184	-0.362	12.68	22.966
H_2	1.8051	47.29	85.36	0.305	-1.187	-0.362	8.70	15.704
H	0.0266	38.25	1.02	0.004	-5.521	-0.022	4.968	0.132
OH	0.0056	60.28	0.34	0.001	-6.908	-0.007	8.64	0.048
	5.9189		349.80	1.000		-1.120		58.807

$$S_c = \Sigma n_j S_j - n_T \cdot R \cdot \Sigma \frac{n_i}{n_T} \ln \frac{n_i}{n_T} - n_T \cdot R \cdot \ln p_c$$

$$S_c = 349.80 - (5.9189)(1.987)(-1.120) - (5.9189)(1.987)(3.5264)$$

$$S_c = 349.80 + 13.172 - 41.473$$

$$S_c = 321.50 \text{ cal/(100 gm) (°K)}$$

$$\text{Mean Molecular Weight} = \frac{100 \text{ gm propellant}}{5.9189 \text{ moles of gas}} = 16.895$$

$$F = H - TS$$

$$F = (-103{,}246 + 122{,}419) - (2650)(321.50)$$

$$F = +19{,}173 - 851{,}975$$

$$F = -832{,}802 \text{ calories/100 gm propellant}$$

Although this free energy is numerically greater than that shown for the system at 2700°K, the enthalpy balance was not completely satisfied at either temperature. Free energy changes become very small as equilibrium is approached. If the exact temperatures were found, the free energy of the dissociated system containing H and OH would be slightly less.

11. Calculation of Exhaust Conditions

During expansion through the nozzle, the minor species H and OH will be converted to H_2 and H_2O so that these, along with N_2, constitute the exhaust gas composition. This is known for this relatively simple example. However, for solving a general case on a high-speed digital computer, the same method of minimization of free energy previously employed would be utilized at constant entropy. At an exhaust temperature of 1250°K, the entropy of the system is:

Specie	n_j	S	$n_j S_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$
N_2	2.2704	56.27	127.801	0.384	-0.957	-0.367
H_2O	1.8168	57.89	105.175	0.308	-1.178	-0.363
H_2	1.8168	41.34	75.107	0.308	-1.178	-0.363
	5.9040		308.083	1.000		-1.093

$$S_e = \Sigma n_j S_j - R \cdot n_T \left[\Sigma \frac{n_i}{n_T} \ln \frac{n_i}{n_T} + \ln p_e \right]$$

$$S_e = 308.083 + (1.987)(5.9040)(1.093)$$

$$S_e = 308.083 + 12.822$$

$$S_e = 320.905$$

$$S_e = 320.905 \cong 321.50 = S_c \text{ (Satisfactory Check)}$$

The enthalpy, heat capacity, and free energy are evaluated as:

Specie	n_j	ΔH_{298}^{1250}	$n_j H_j$	$\Delta H_{f_{j298}}$	$n_j \Delta H_{f_{j298}}$	c_p	$n_j c_{p_j}$
N_2	2.2704	7.12	16.165	0	0	8.11	18.413
H_2O	1.8168	8.79	15.970	-57.798	-105.007	10.54	19.149
H_2	1.8168	6.78	12.318	0	0	7.48	13.590
	5.9040		44.453		-105.007		51.152

$F = H - TS$

$F = (44.453 - 105.007) - (1250)\ (320.905)$

$F = -60.554 - 401.131$

$F = -461.685$ calories/100 gm propellant

$$\text{Mean Molecular Weight} = \frac{\text{100 gm propellant}}{\text{5.9040 moles of gas}} = 16.95$$

12. Calculation of Rocket Performance Parameters

(a) $Isp = 9.330\sqrt{H_c - H_e} = 9.330\sqrt{797.27}$

$Isp = (9.330)\ (28.236)$

$Isp = 263.0$ seconds

(b) $$Ivsp = \rho \cdot Isp = \frac{(1.148)\ (263.0)}{(453.6)\ (.06102)} = 10.90 \text{ lb-sec/in}^3$$

(c) $u_e = Isp \cdot g = (263.0)\ (32.2) = 8465$ ft/sec

(d) $$k = \frac{c_p}{c_p - R\,n_T} = \frac{58.807}{58.807 - (1.987)\ (5.9189)} = 1.250$$

(e) $$\frac{p_e A_e}{m} = \frac{1}{a}\, n_T \left[\frac{T_e}{Isp}\right]_{\text{shifting}} = \frac{(5.9040)\ (1250)}{(1.15667)\ (263)} = 24.35$$

(f) $$g/c^* = a^{1/2}\left[\frac{k}{n_T\, T_c}\right]^{\frac{1}{2}}\left[\frac{2}{k+1}\right]^{\frac{k+1}{2(k-1)}}$$

$$g/c^* = (1.074)\left[\frac{1.250}{(5.9189)(2650)}\right]^{\frac{1}{2}}\left[\frac{2}{2.25}\right]^{4.50}$$

$g/c^* = (1.074)\ (0.00892)\ (0.591) = 0.00567$

$$c^* = \frac{g}{0.00567} = 5680 \text{ ft/sec}$$

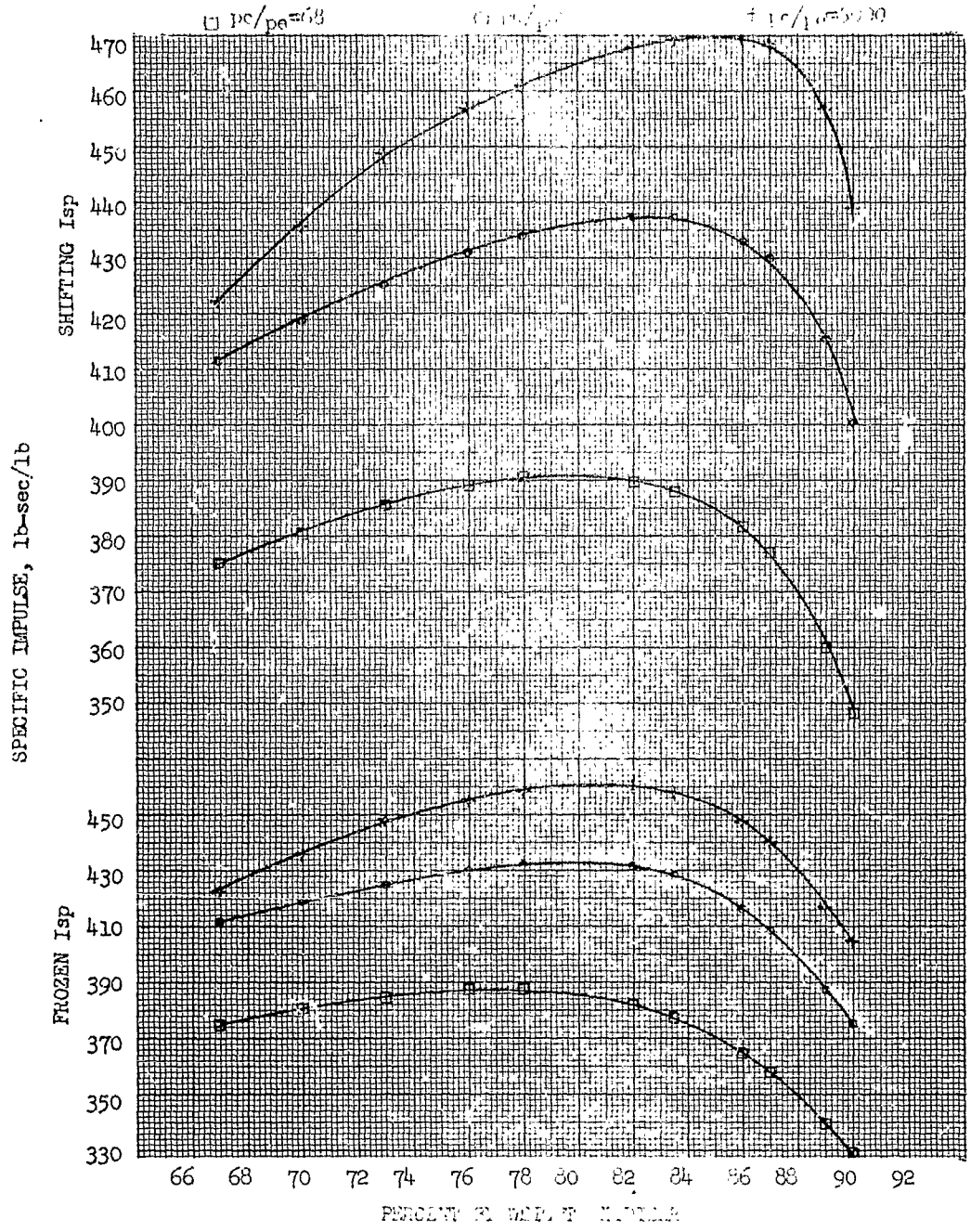
(g) $$c_F = \frac{Isp \cdot g}{c^*} = \frac{8465}{5680} = 1.491$$

(h) $$\frac{A_e}{A^*} = \frac{g}{c^*} \cdot \frac{p_c}{p_e} \cdot \frac{p_e A_e}{m} = (0.00567)\ (34.0)\ (24.25) = 4.69$$

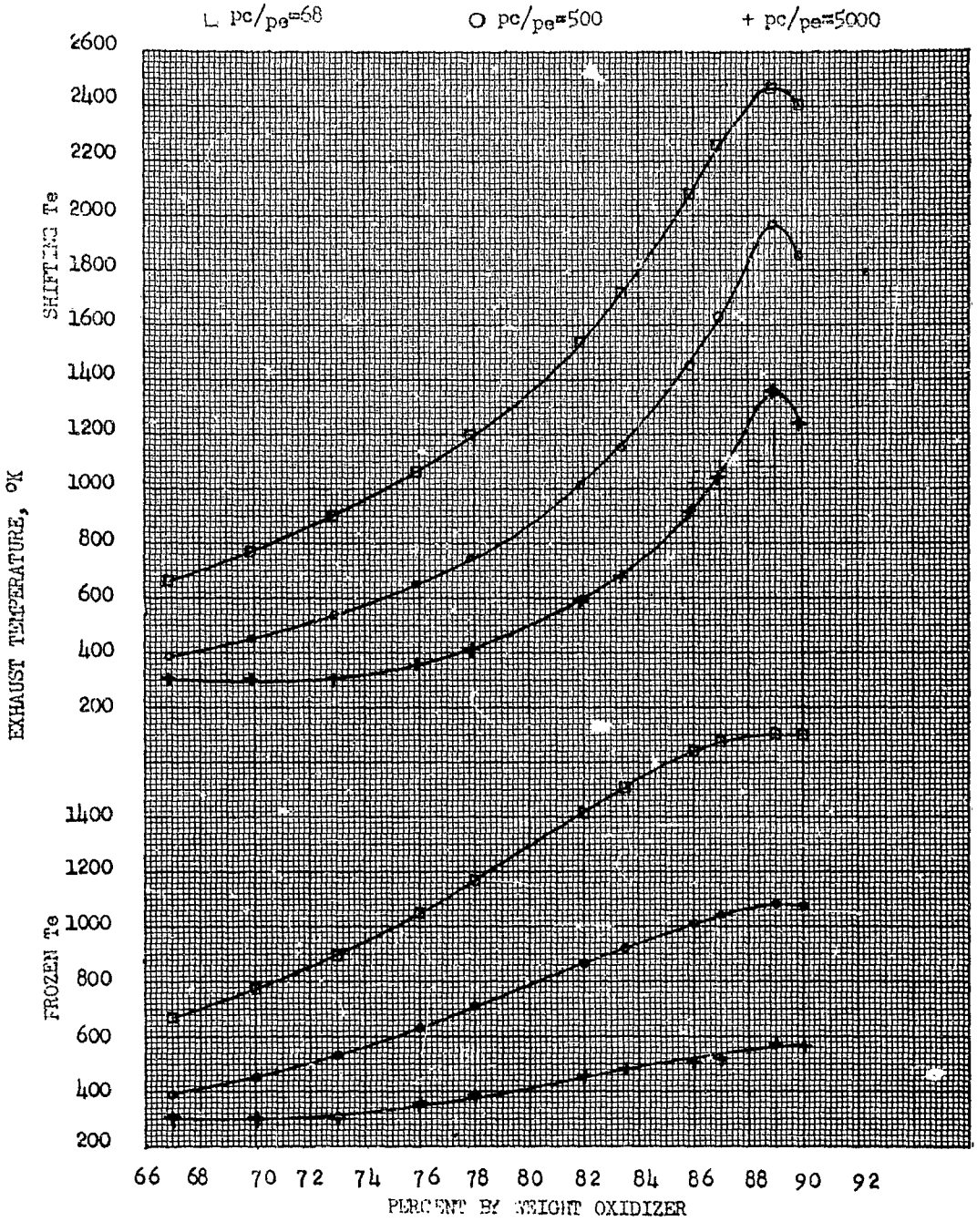
APPENDIX C

Theoretical Performance Curves for the Various Propellant Systems

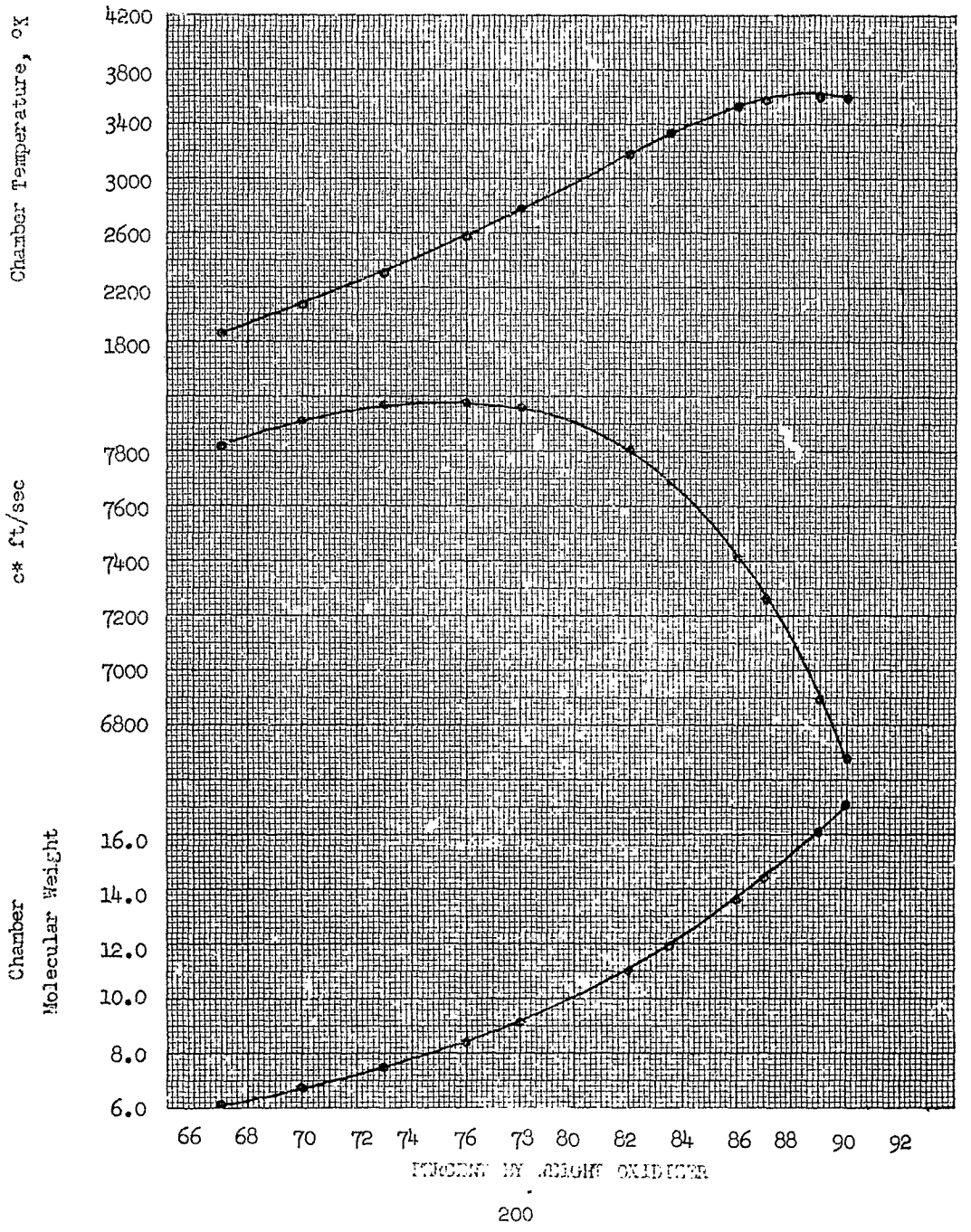
LIQUID HYDROGEN - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 1



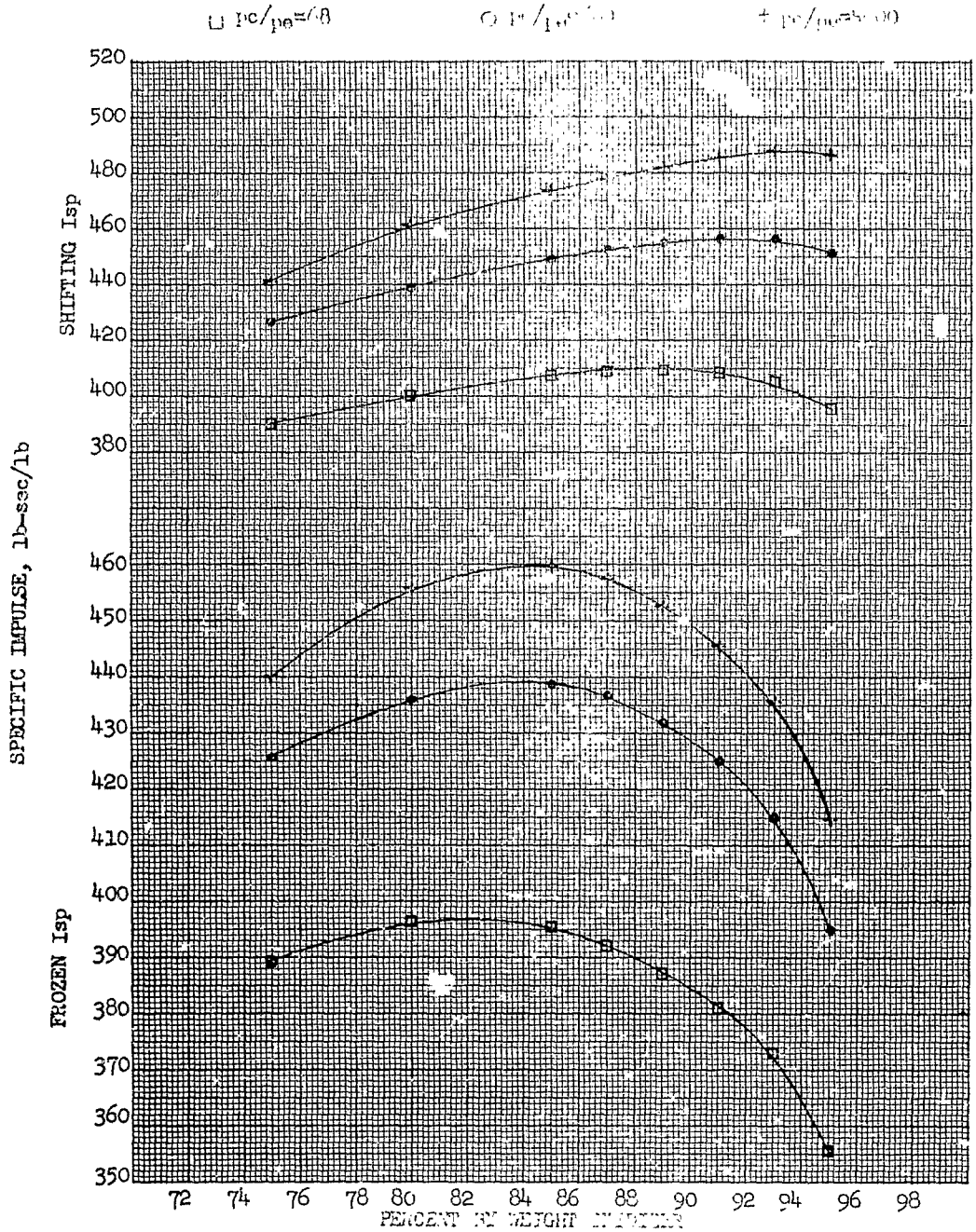
LIQUID HYDROGEN - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 2



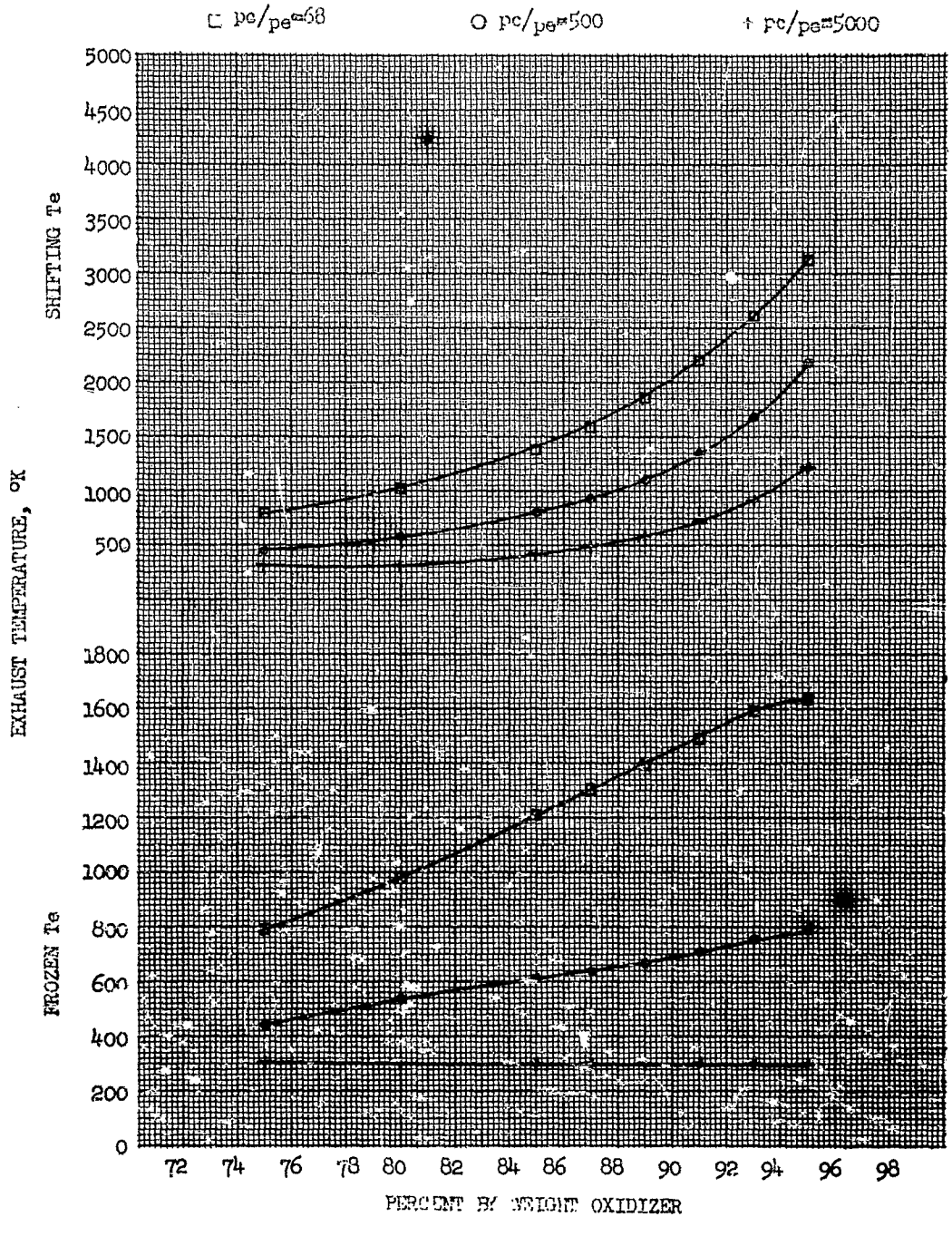
LIQUID HYDROGEN - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 3



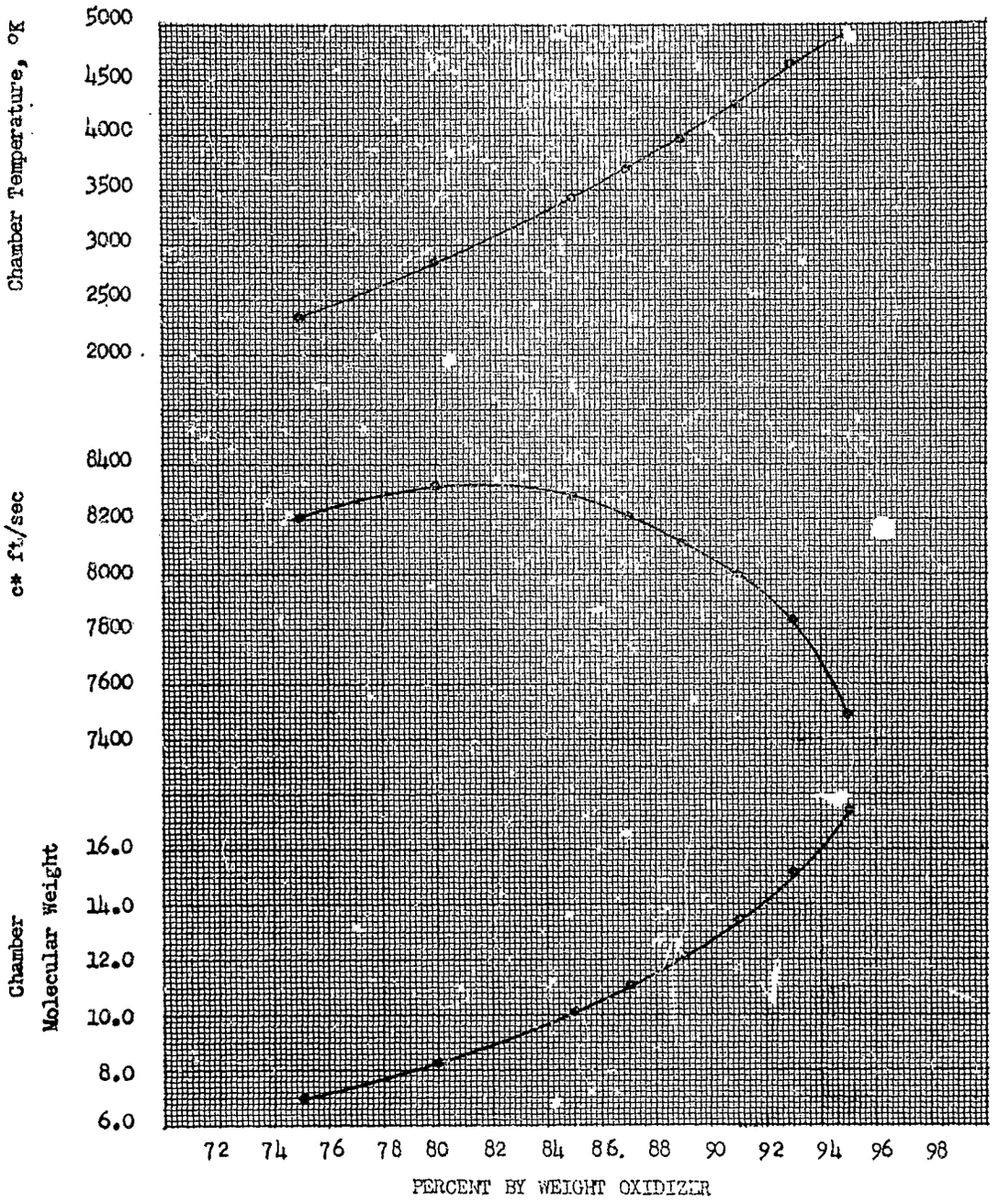
LIQUID HYDROGEN - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 4



LIQUID HYDROGEN - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 5



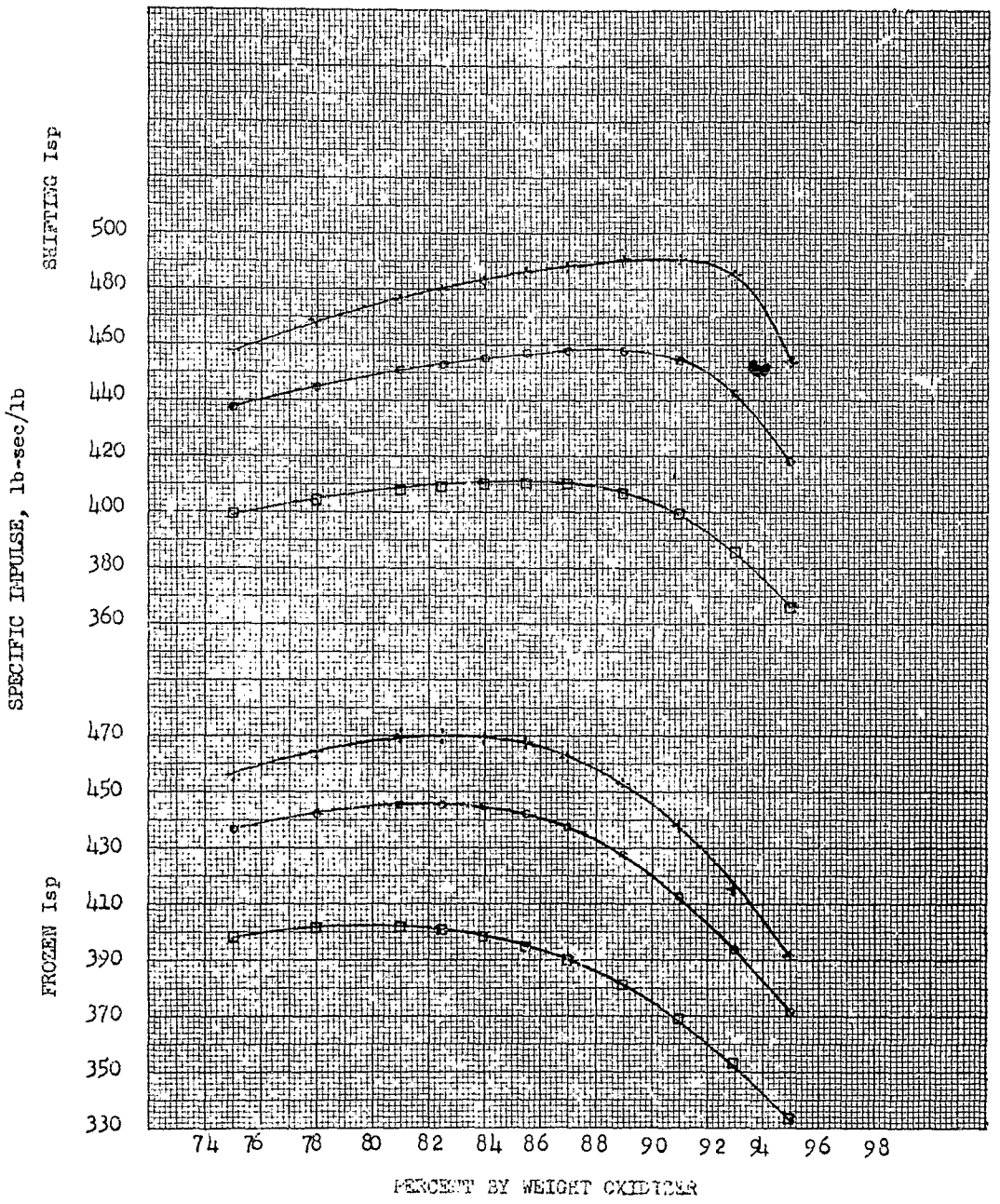
LIQUID HYDROGEN - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 6



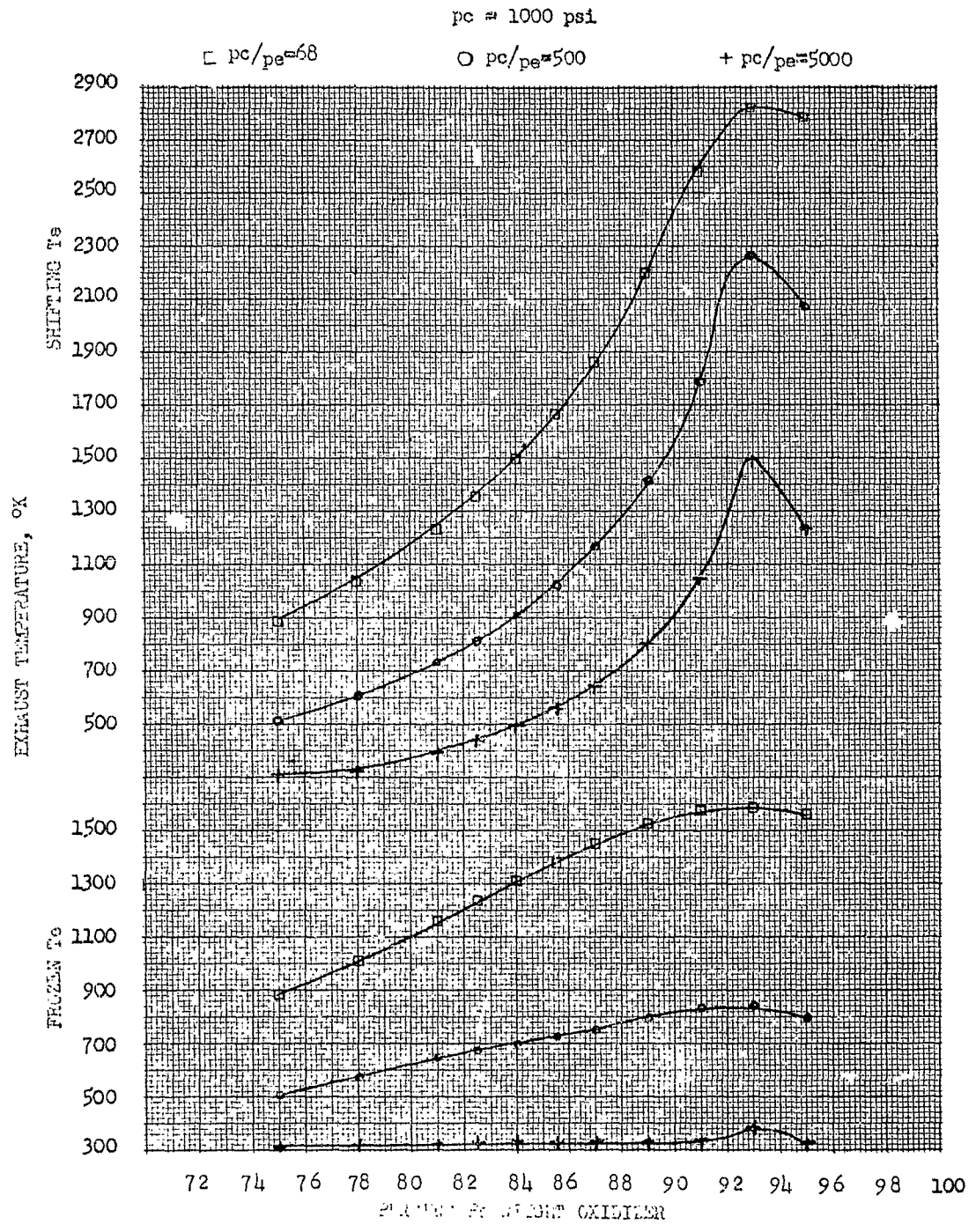
LIQUID HYDROGEN - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 7

p_e = 1000 psi

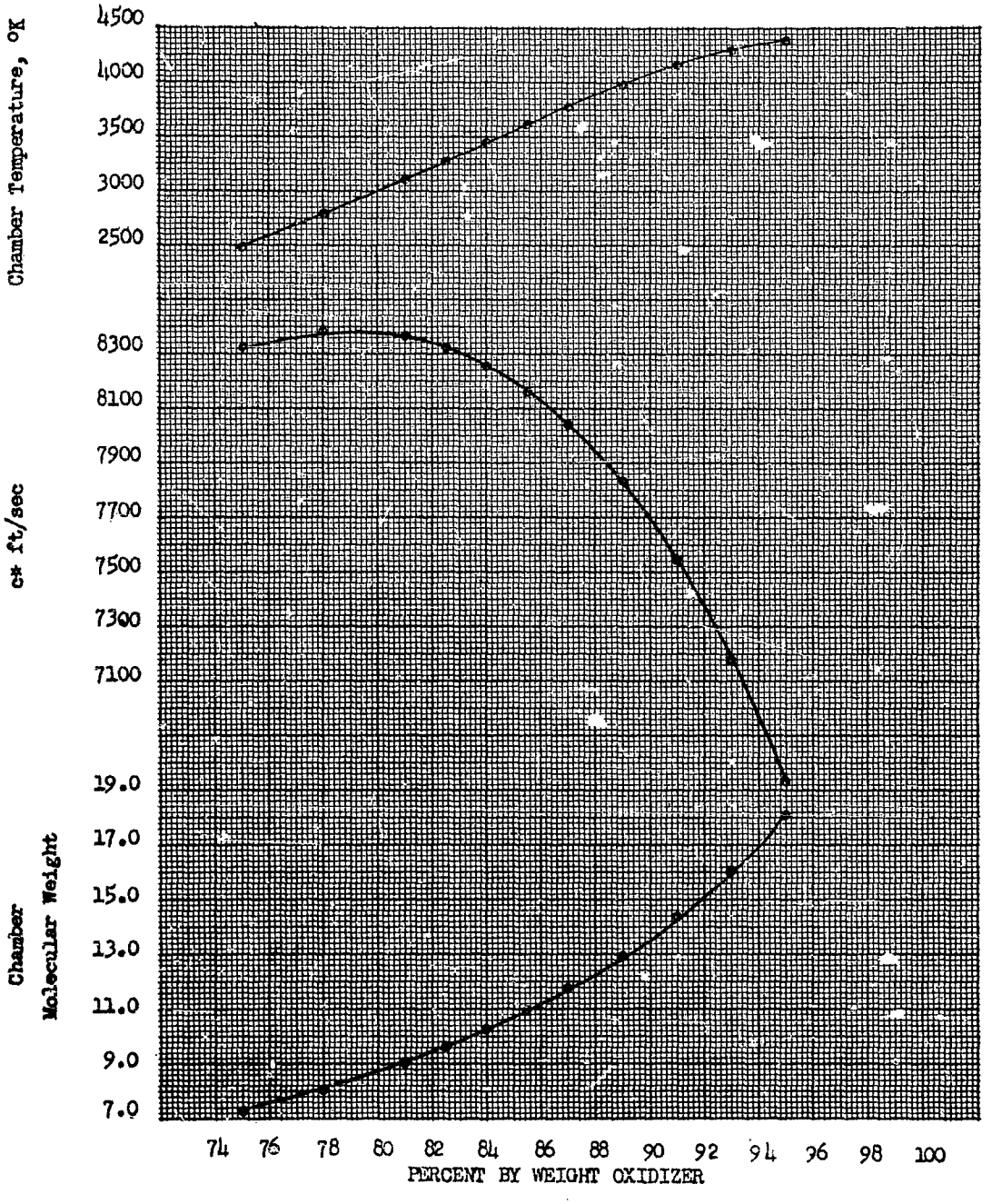
□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



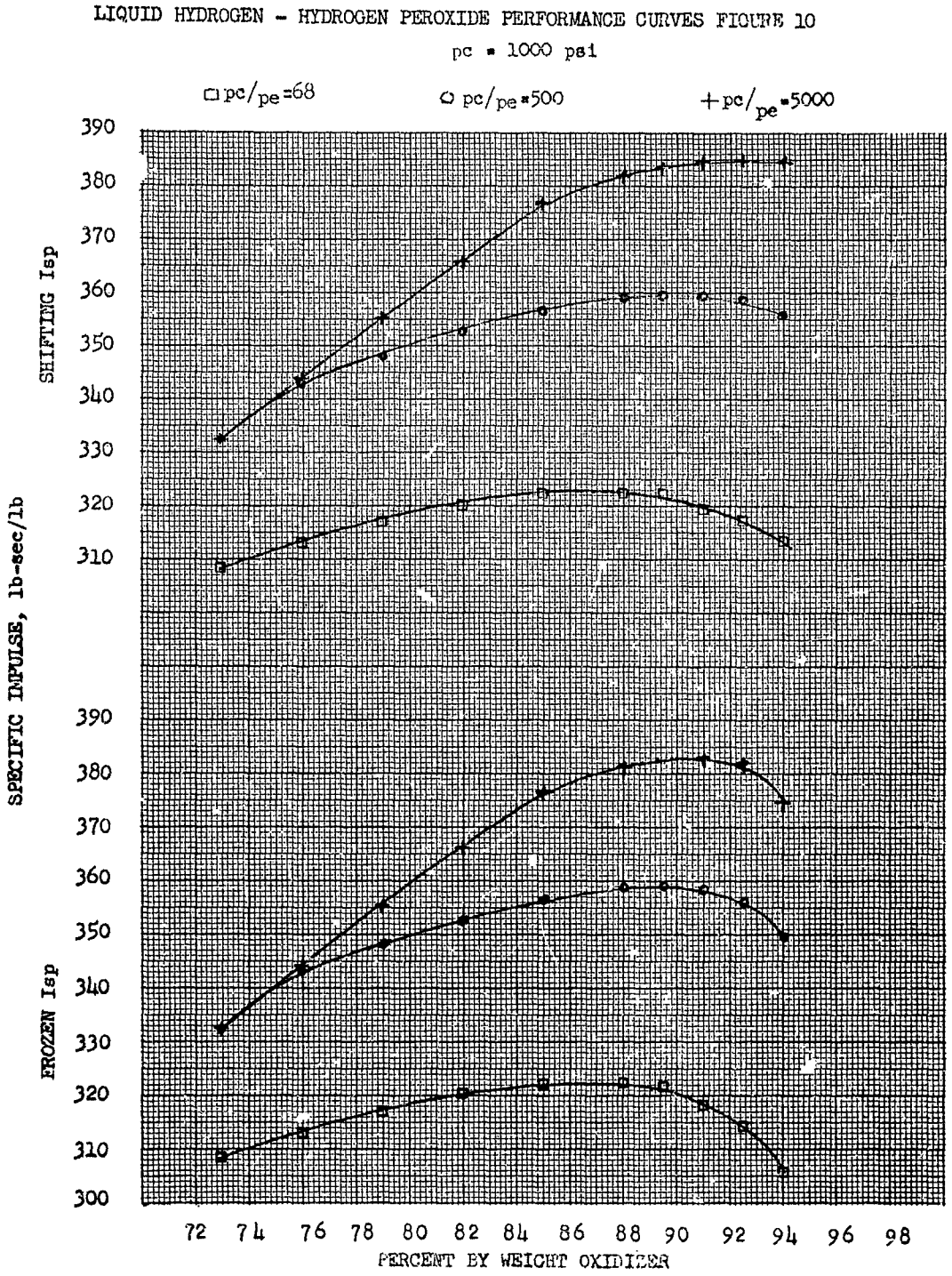
LIQUID HYDROGEN - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 8

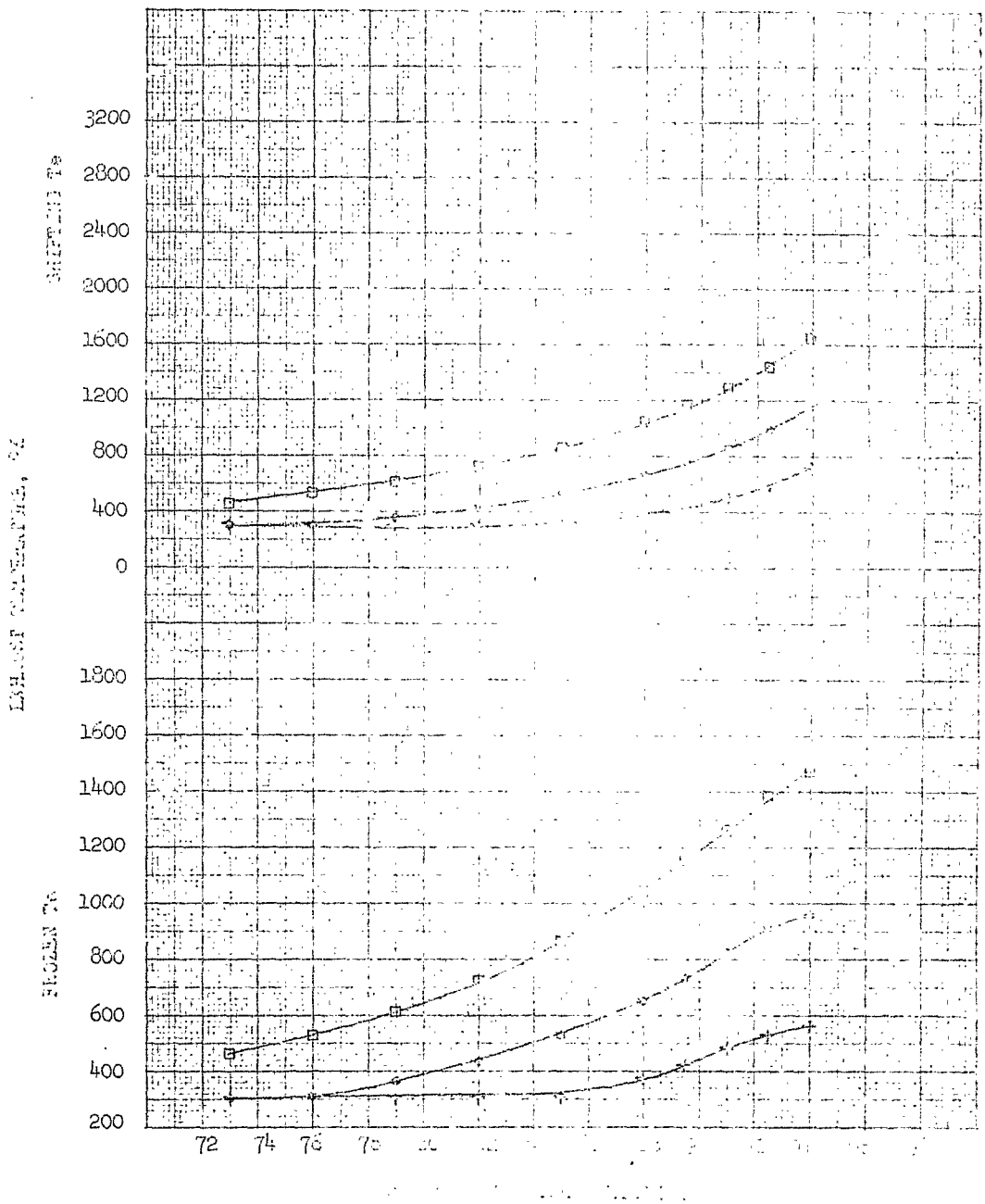


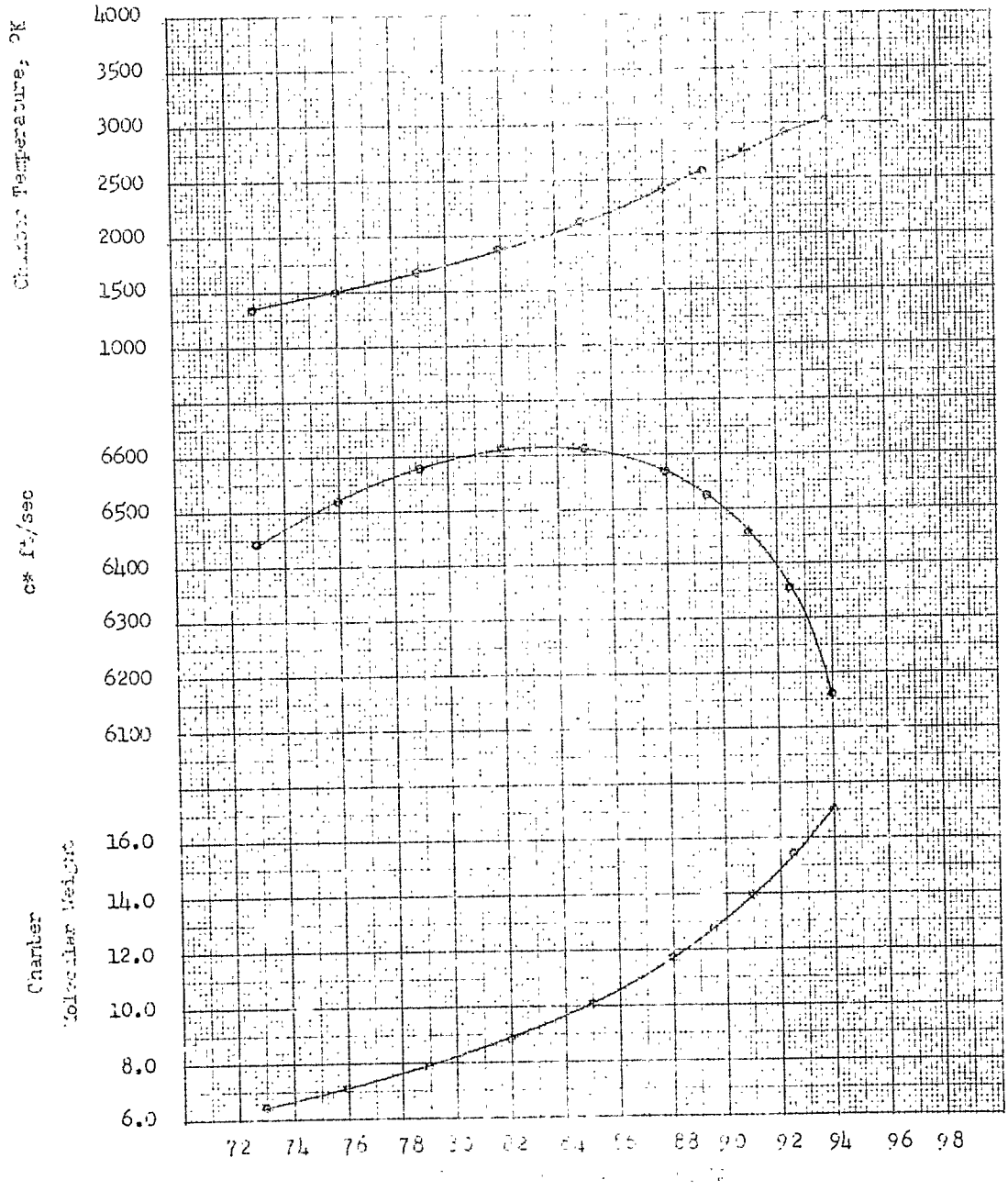
LIQUID HYDROGEN - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 9



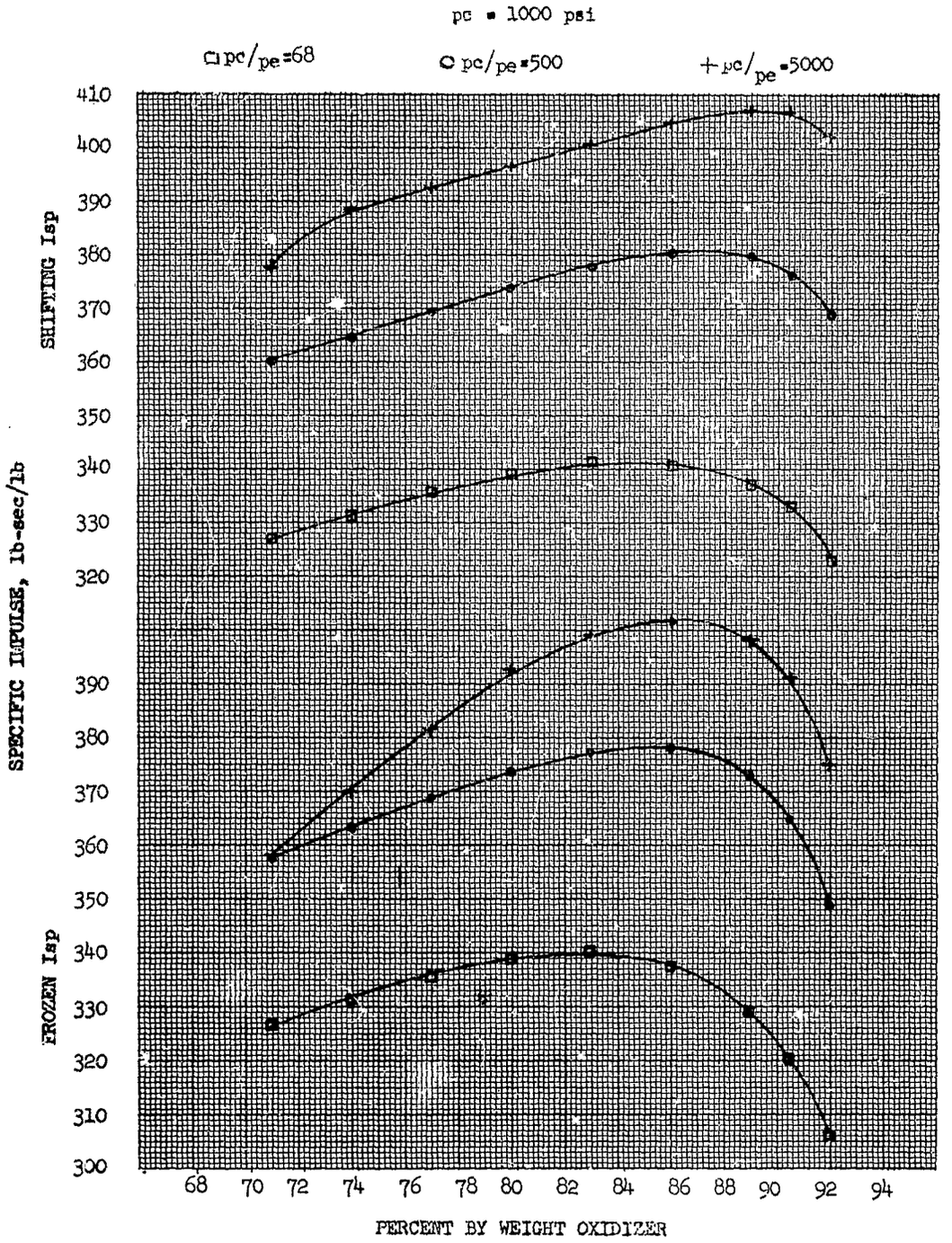
LIQUID HYDROGEN - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 10



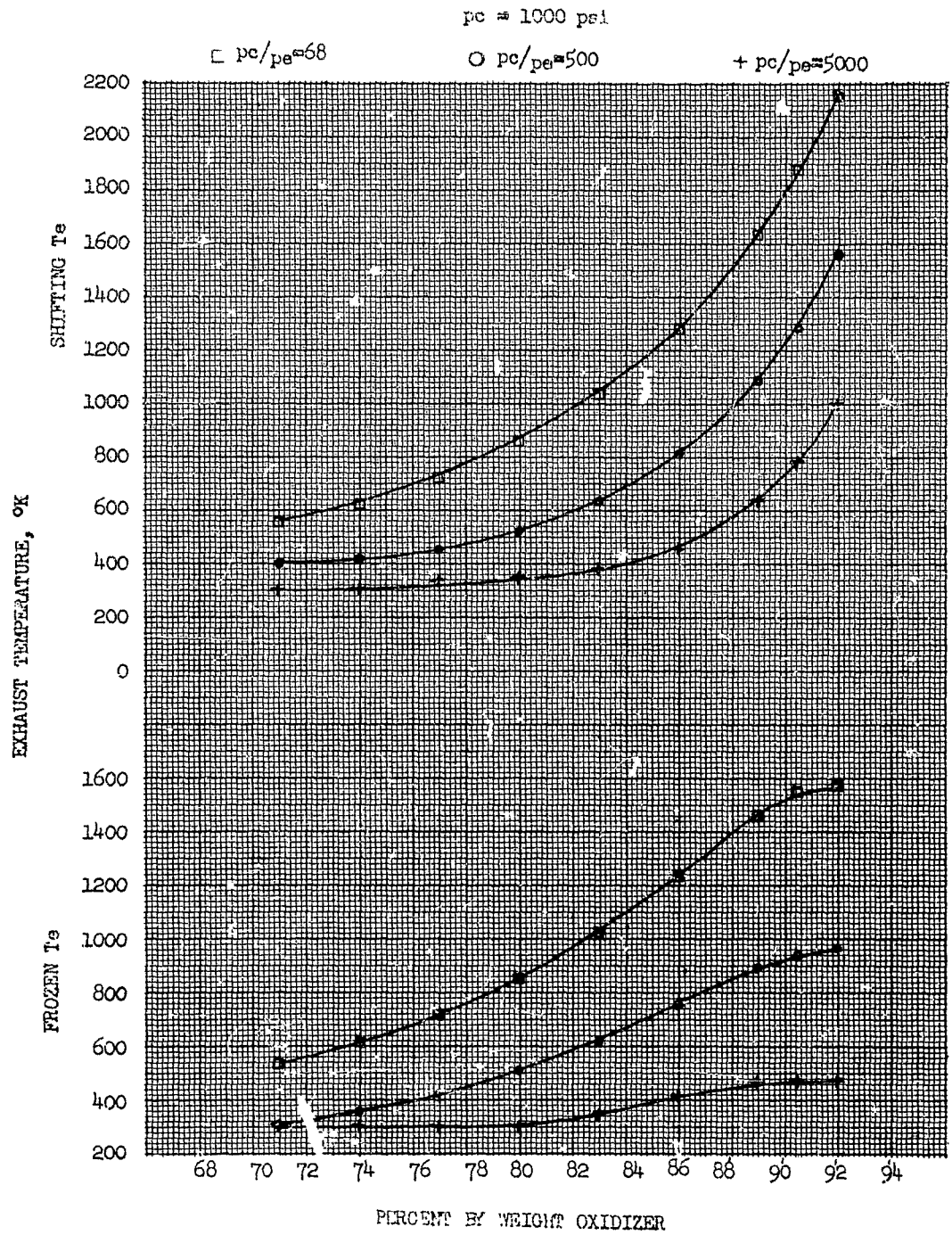

3200
2800
2400
2000
1600
1200
800
400
0
1800
1600
1400
1200
1000
800
600
400
200
72
74

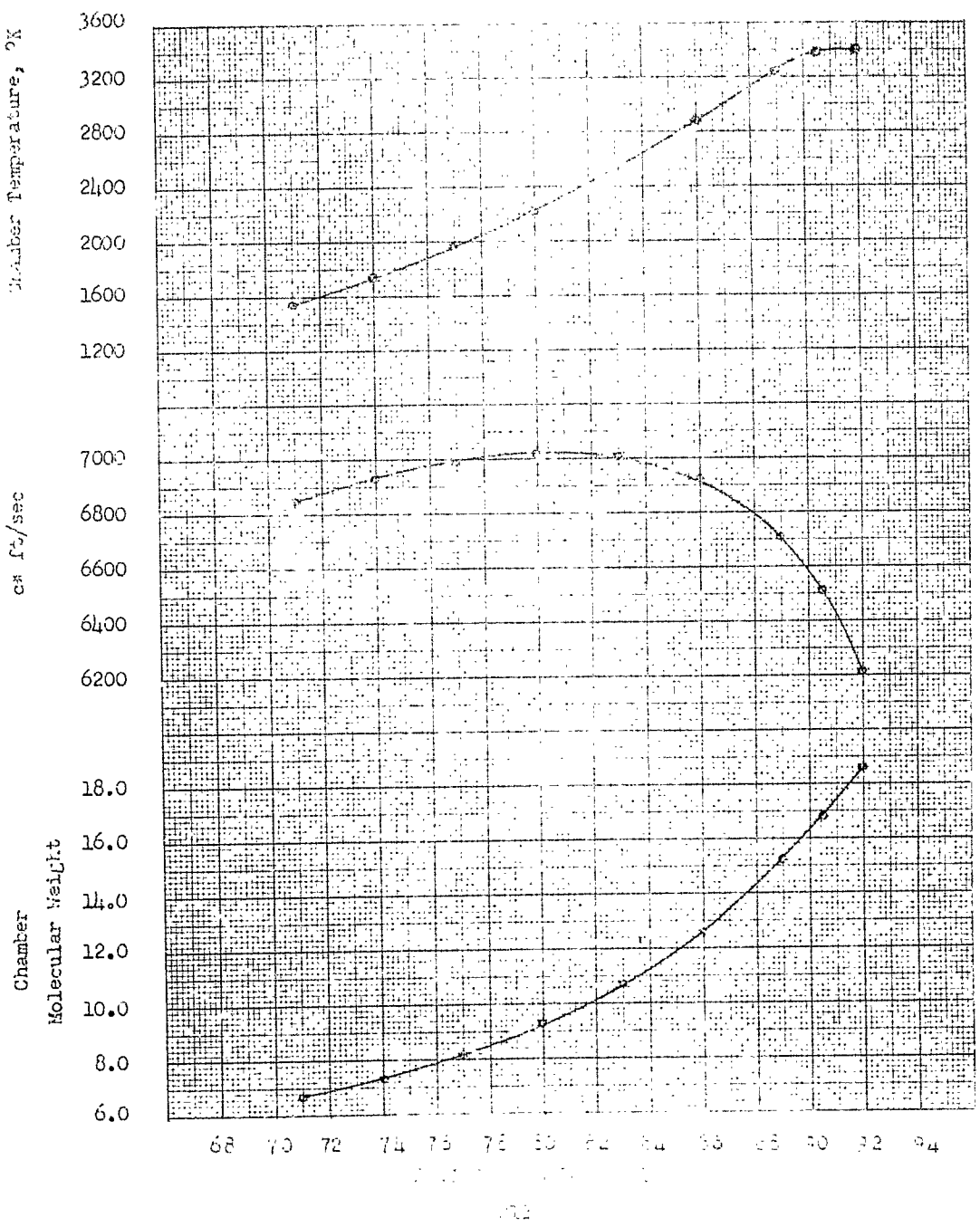

Chamber Temperature, °K
4000
3500
3000
2500
2000
1500
1000
c* ft/sec
6600
6500
6400
6300
6200
6100
Chamber
16.0
14.0
12.0
10.0
8.0
6.0
72
74
76
78
80
82
84
86
88
90
92
94
96
98

LIQUID HYDROGEN - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 13



LIQUID HYDROGEN - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 14

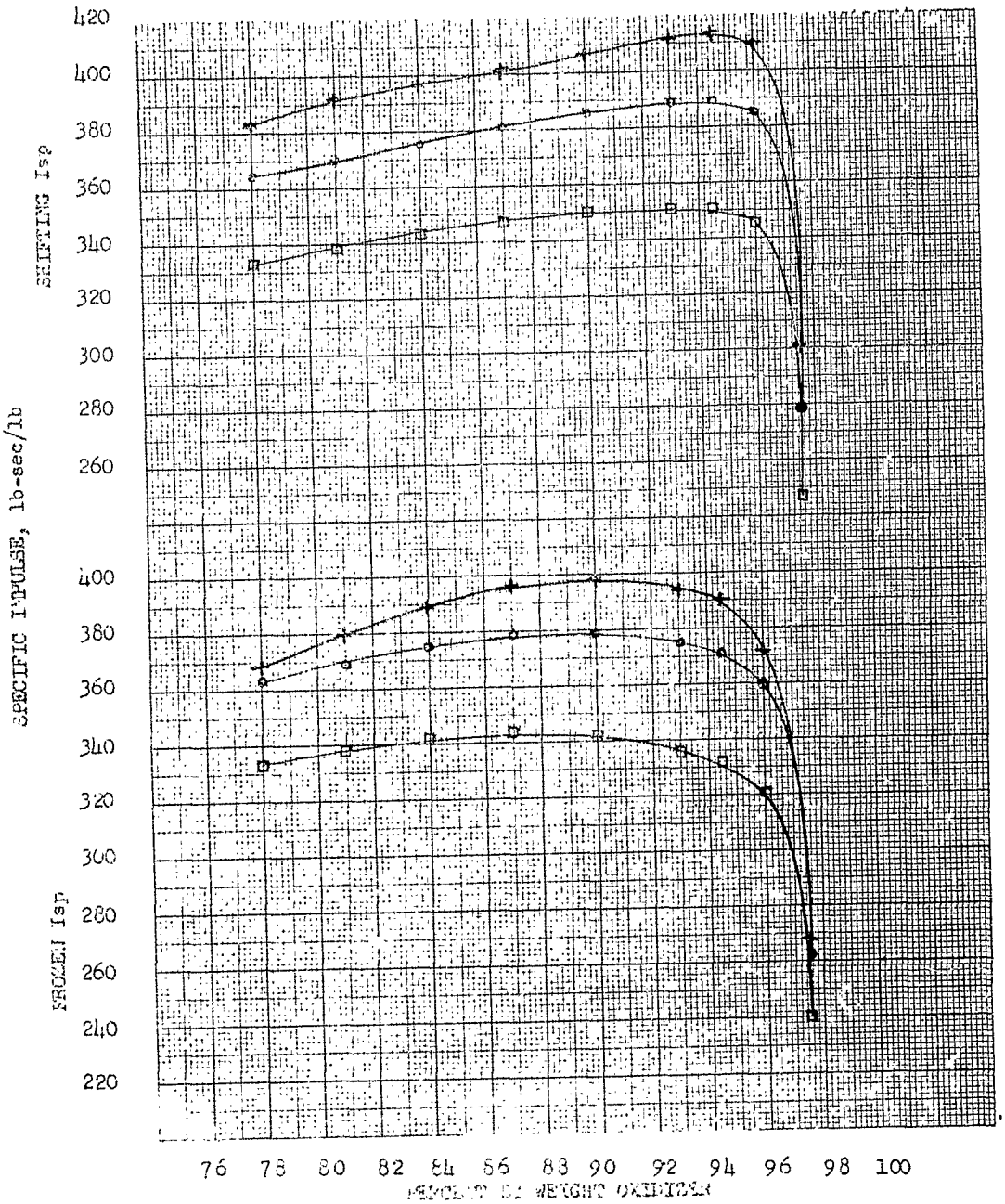



Chamber Temperature, °K
3600
3200
2800
2400
2000
1600
1200
ca ft/sec
7000
6800
6600
6400
6200
Chamber Molecular Weight
18.0
16.0
14.0
12.0
10.0
8.0
6.0
68
70
72
74
76
78
80
82
84
86
88
90
92
94

LIQUID NITROGEN - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 16

p_c = 1000 psi

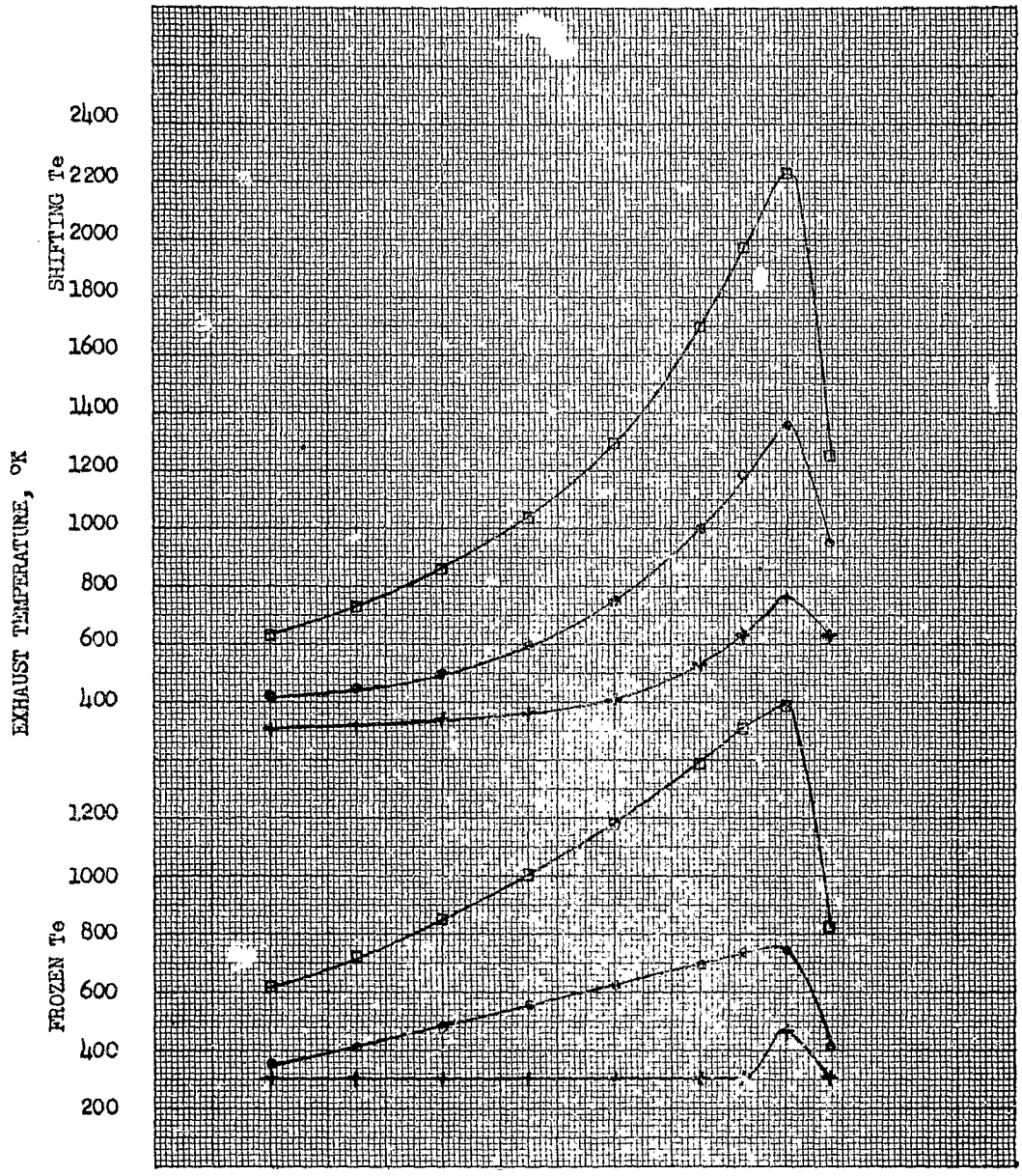
□ p_e/p_c=68 ○ p_e/p_c=500 + p_s/p_e=5000



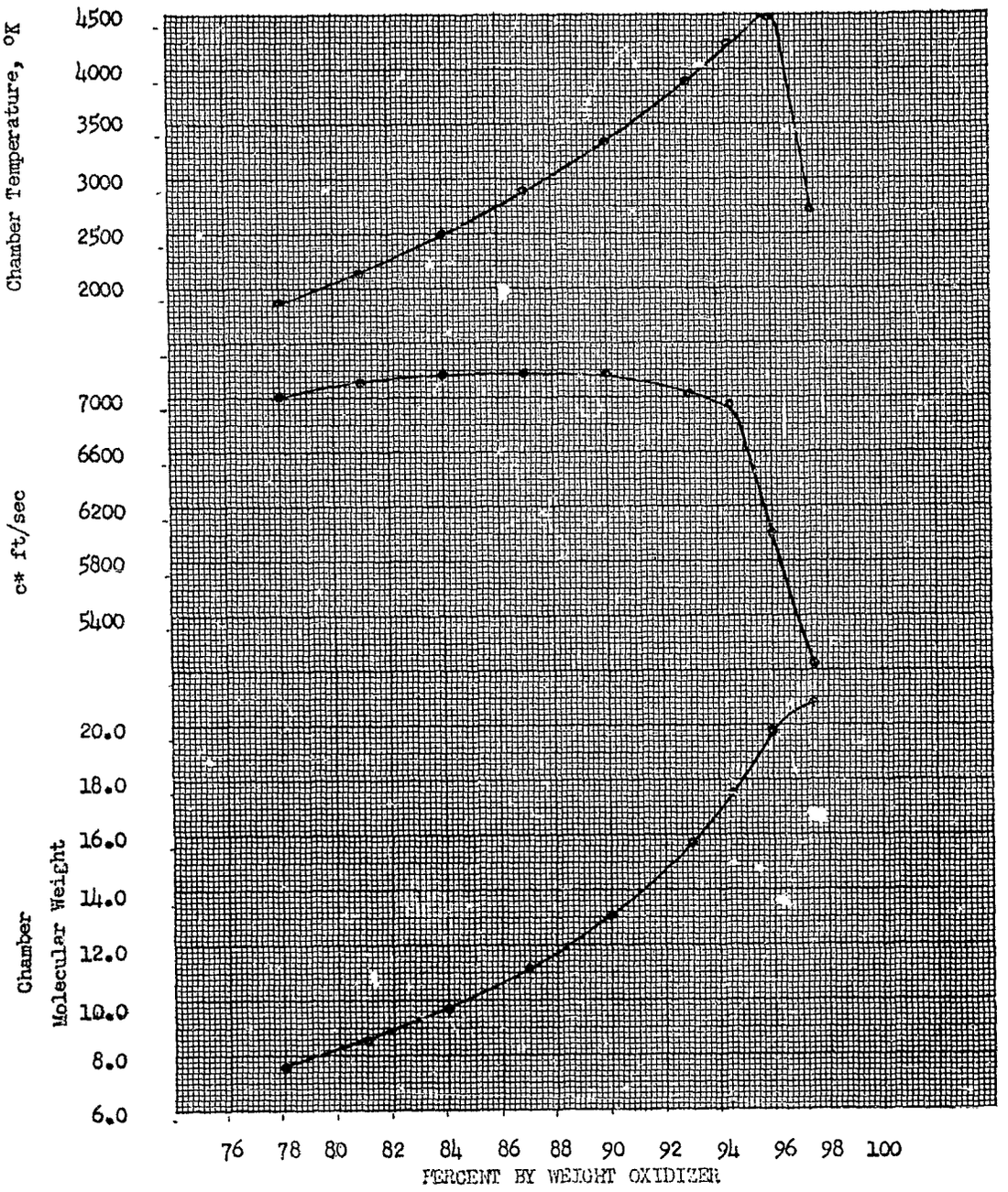
LIQUID HYDROGEN - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 17

p_c = 1000 psi

□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



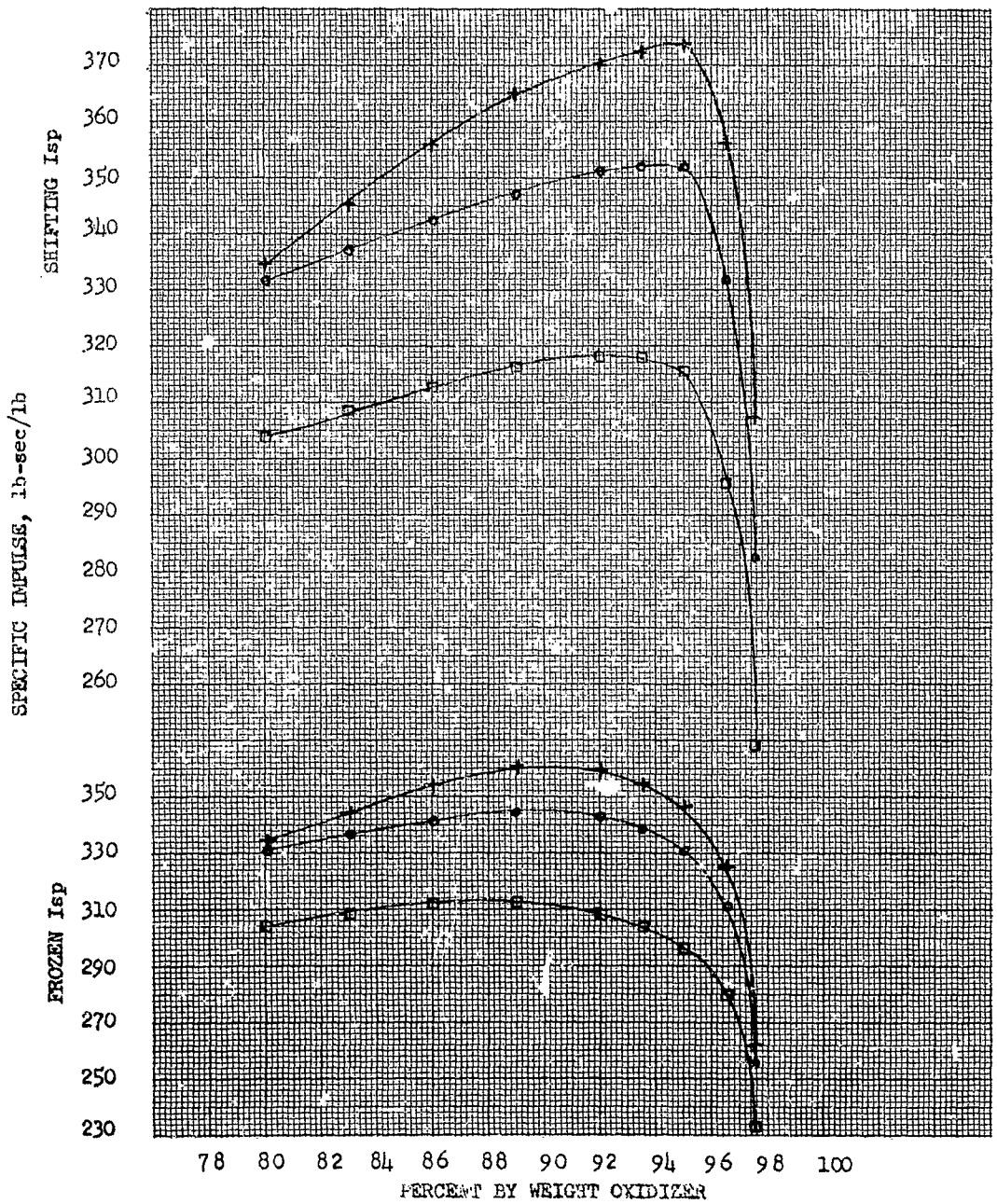
LIQUID HYDROGEN - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 18



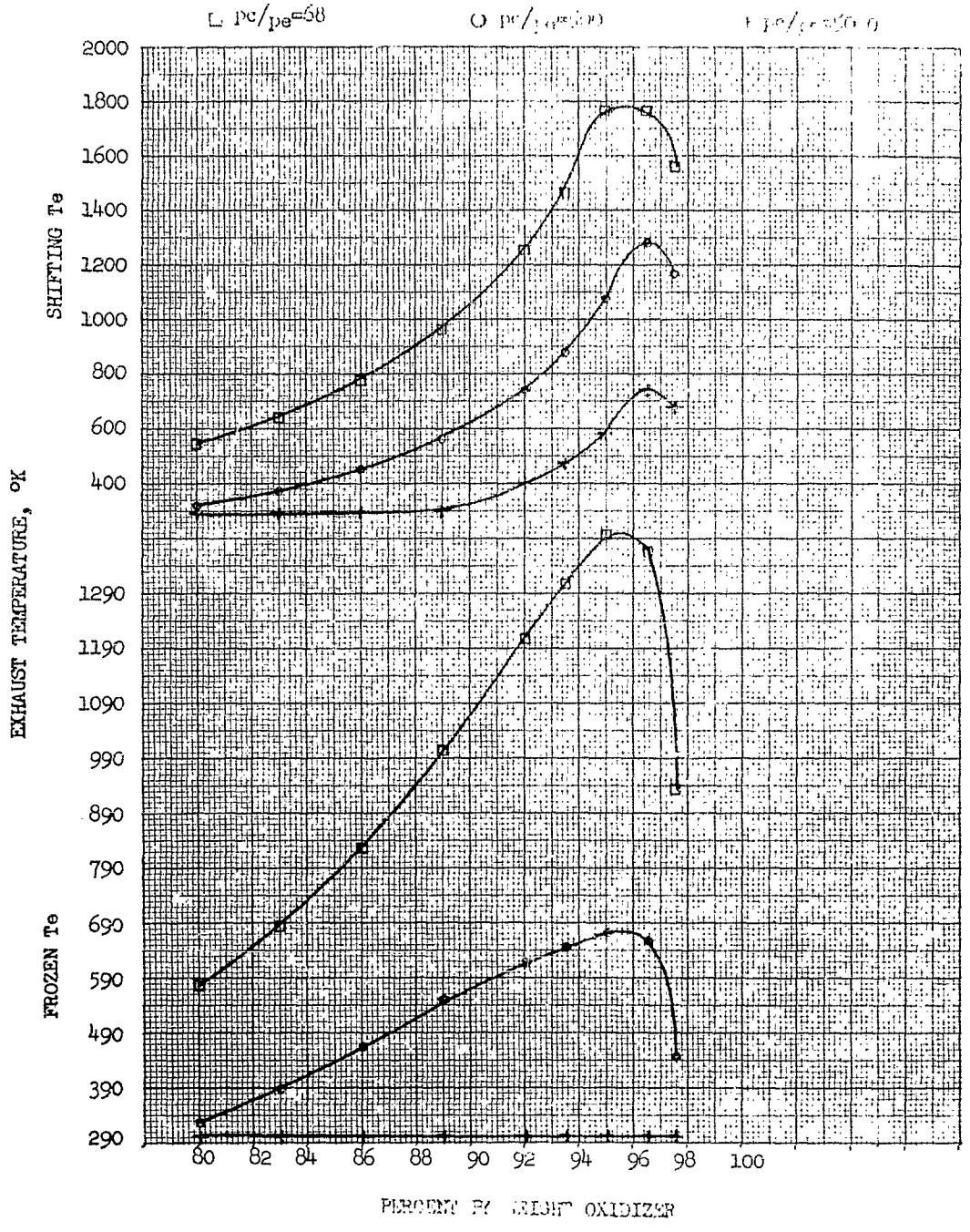
LIQUID HYDROGEN - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 19

pc = 1000 psi

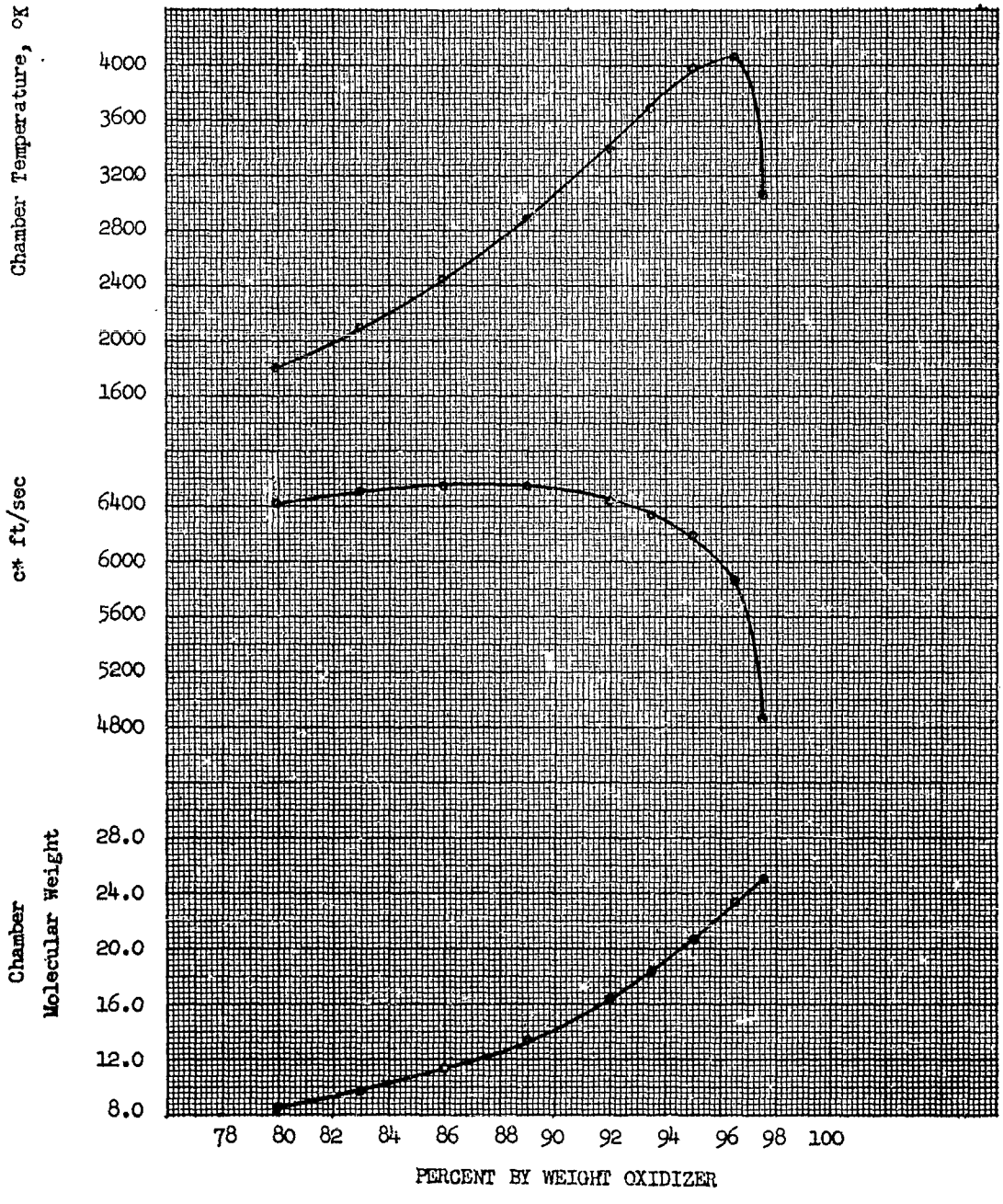
□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



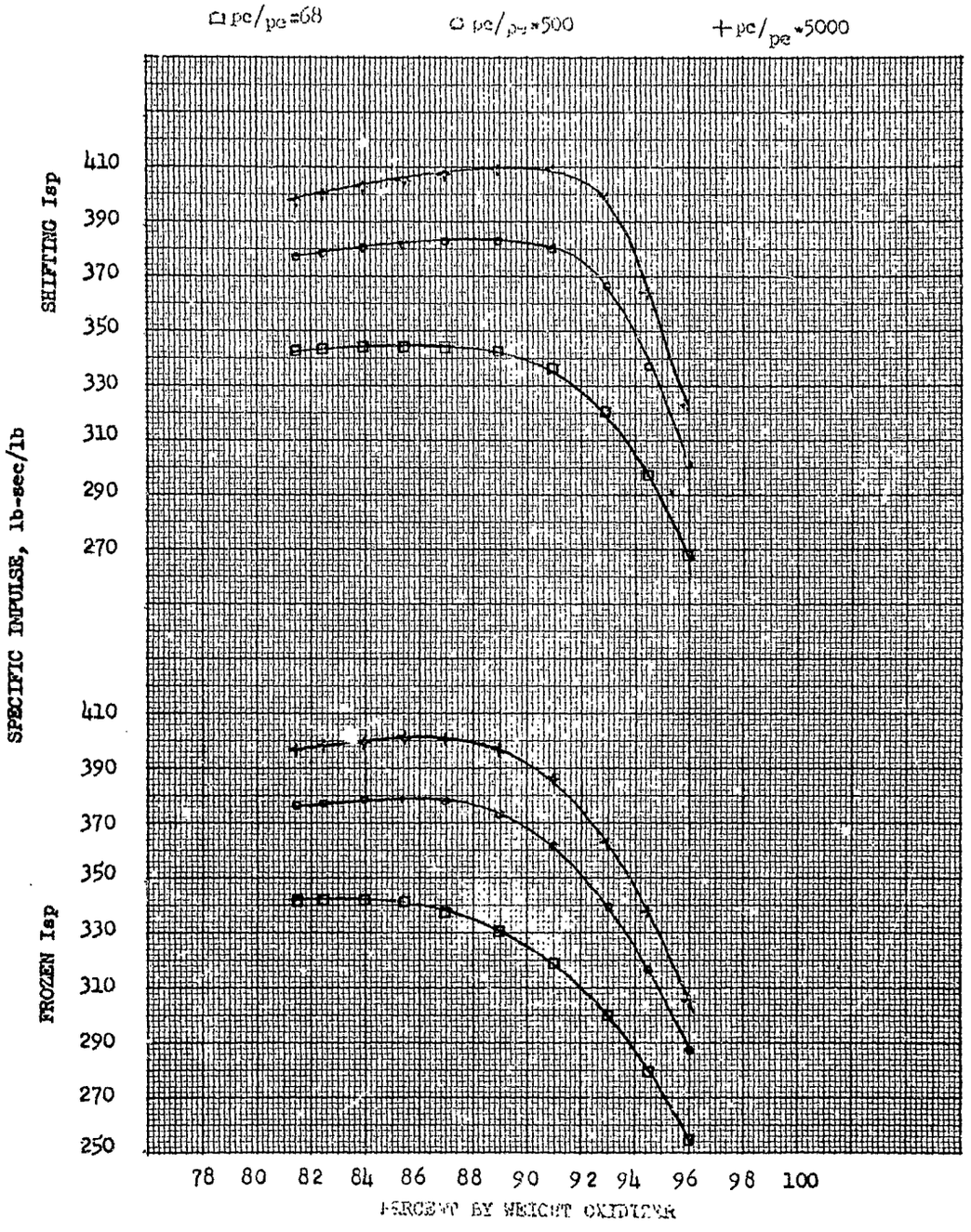
LIQUID HYDROGEN - CHLORINE TRIFLUORIDE [illegible]



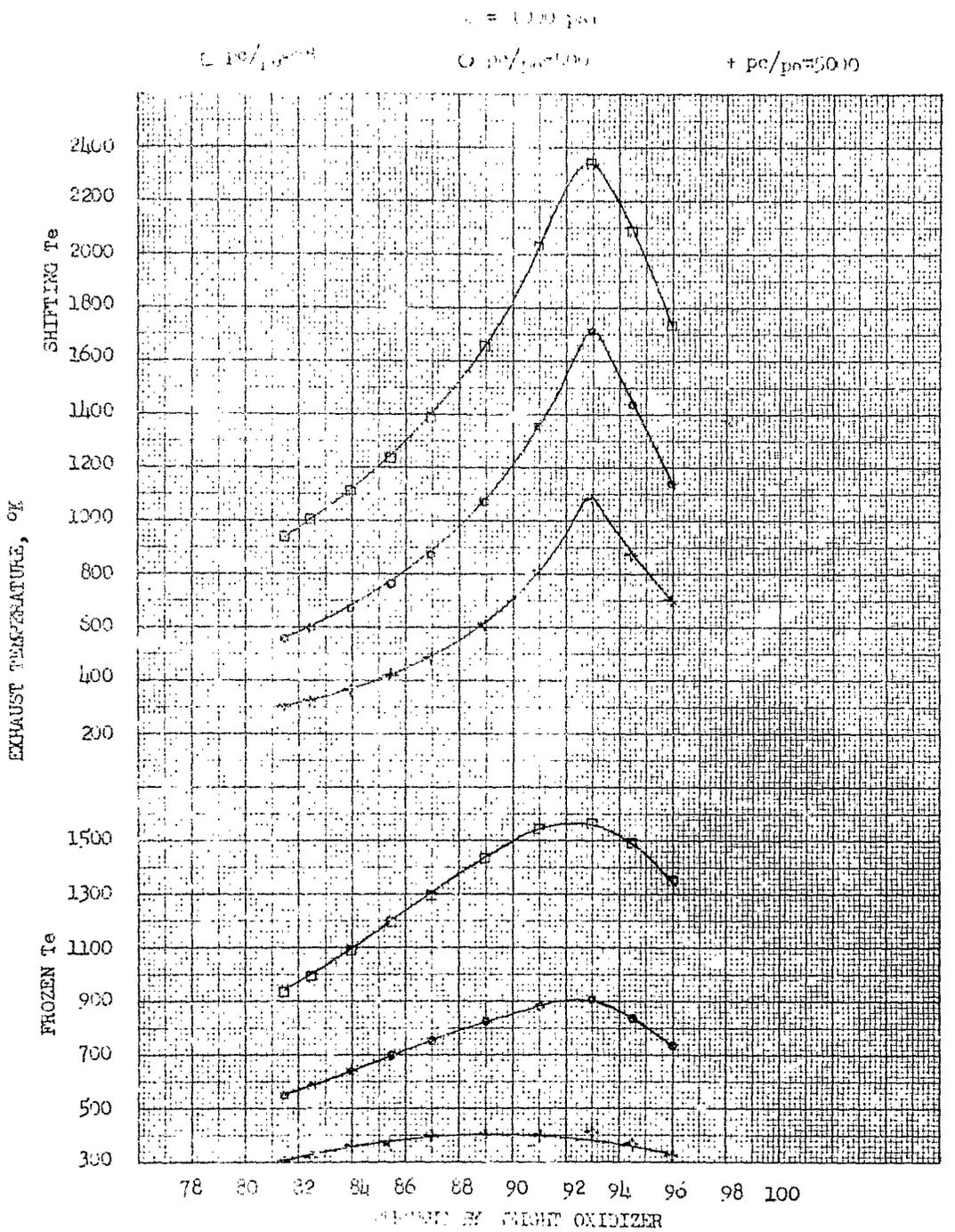
LIQUID HYDROGEN - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 21



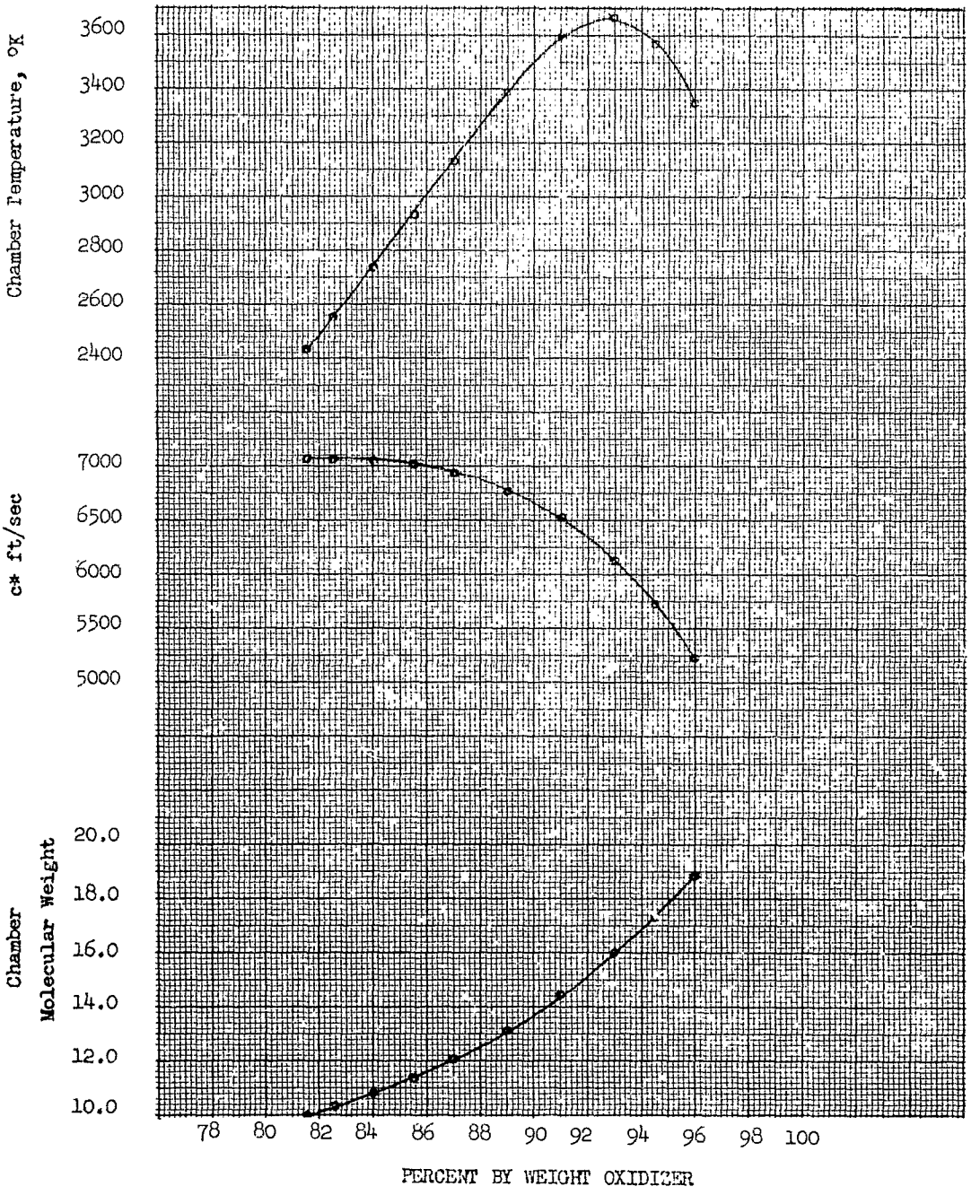
LIQUID HYDROGEN - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 22



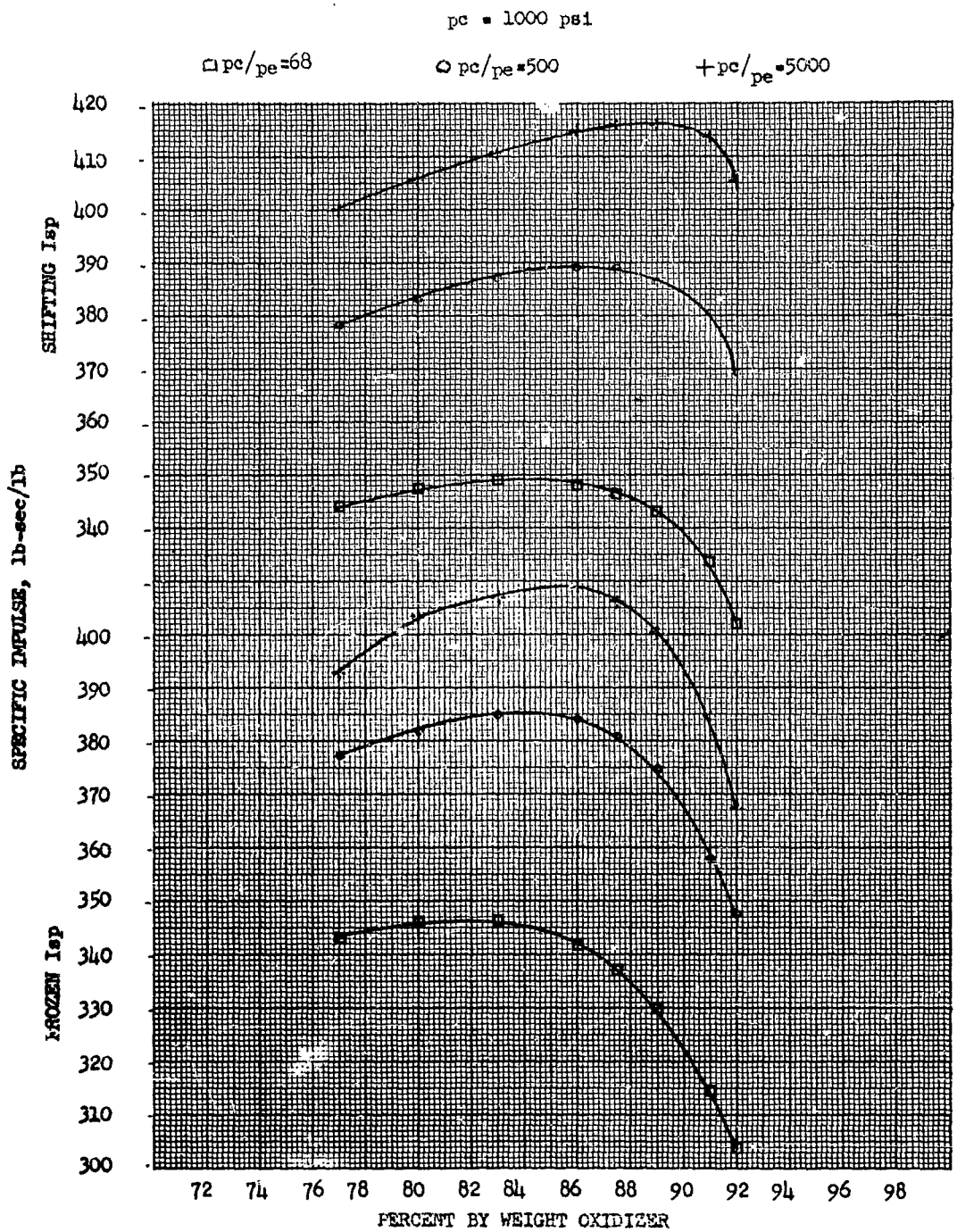
[illegible] FIGURE 23


pc/pe=50:1
pc/pe=500
pc/pe=50:0
SHIFTING Te
FROZEN Te
EXHAUST TEMPERATURE, °K
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
1500
1300
1100
900
700
500
300
78
80
82
84
86
88
90
92
94
96
98
100
PERCENT BY WEIGHT OXIDIZER

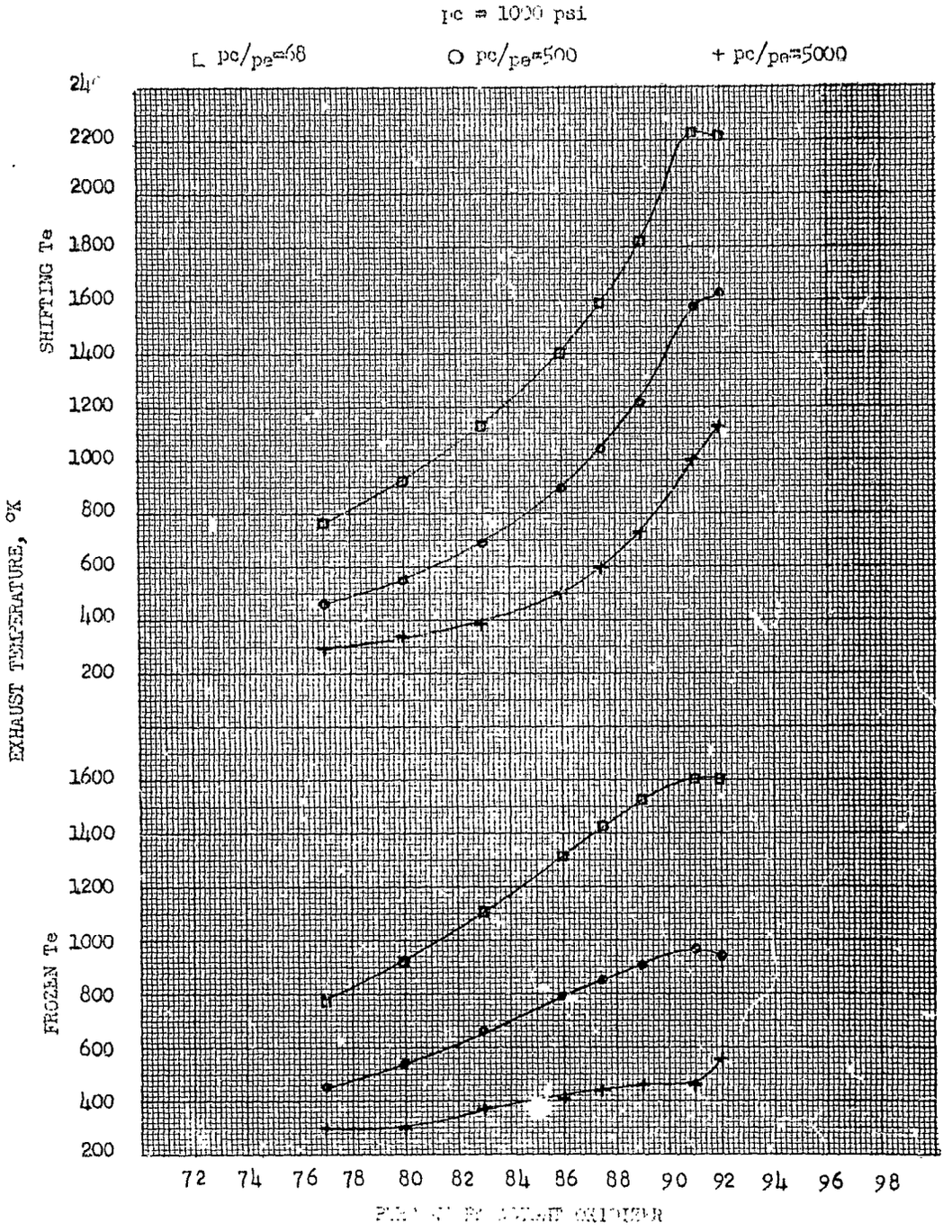
LIQUID HYDROGEN - PERCHLORYL FLUORIDE [illegible]



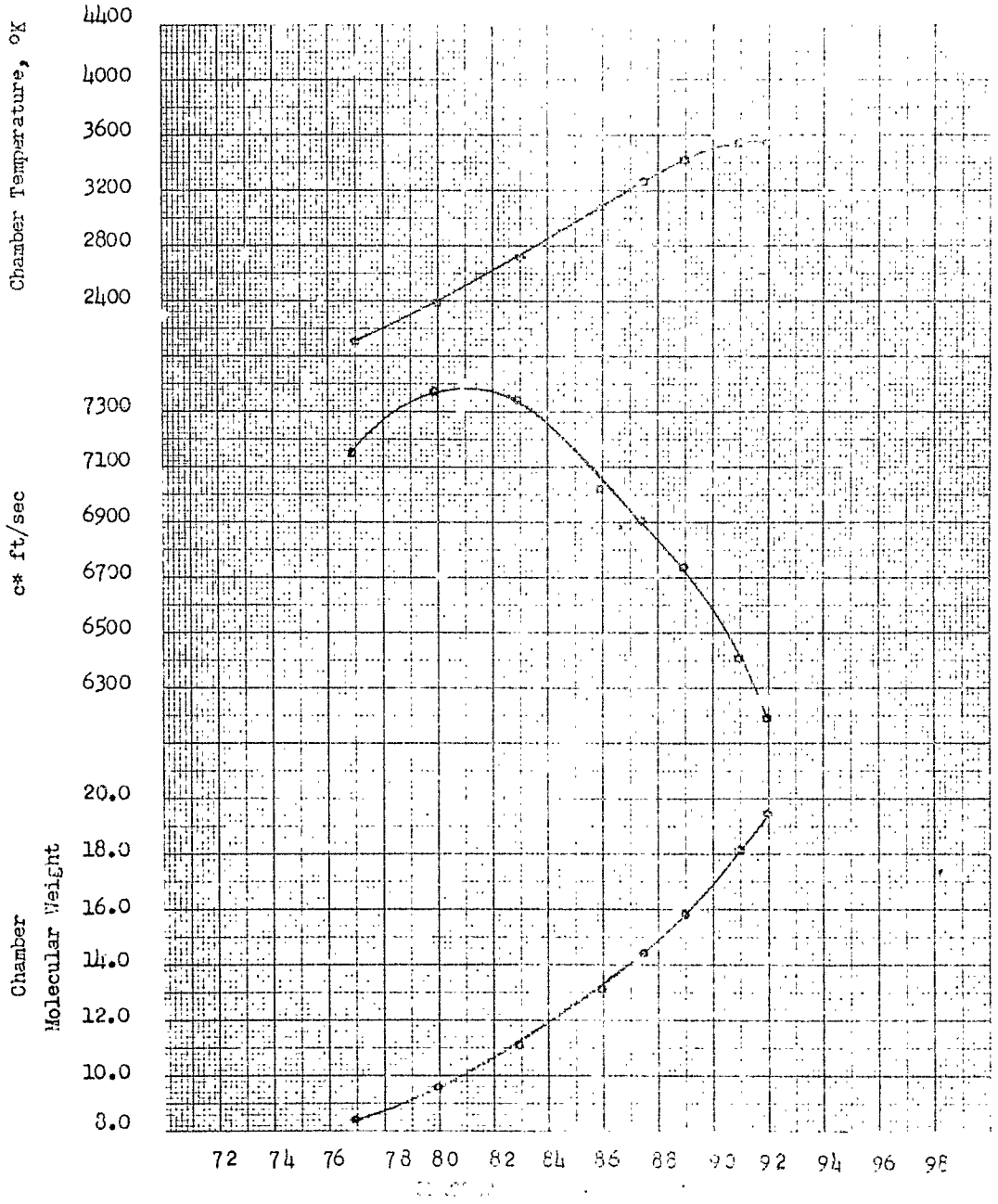
LIQUID HYDROGEN - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 25

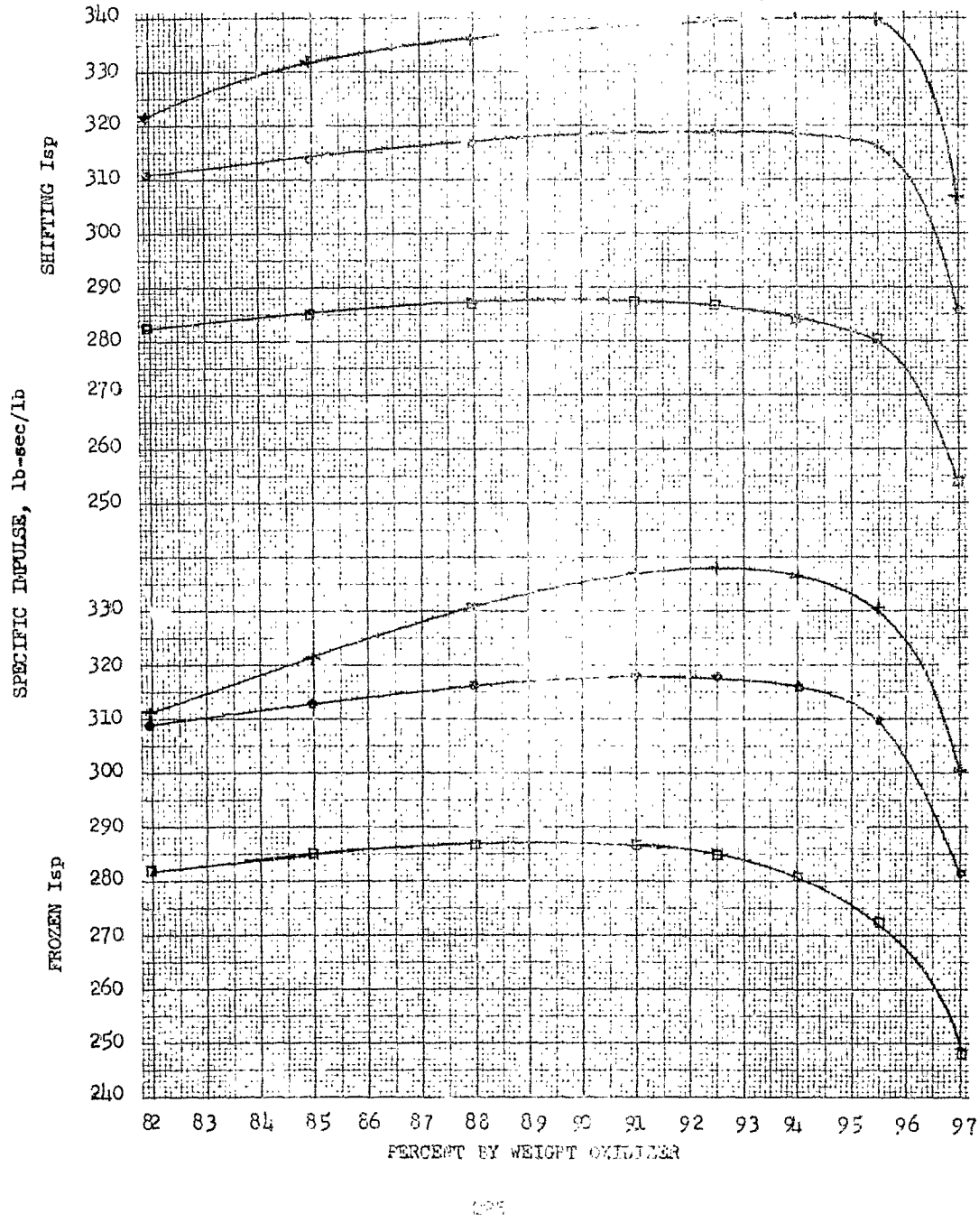


LIQUID HYDROGEN - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 26

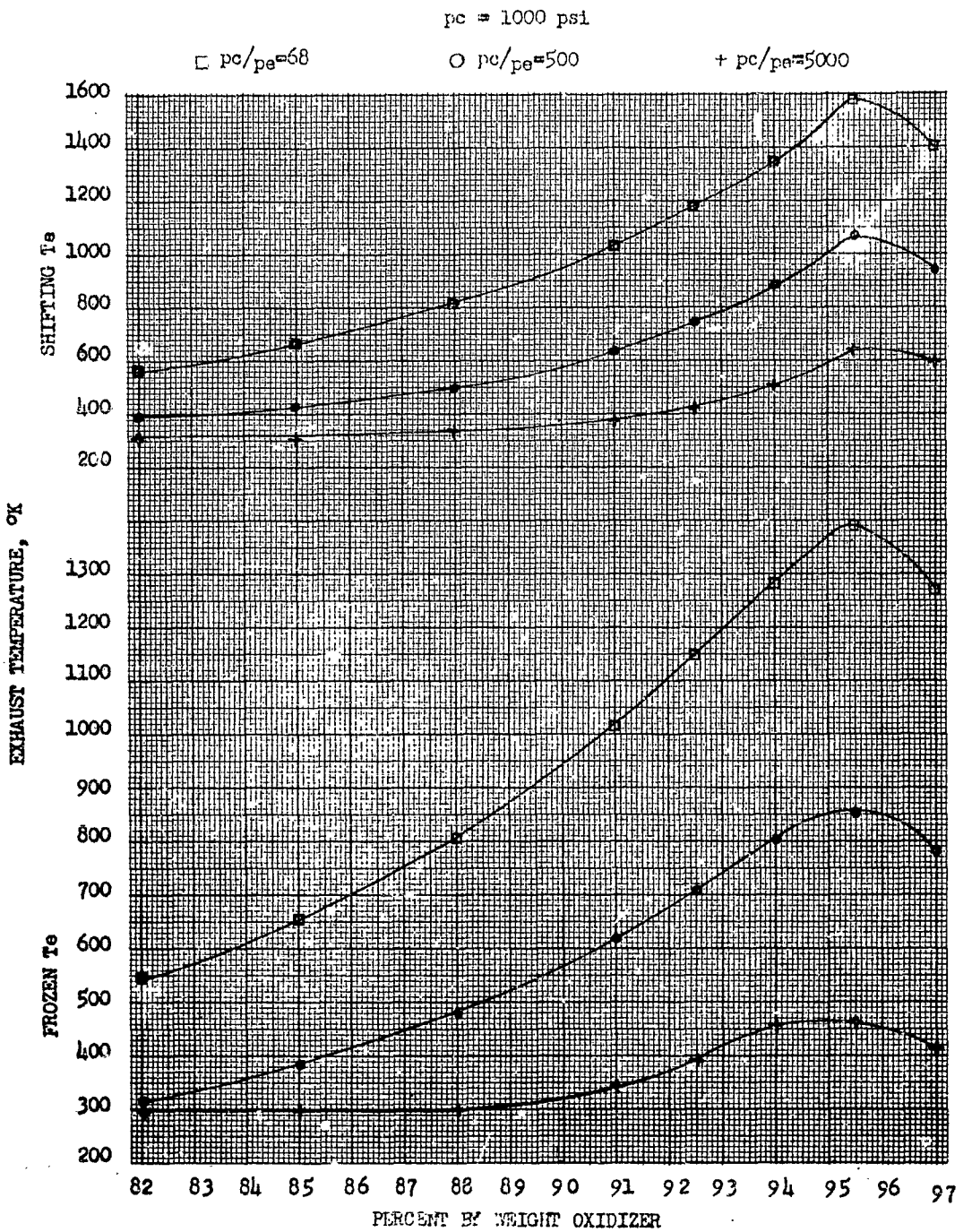


LIQUID HYDROGEN – [illegible]

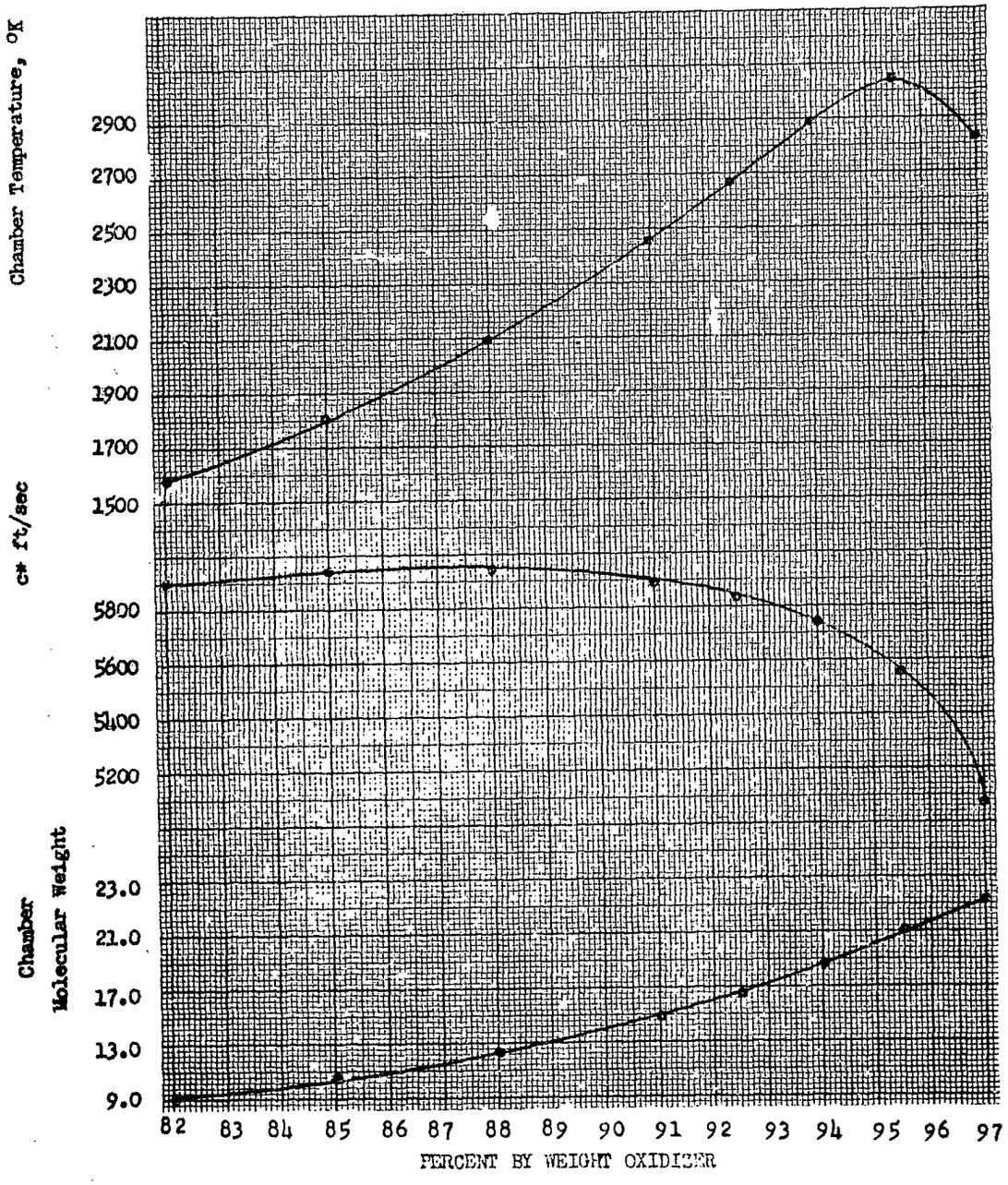


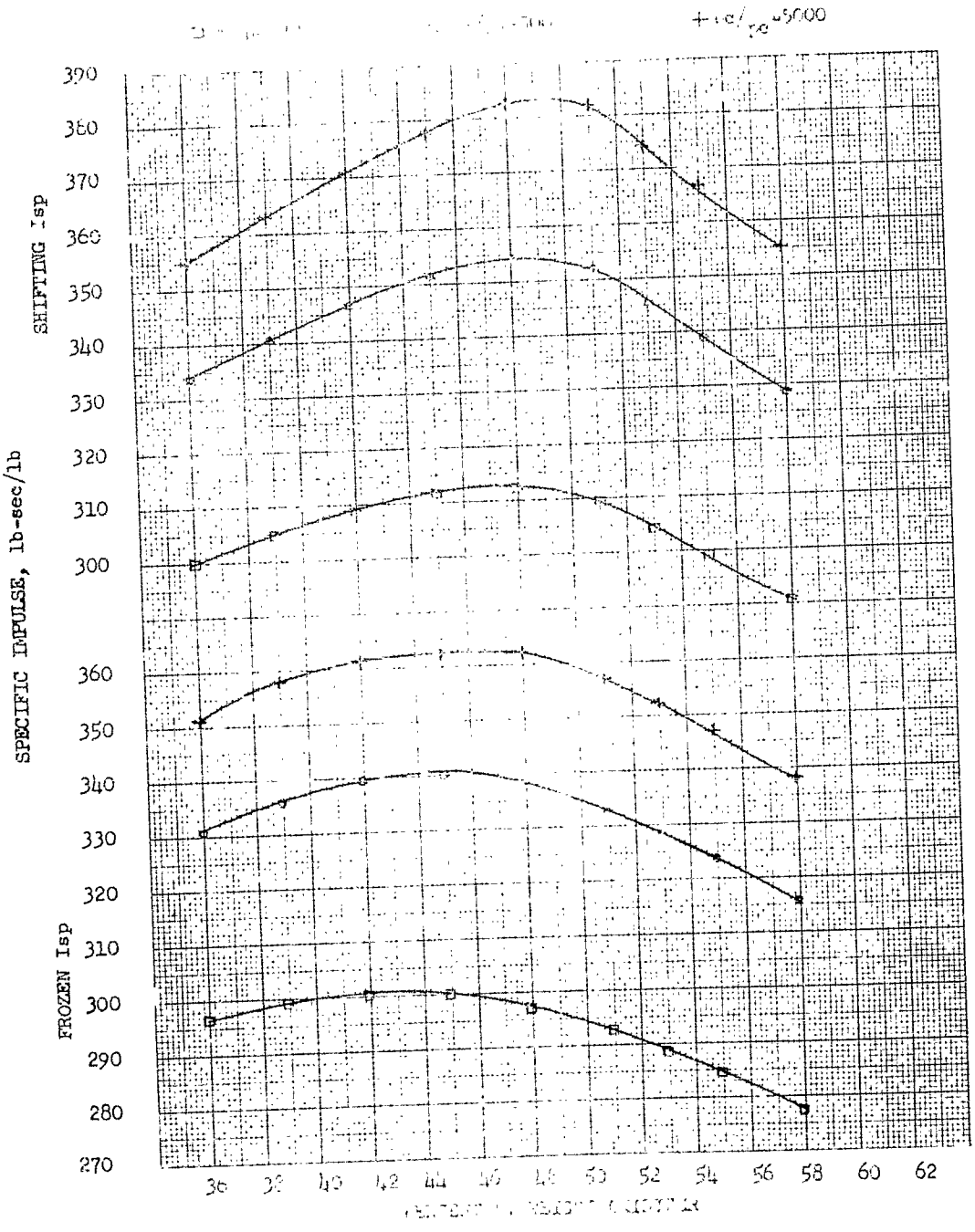

SHIFTING Isp
FROZEN Isp
SPECIFIC IMPULSE, lb-sec/lb
340
330
320
310
300
290
280
270
260
250
330
320
310
300
290
280
270
260
250
240
82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97
PERCENT BY WEIGHT OXIDIZER

LIQUID HYDROGEN - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 29



LIQUID HYDROGEN - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 30

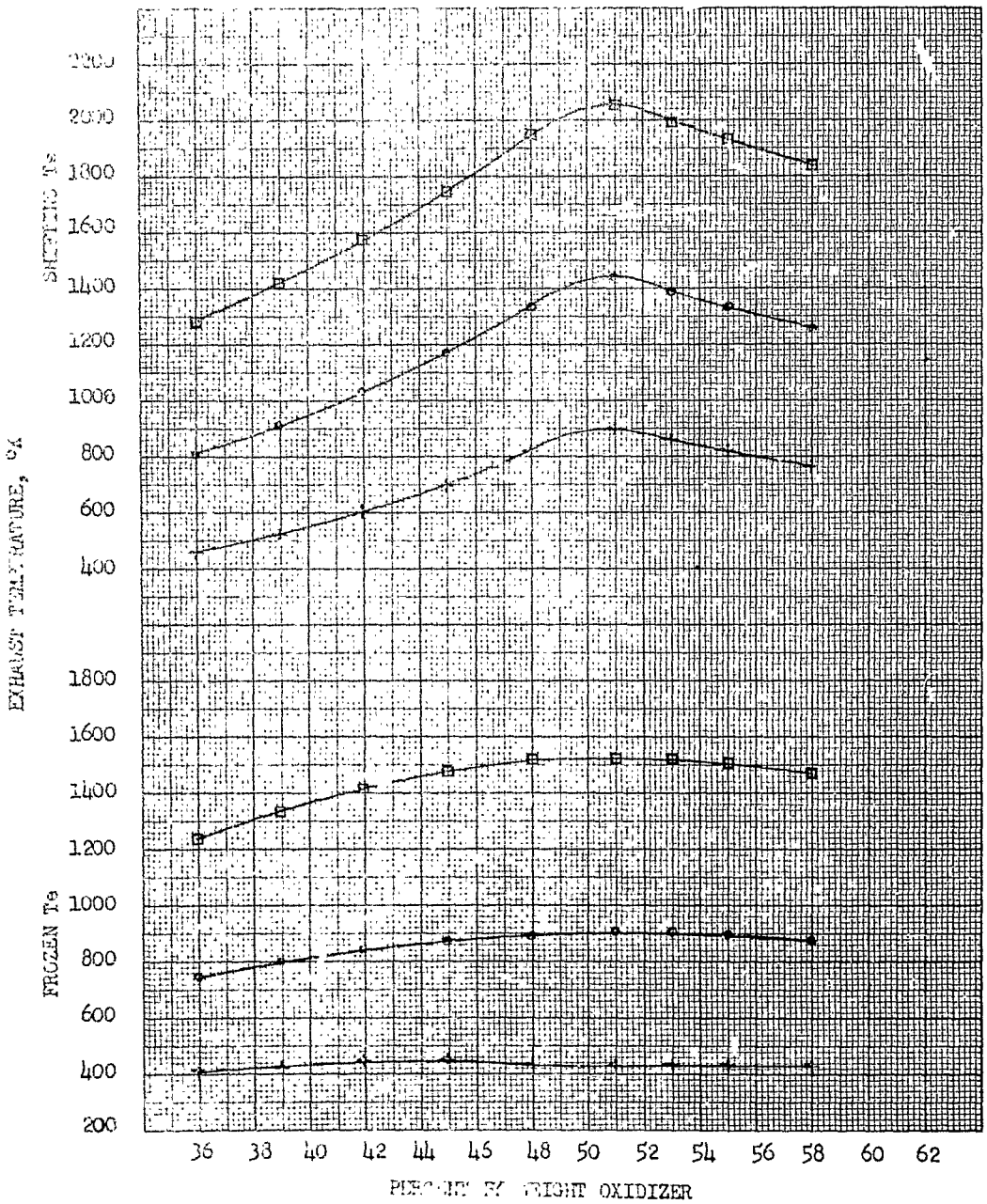


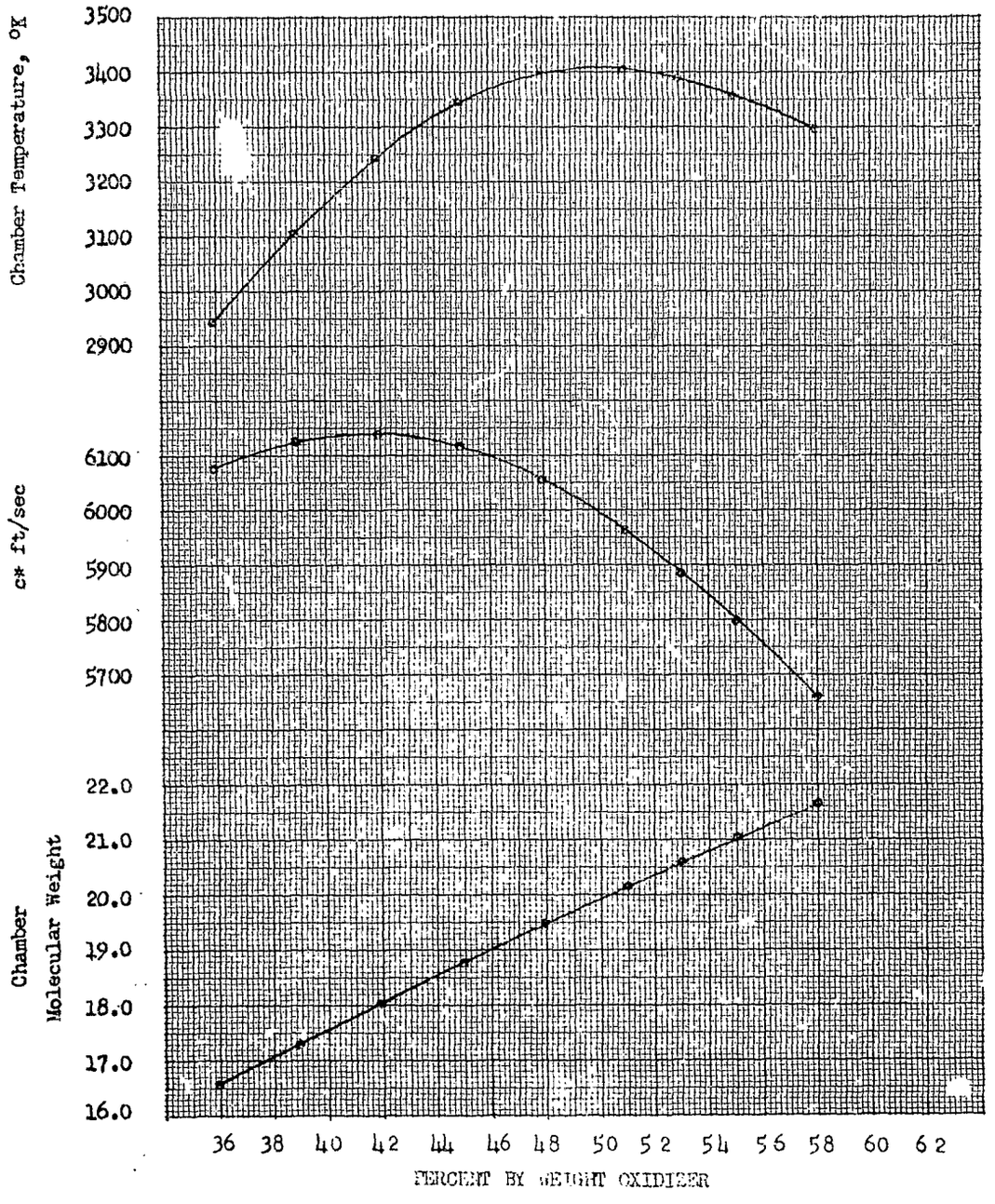

SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
390
380
370
360
350
340
330
320
310
300
360
350
340
330
320
310
300
290
280
270
36
38
40
42
44
46
48
50
52
54
56
58
60
62

[illegible] CURVES FIGURE 32

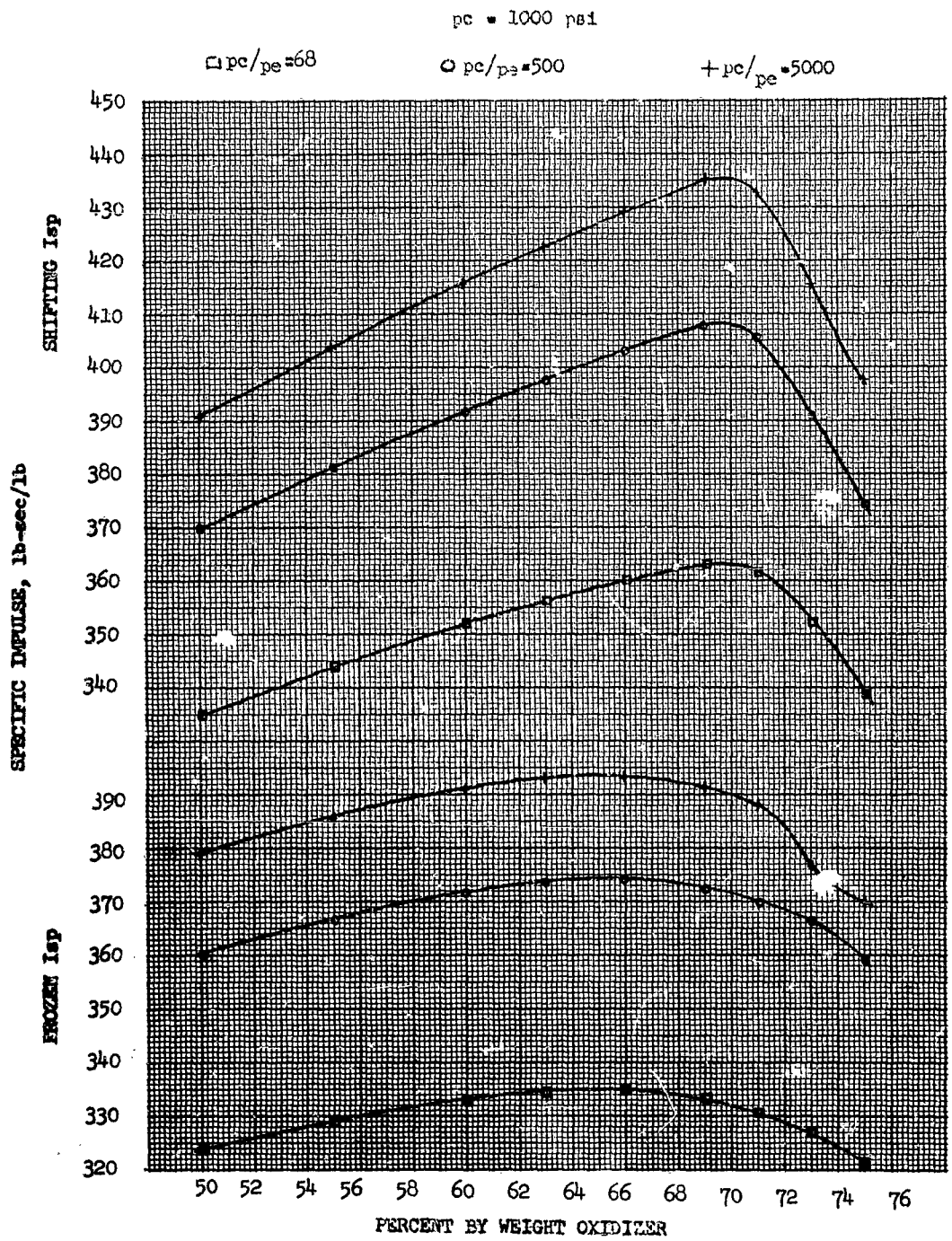
[illegible]

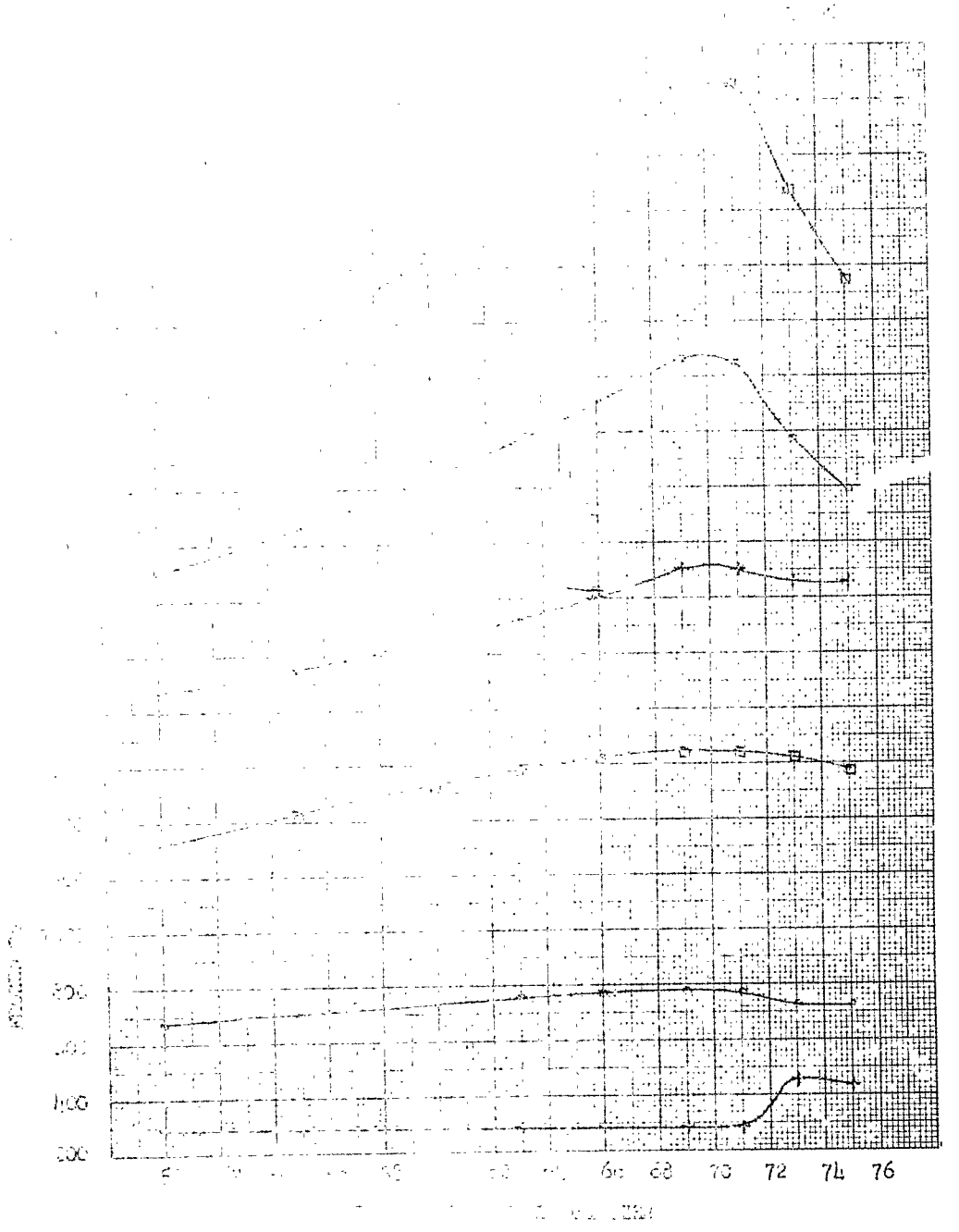
[illegible] pc/pe=[illegible] ○ pc/pe=[illegible] + pc/pe=5000



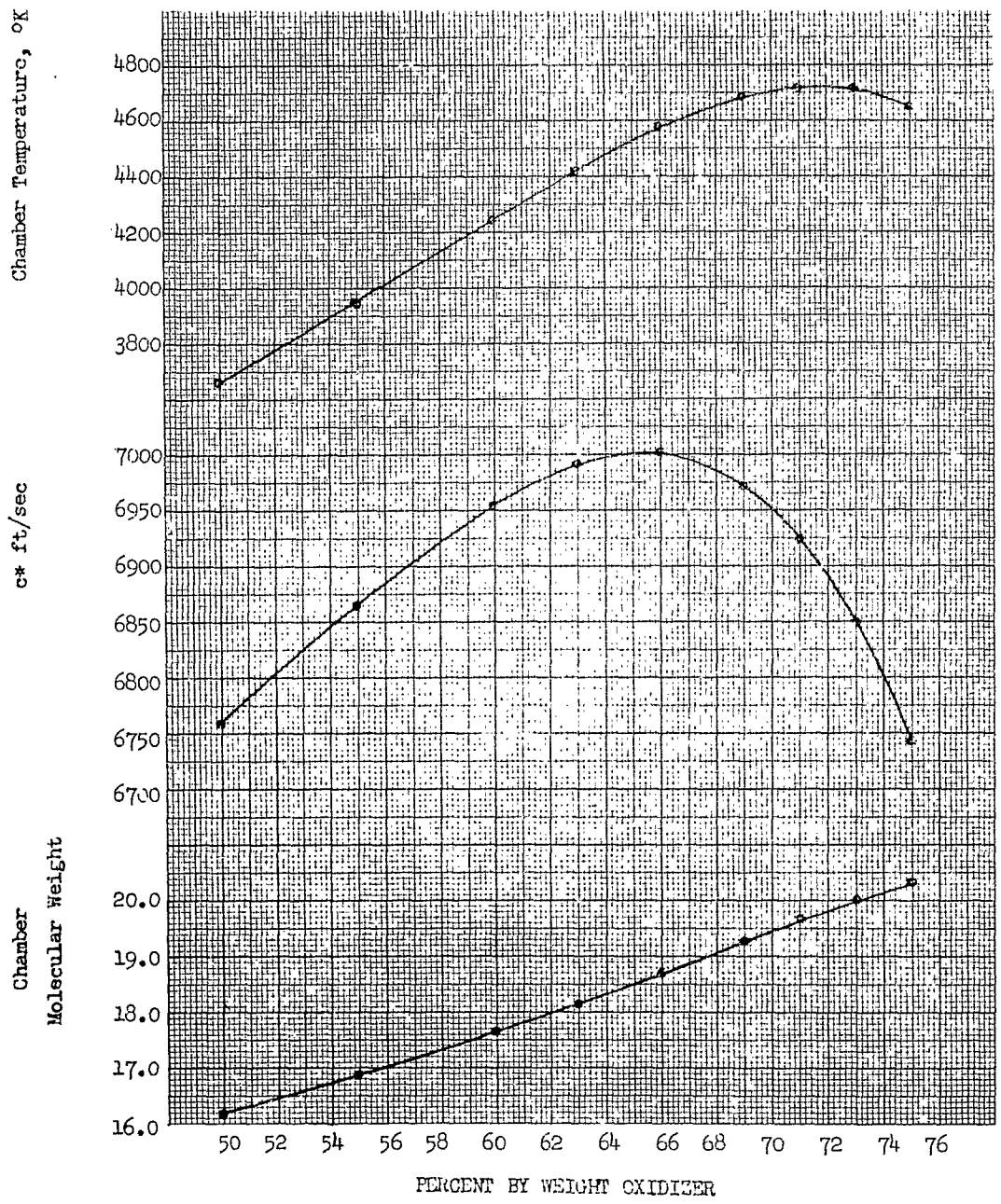

Chamber Temperature, °K
3500
3400
3300
3200
3100
3000
2900
c* ft/sec
6100
6000
5900
5800
5700
Chamber Molecular Weight
22.0
21.0
20.0
19.0
18.0
17.0
16.0
36 38 40 42 44 46 48 50 52 54 56 58 60 62
PERCENT BY WEIGHT OXIDIZER

HYDRAZINE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 34

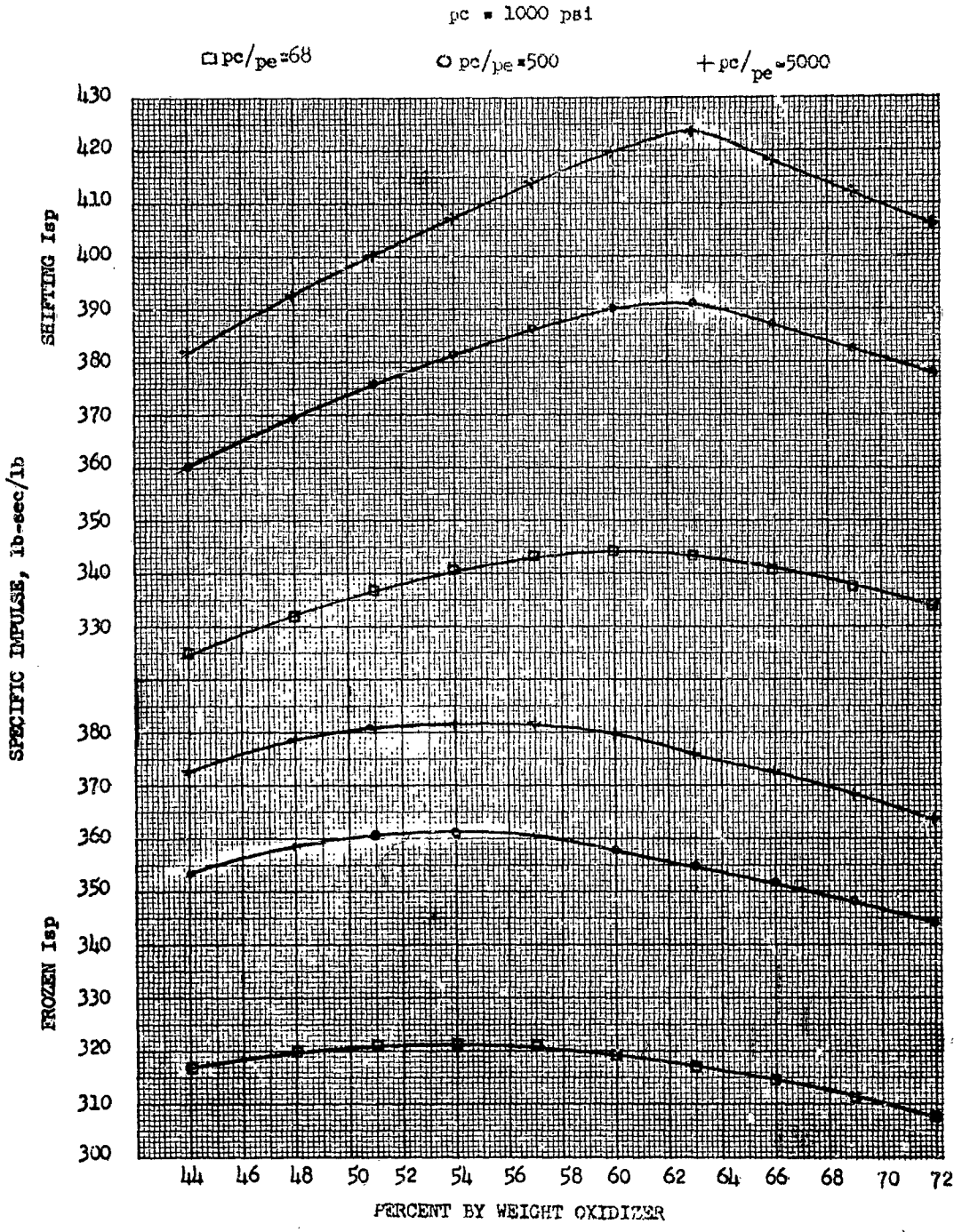



200
100
68
70
72
74
76

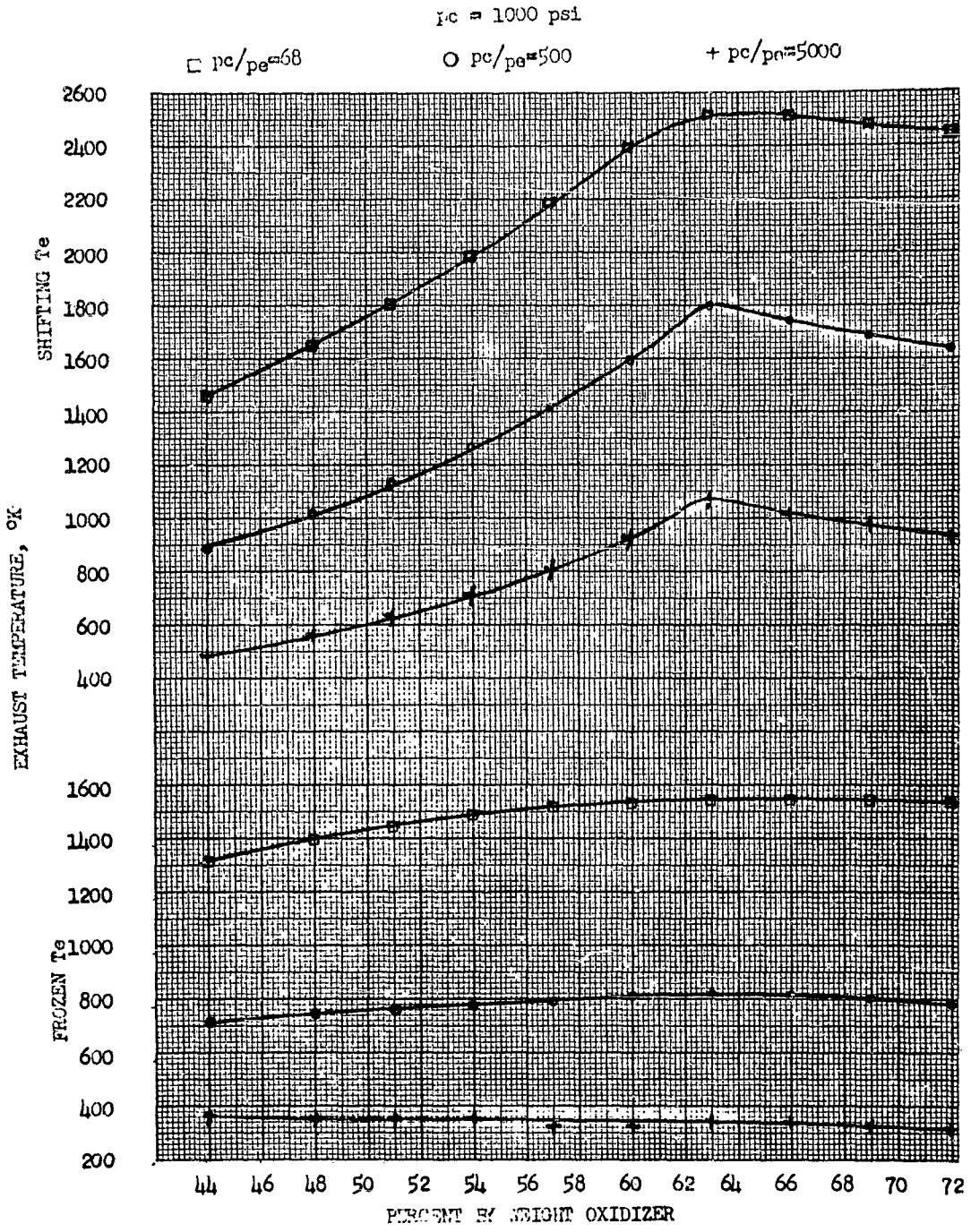
HYDRAZINE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 7

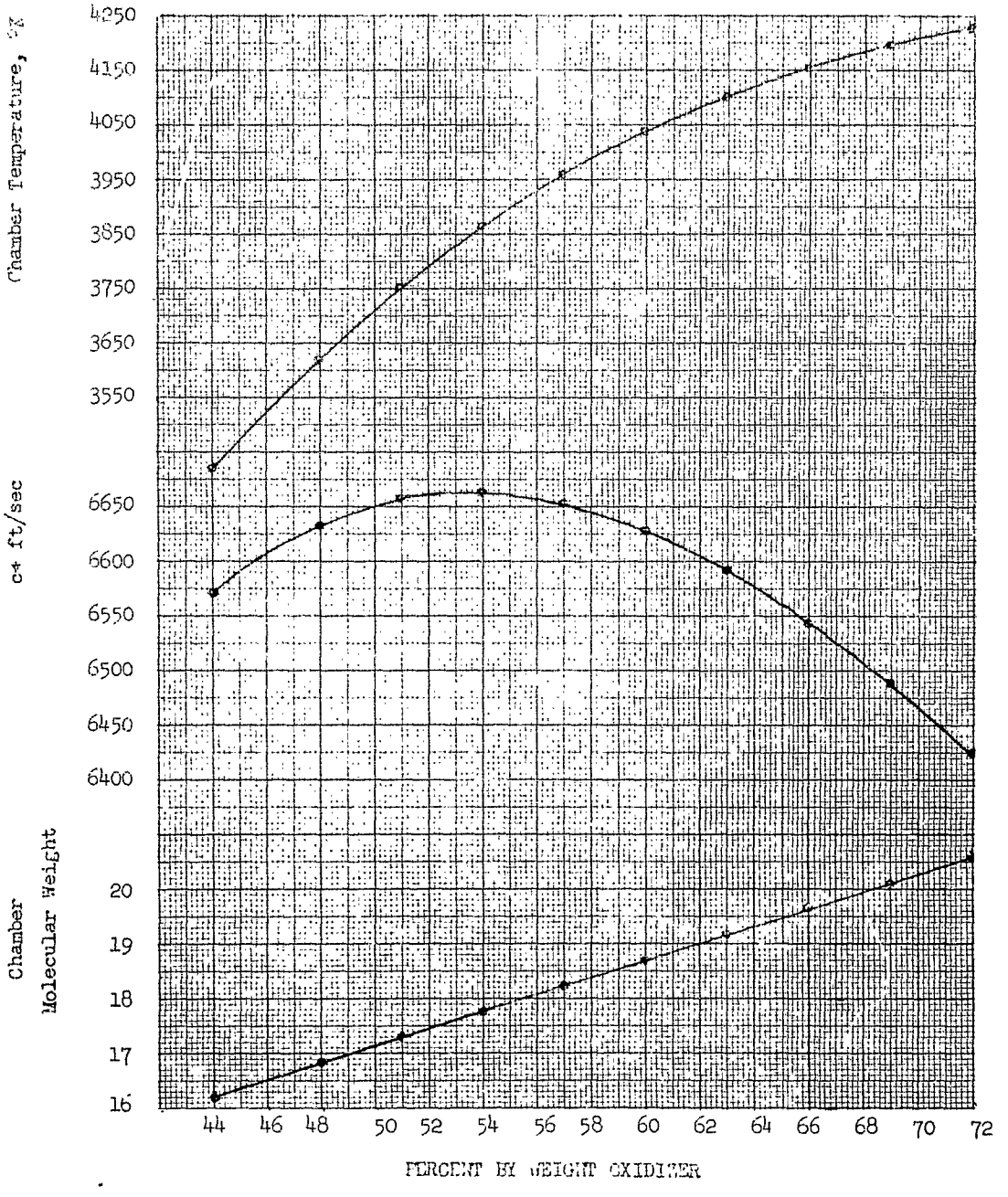


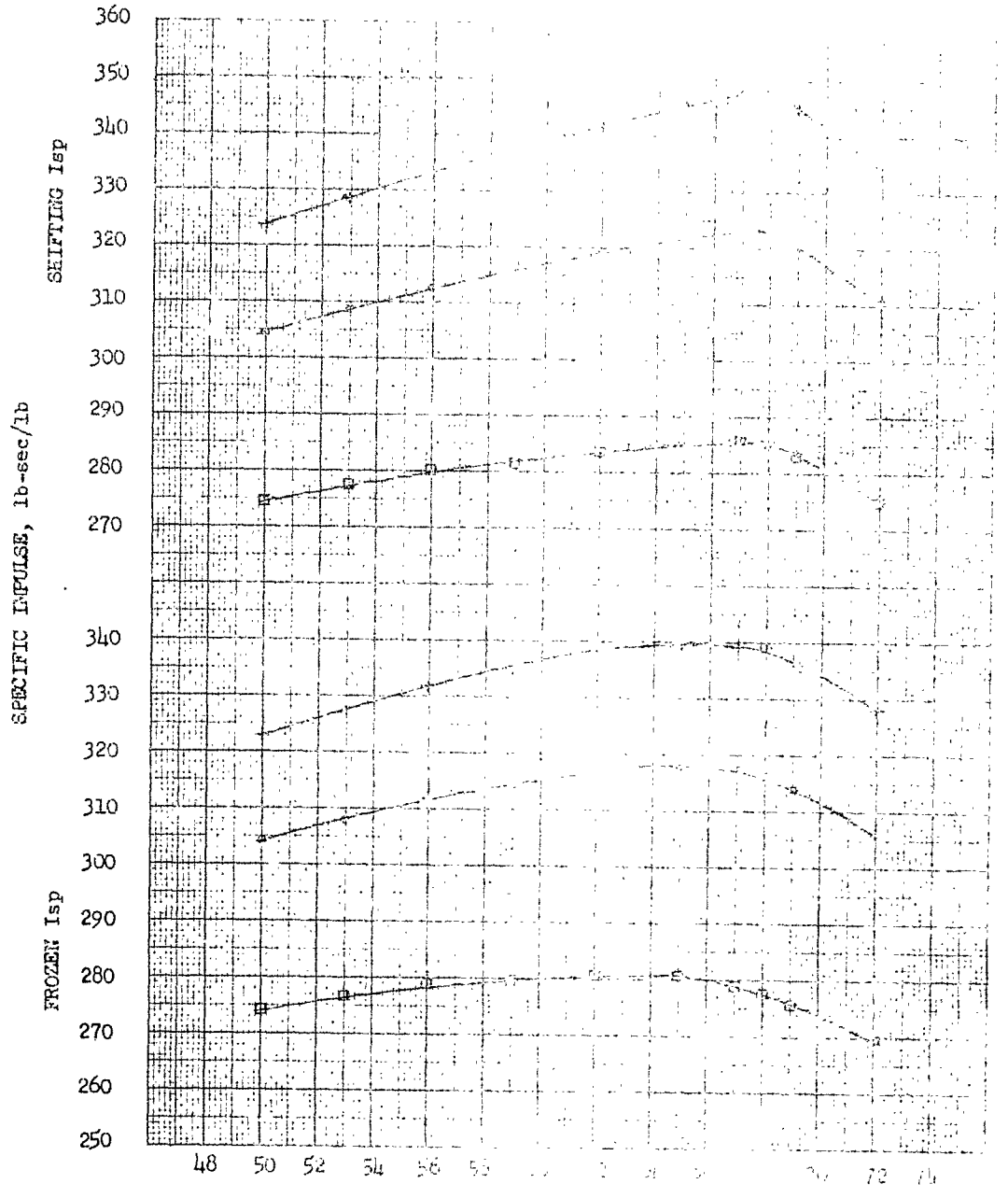
HYDRAZINE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 37



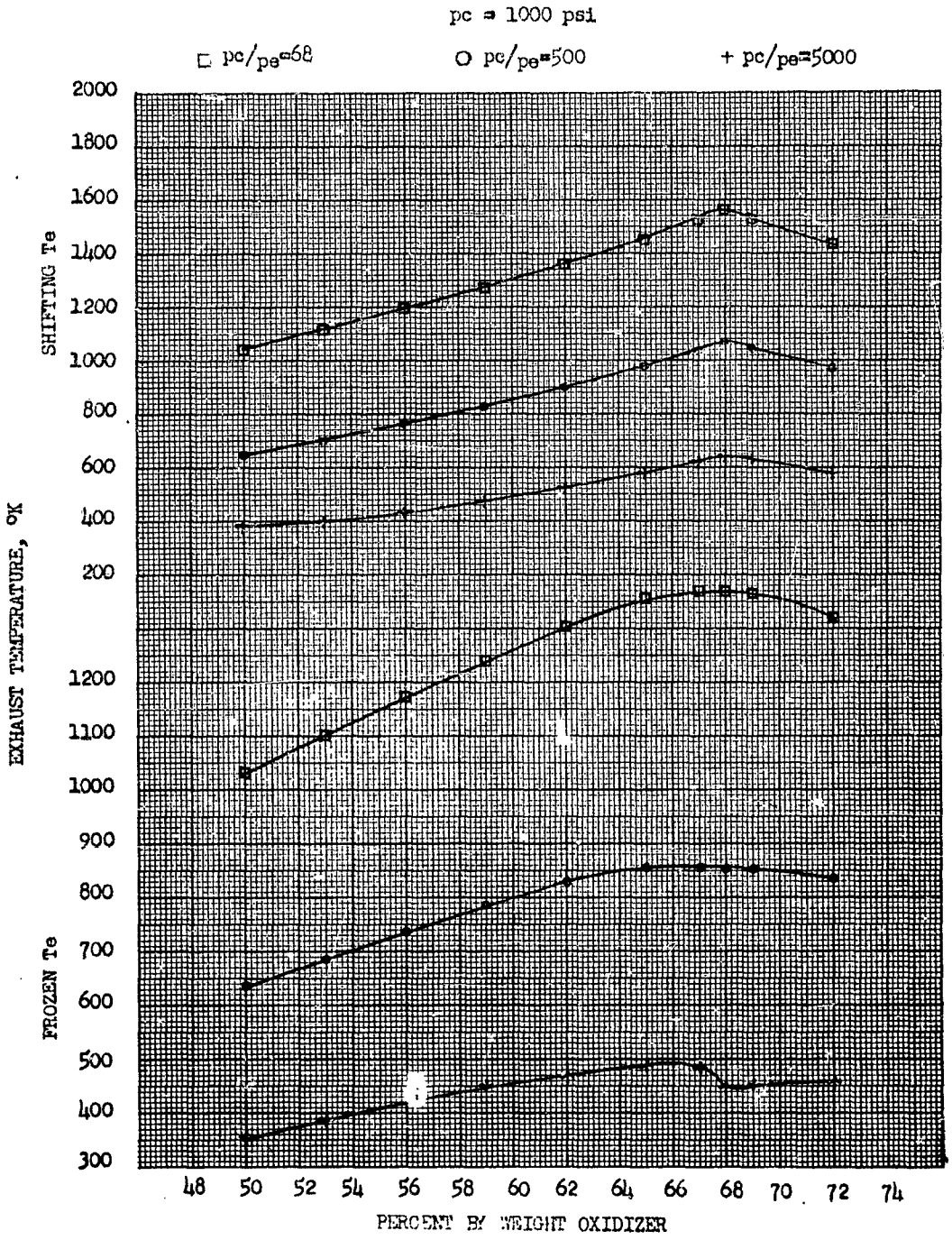
HYDRAZINE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 38



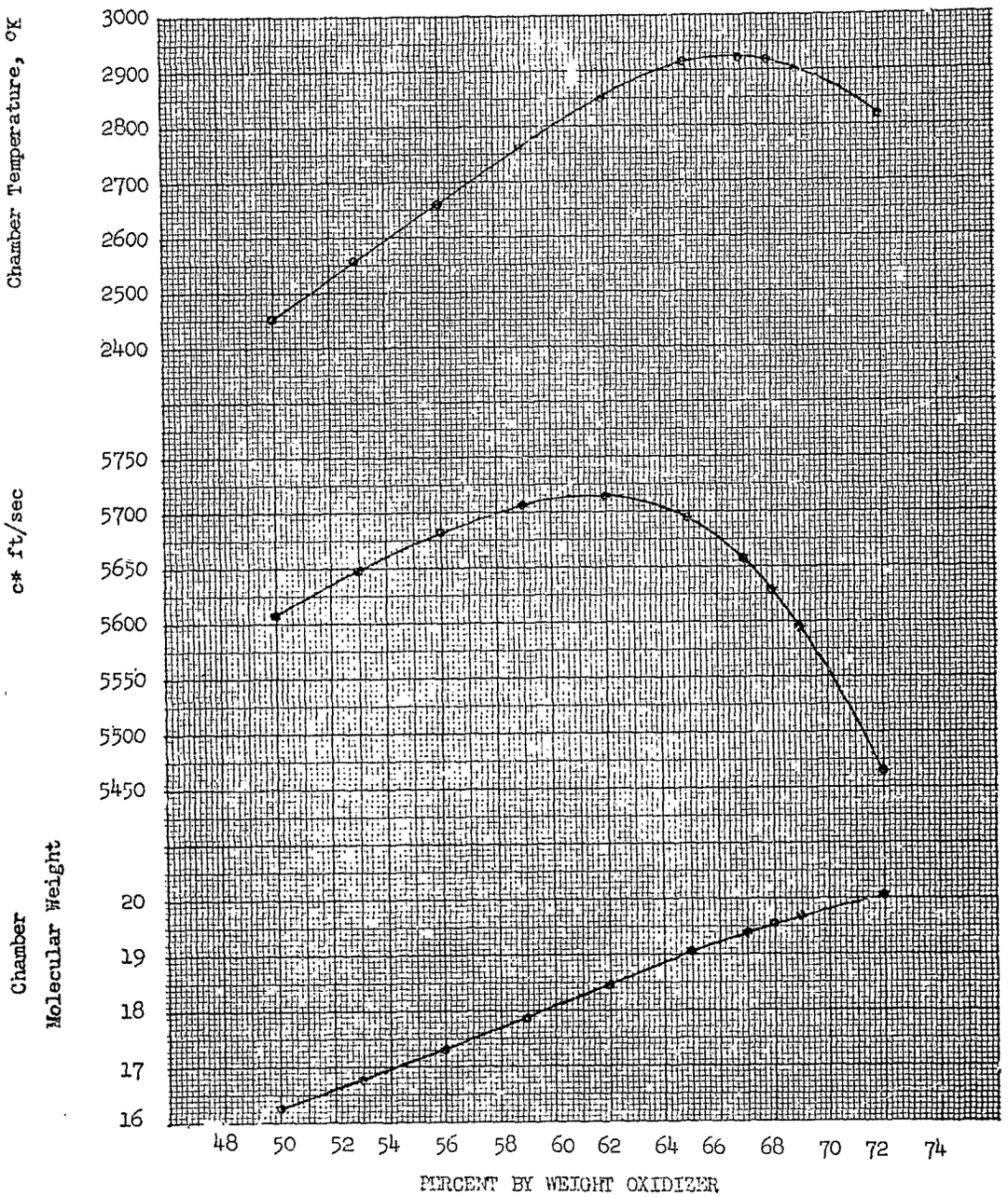

Chamber Temperature, °K
4250
4150
4050
3950
3850
3750
3650
3550
c* ft/sec
6650
6600
6550
6500
6450
6400
Chamber Molecular Weight
20
19
18
17
16
44 46 48 50 52 54 56 58 60 62 64 66 68 70 72
PERCENT BY WEIGHT OXIDIZER


SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
360
350
340
330
320
310
300
290
280
270
340
330
320
310
300
290
280
270
260
250
48
50
52
54

HYDRAZINE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 41



HYDRAZINE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 42

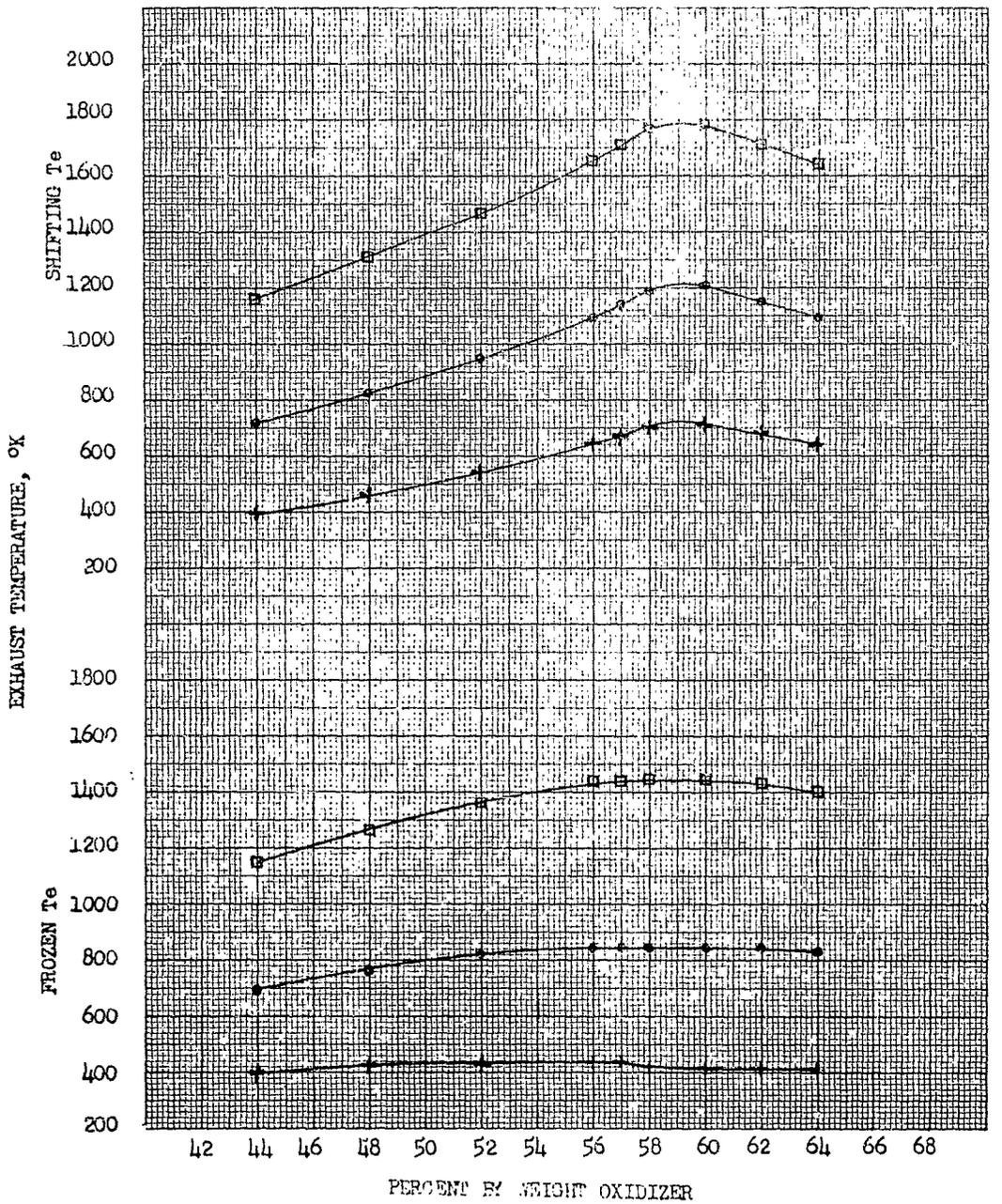


60
62
64
66
68

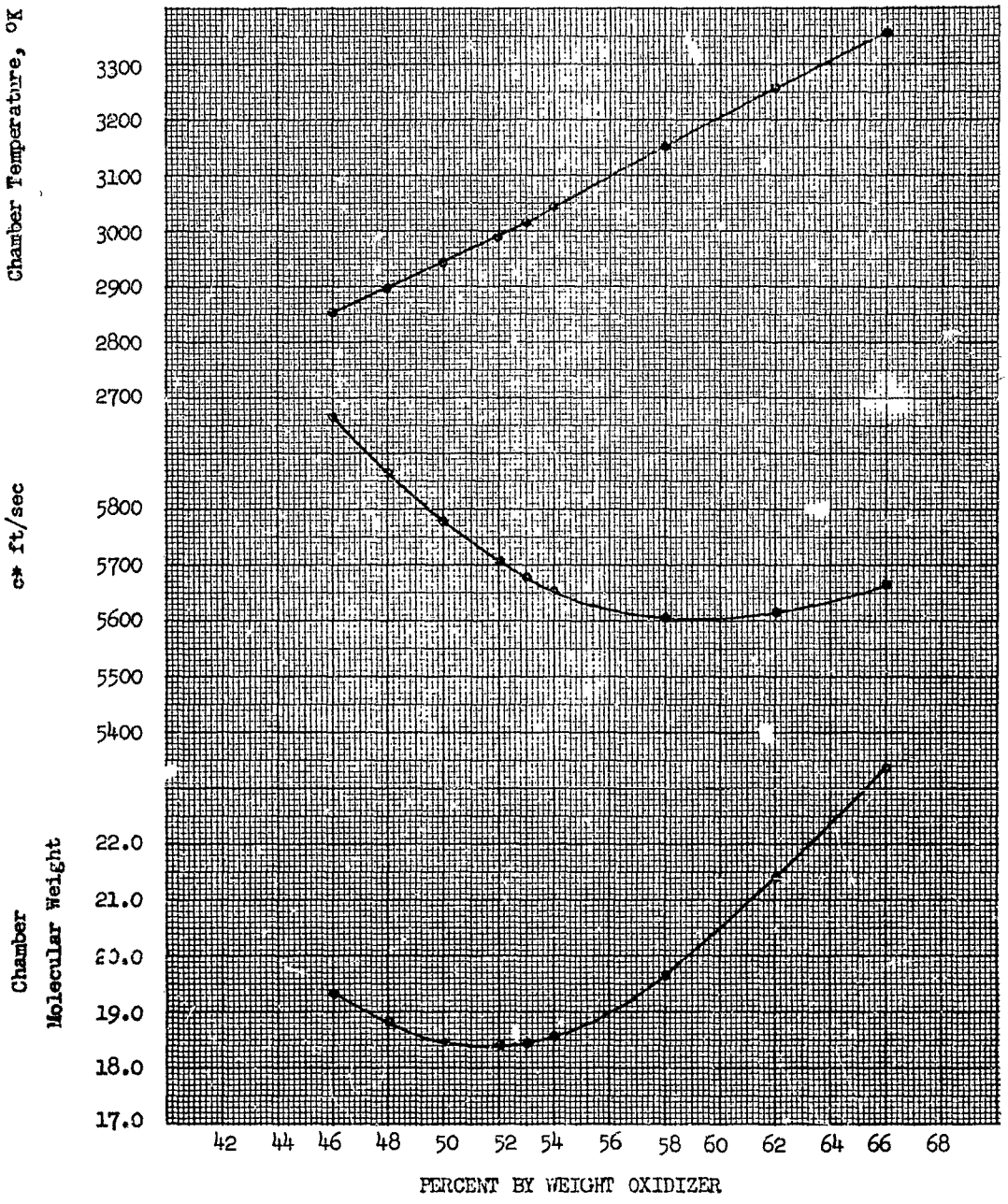
HYDRAZINE - NITROGEN [illegible]

p_c = [illegible]

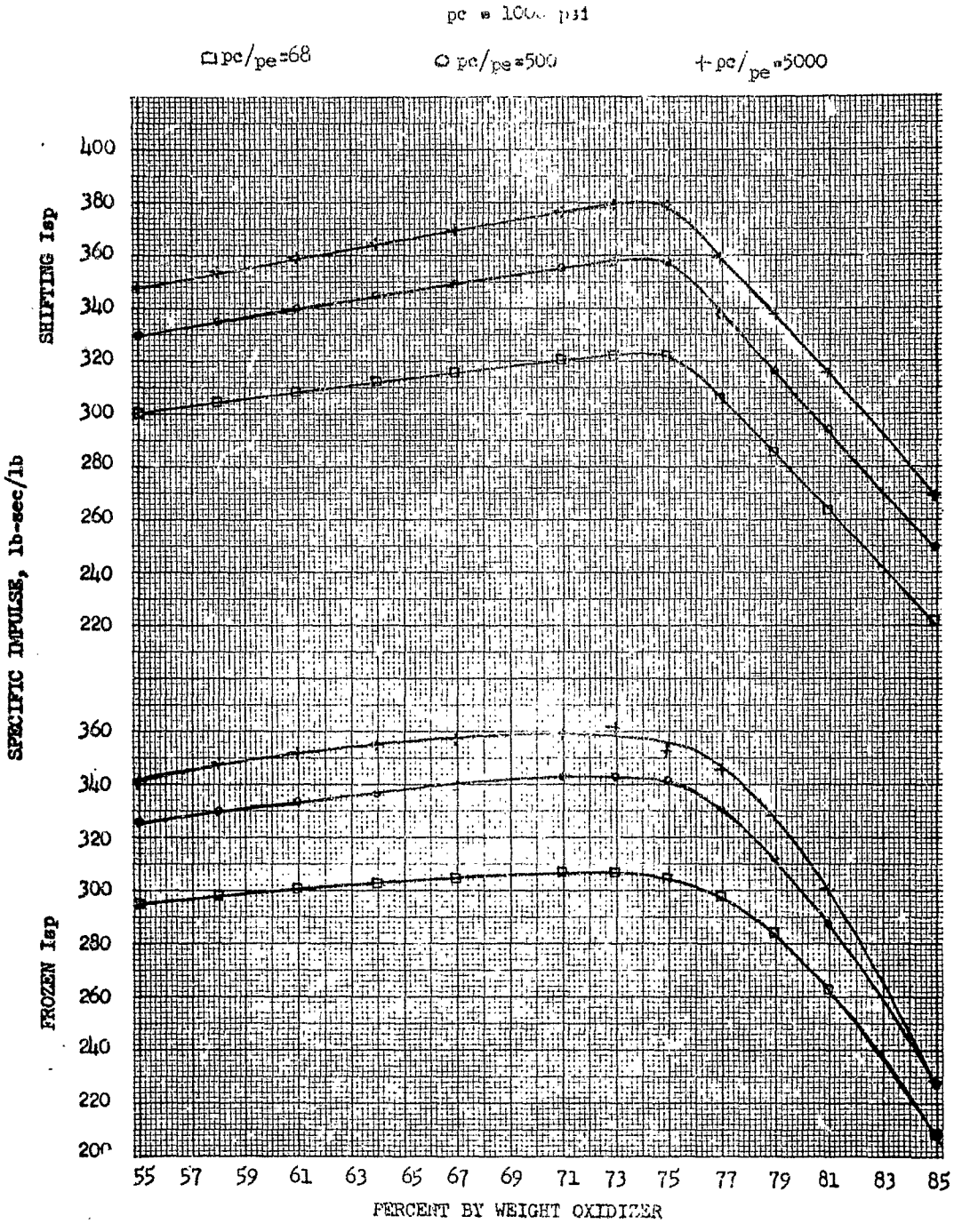
△ p_c/p_a=38 ○ p_c/p_a=[illegible] □ p_c/p_a=5000



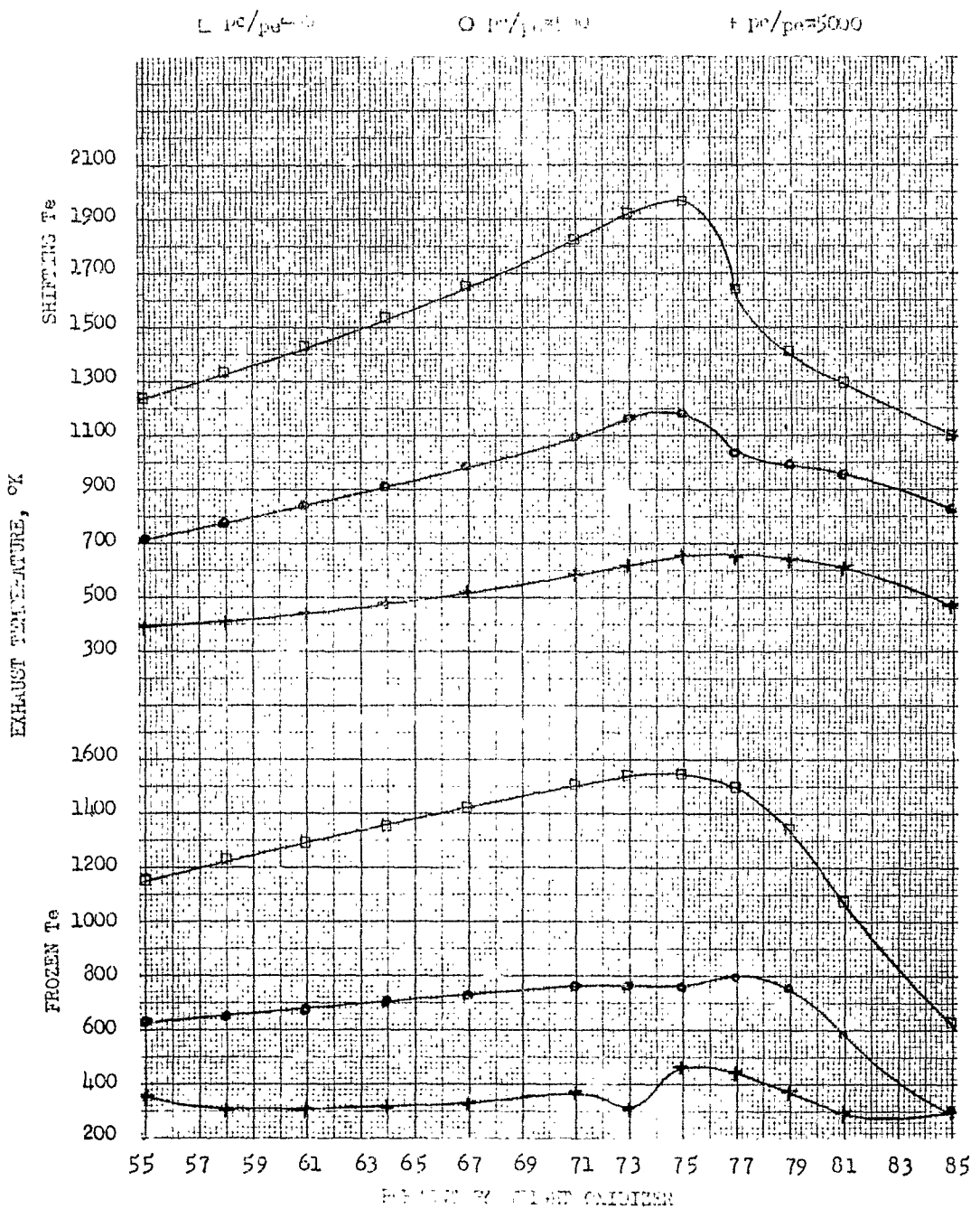
HYDRAZINE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 45



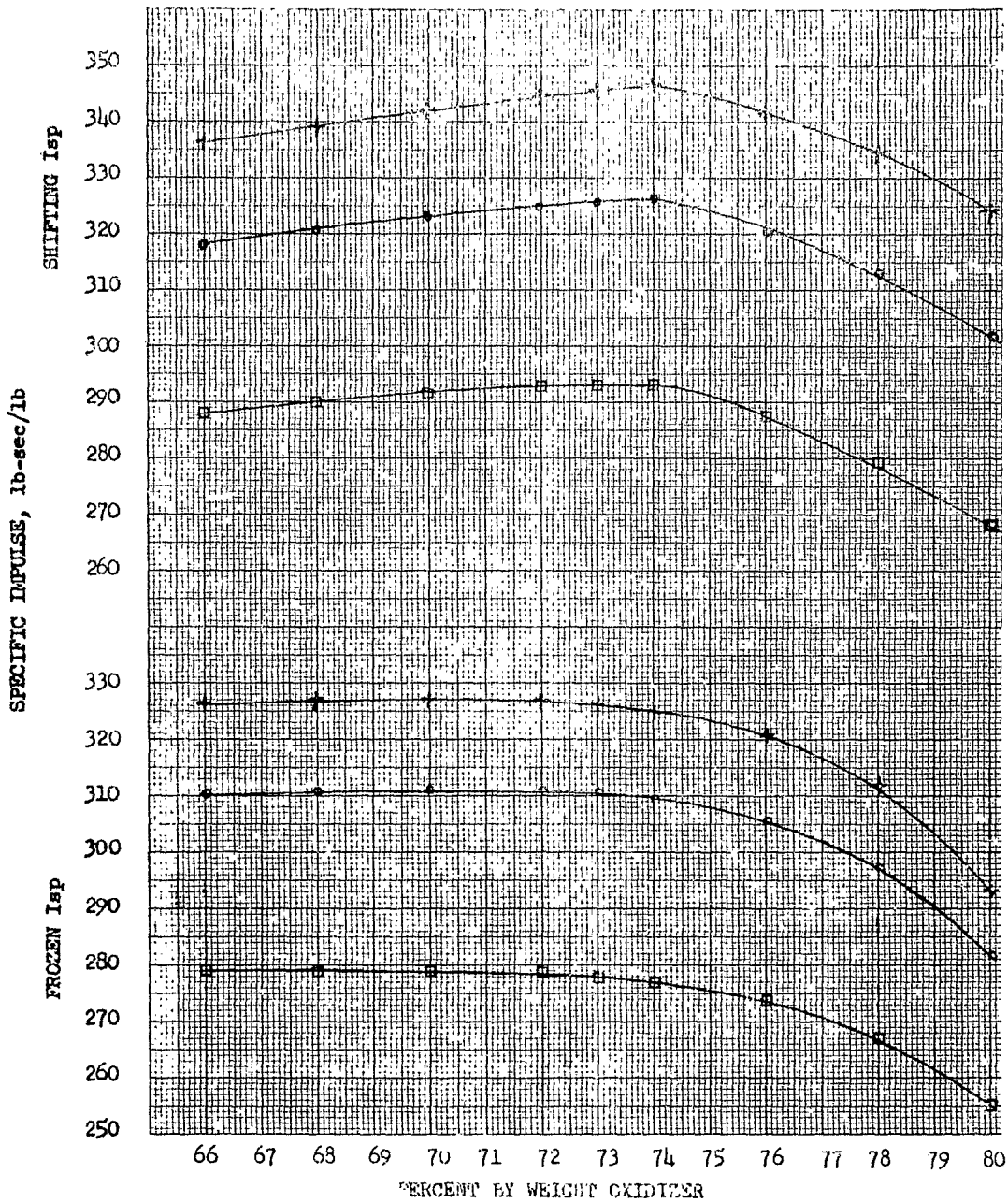
HYDRAZINE - NITROGEN TETRAFLUORIDE PERFORMANCE DATA FIGURE 46



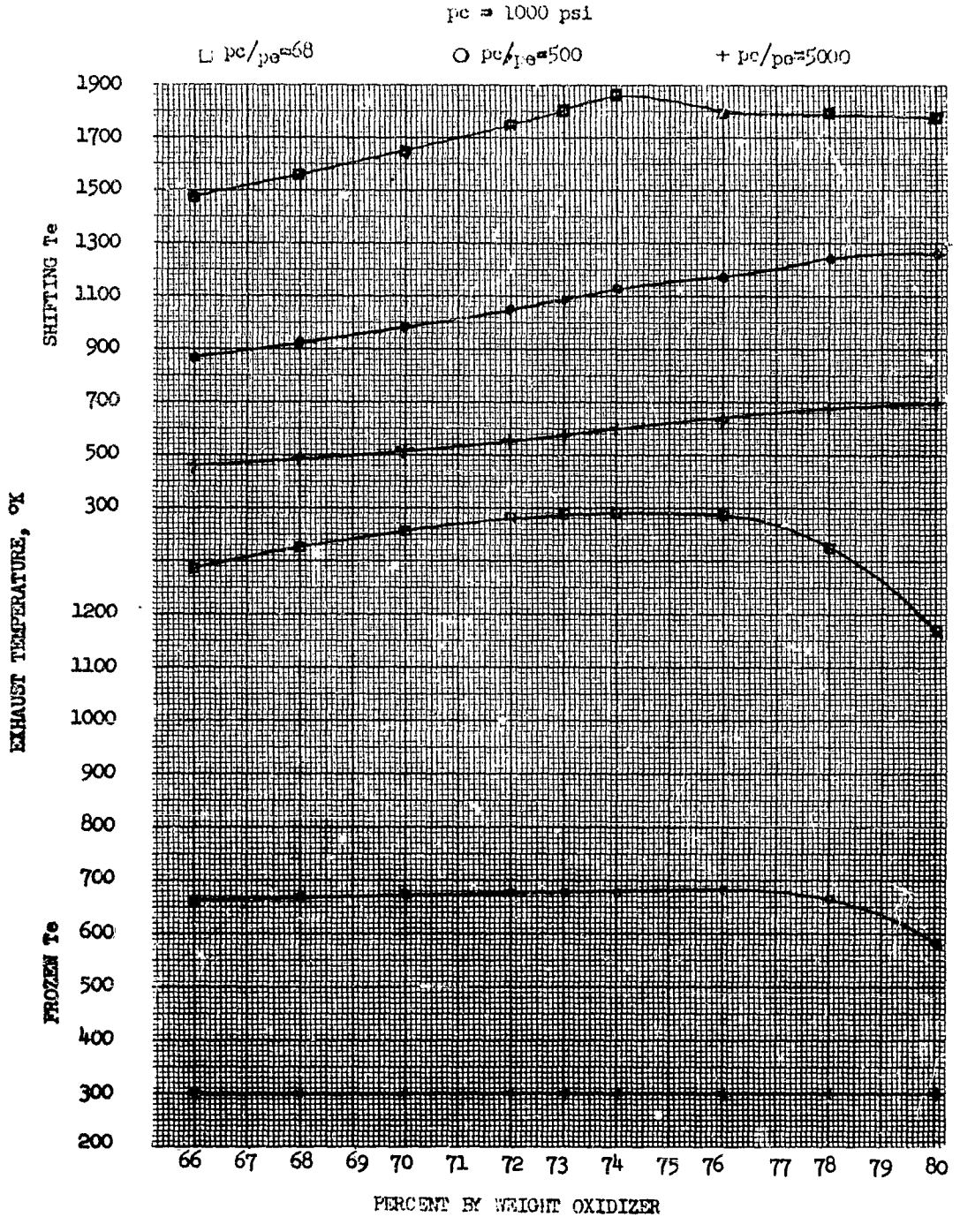
HYDRAZINE – NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 47

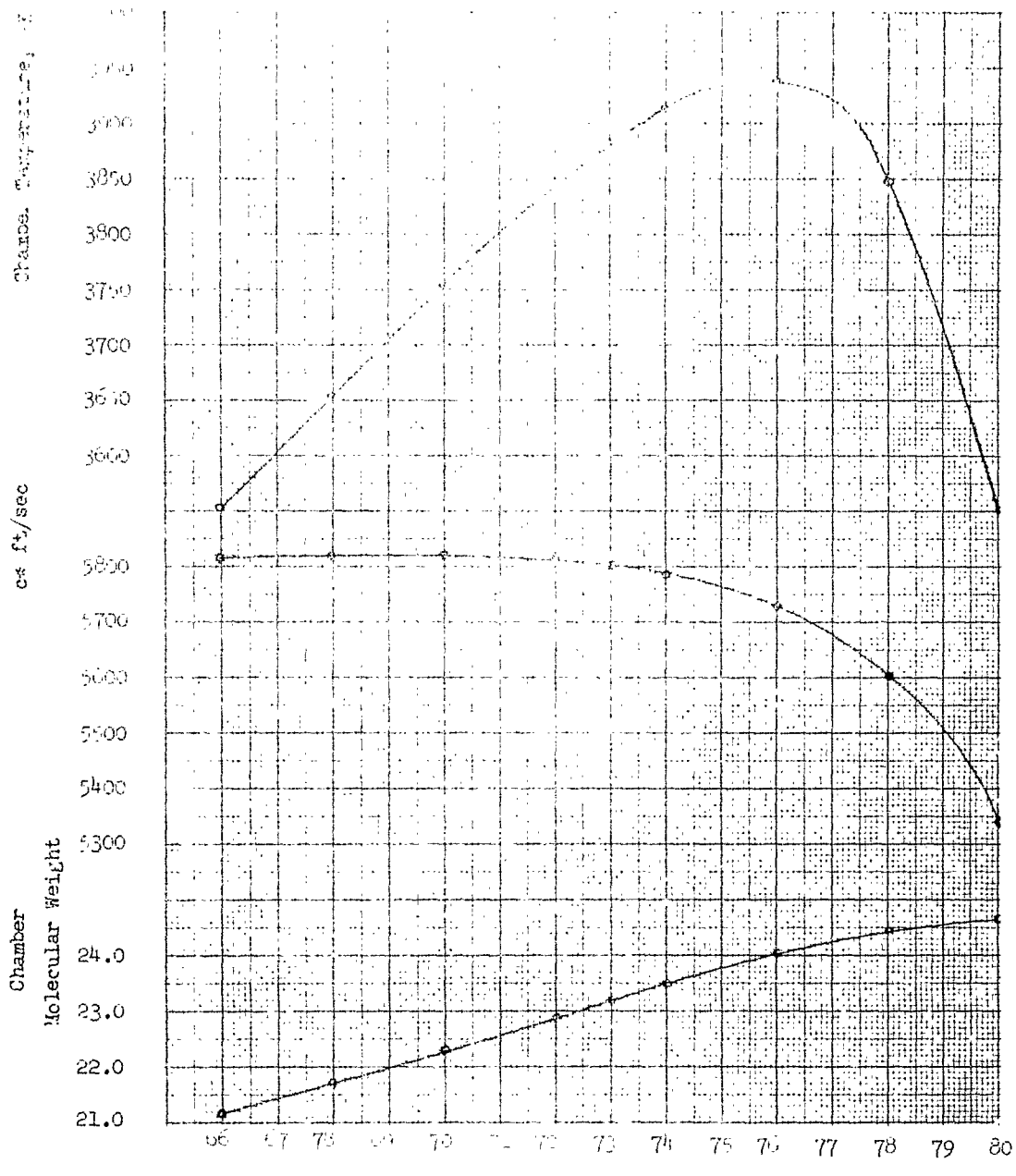


Chamber Temperature, °F
4600
4000
3600
2800
2400
2000
6300
5900
5500
5100
4700
4300
Chamber Molecular Weight
21.0
20.0
19.0
18.0
17.0
55
57
59
61

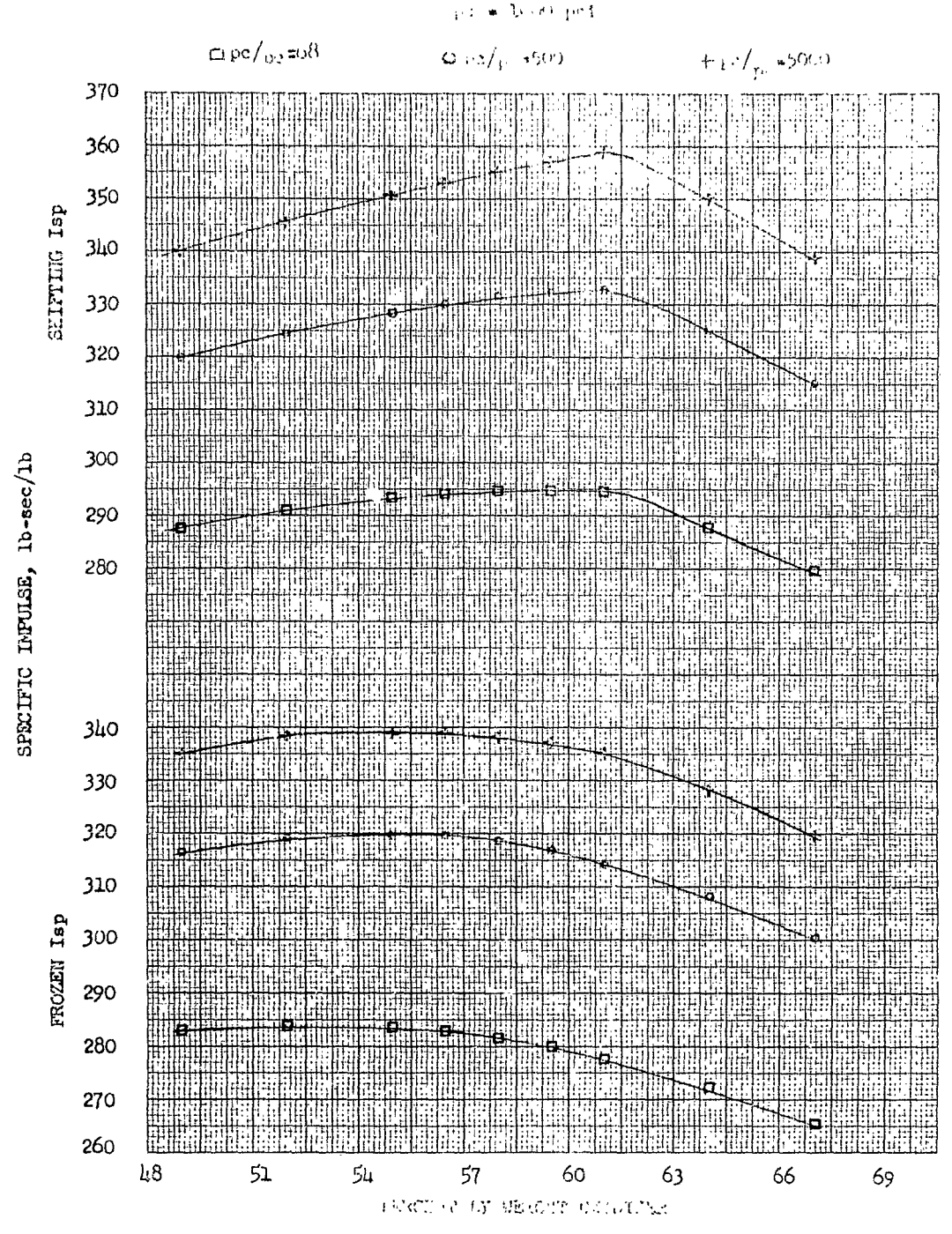

SHIFTING Isp
FROZEN Isp
SPECIFIC IMPULSE, lb-sec/lb
350
340
330
320
310
300
290
280
270
260
330
320
310
300
290
280
270
260
250
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
PERCENT BY WEIGHT OXIDIZER

HYDRAZINE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 50

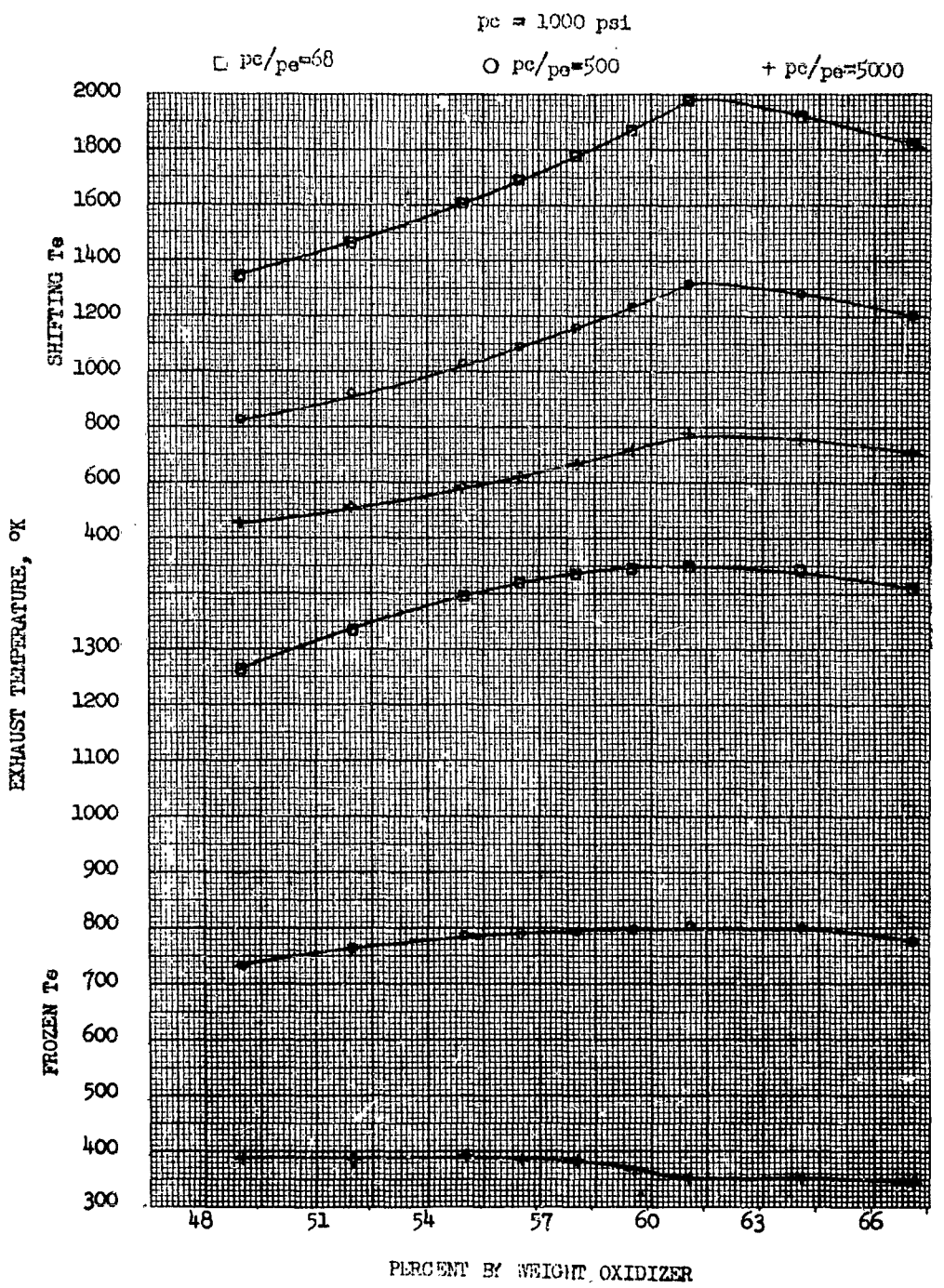



c* ft/sec
3850
3800
3750
3700
3650
3600
5800
5700
5600
5500
5400
5300
Chamber
Molecular Weight
24.0
23.0
22.0
21.0
73
74
75
76
77
78
79
80

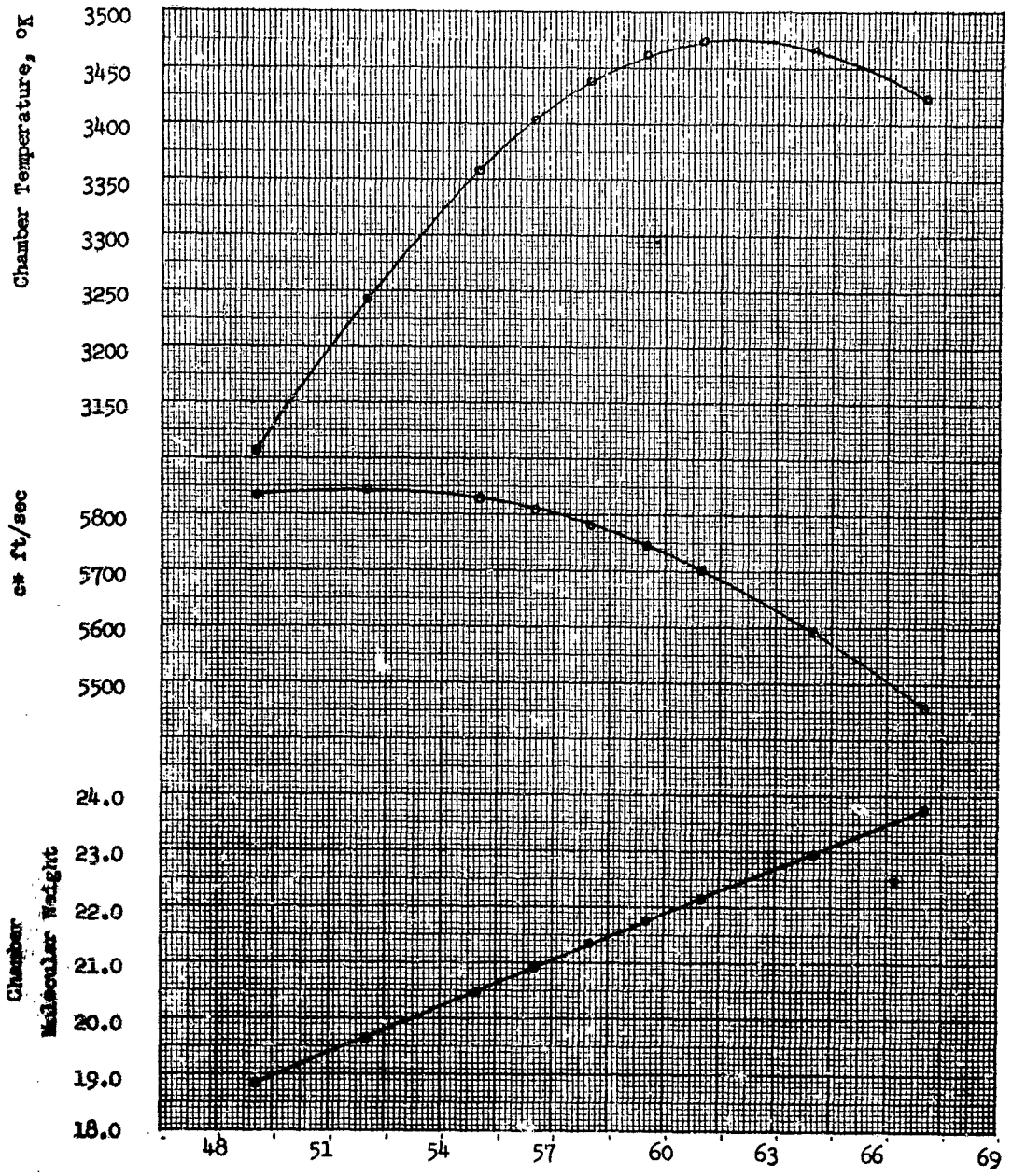
HYDRAZINE – PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 52



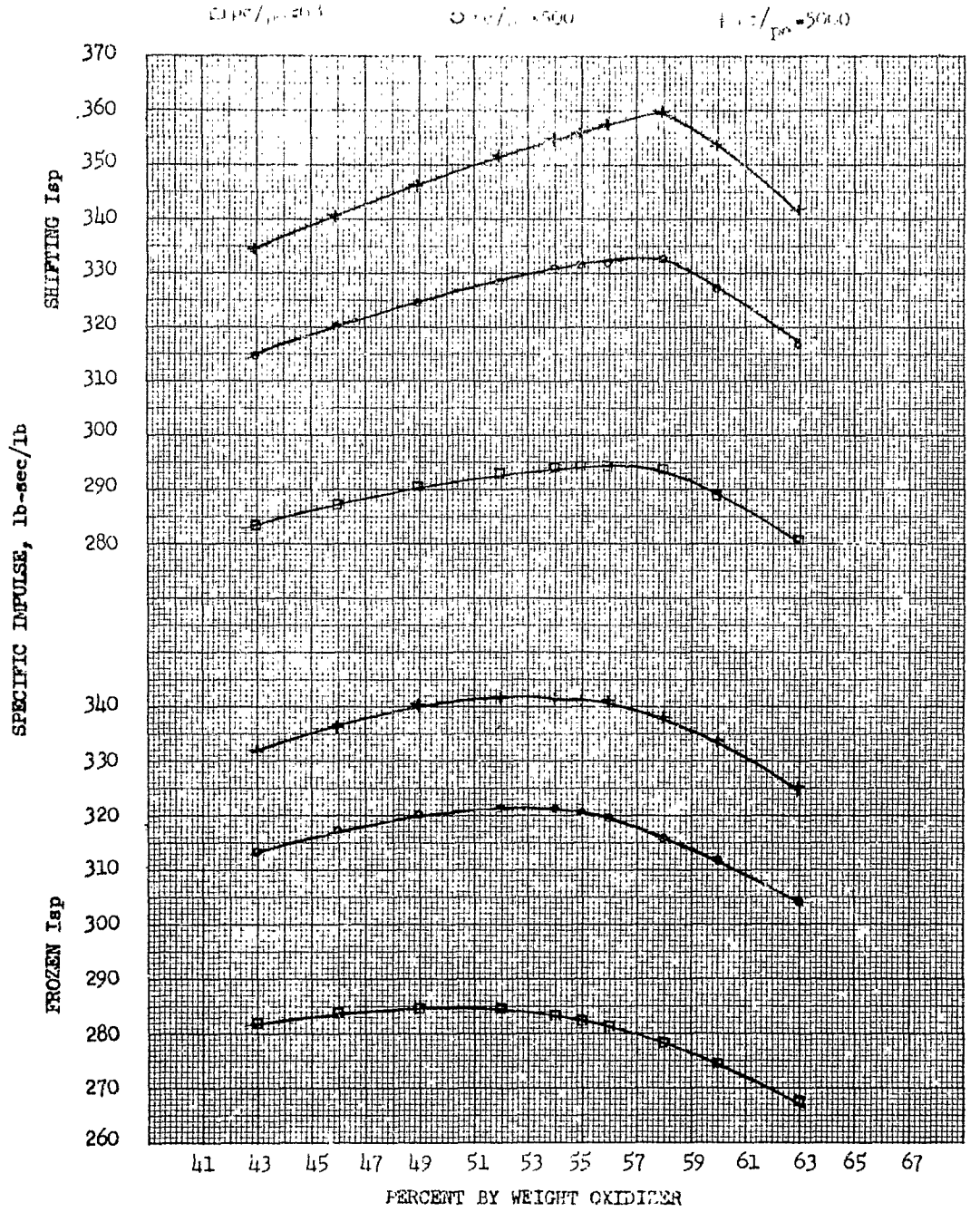
HYDRAZINE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 53

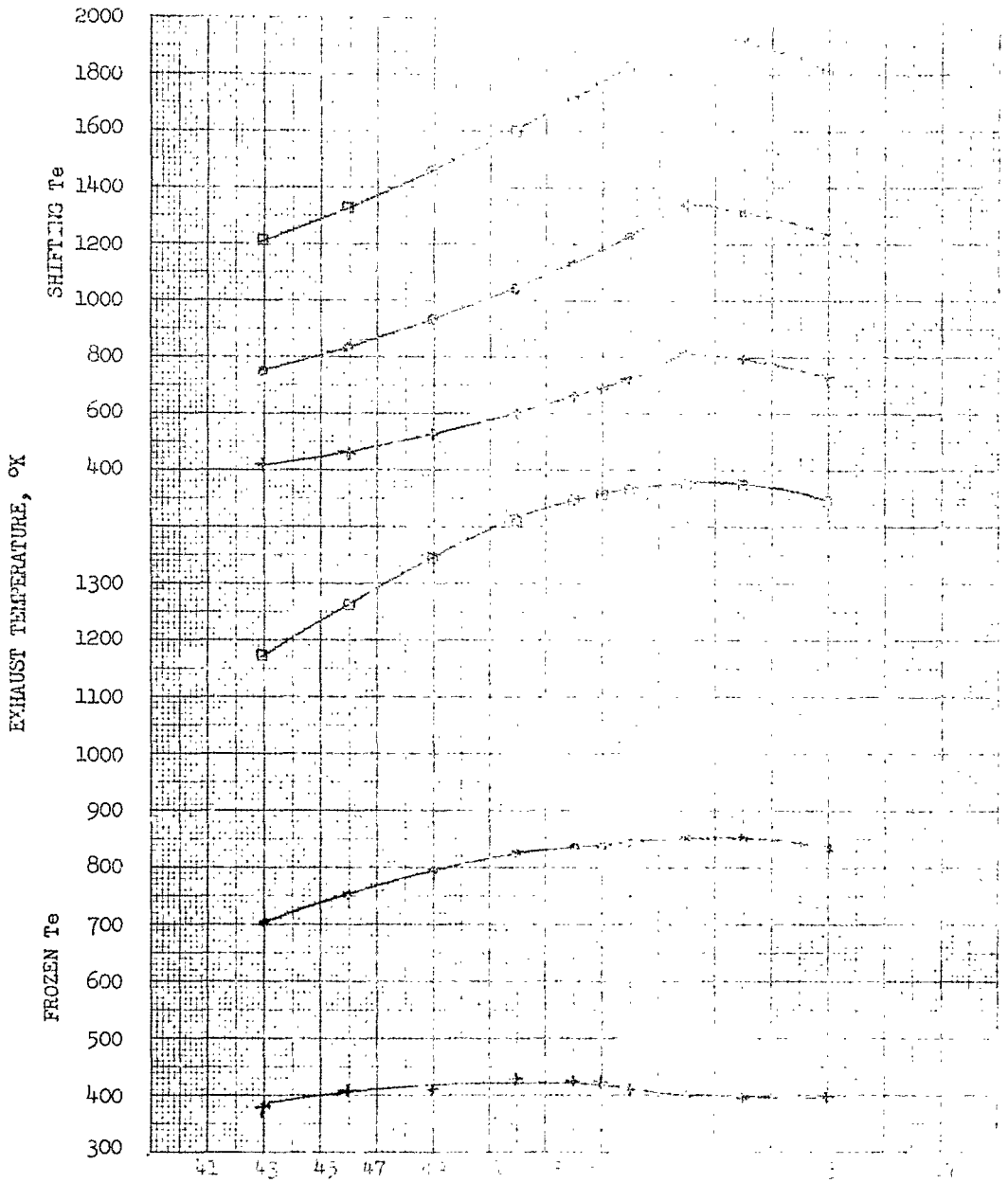


HYDRAZINE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 54

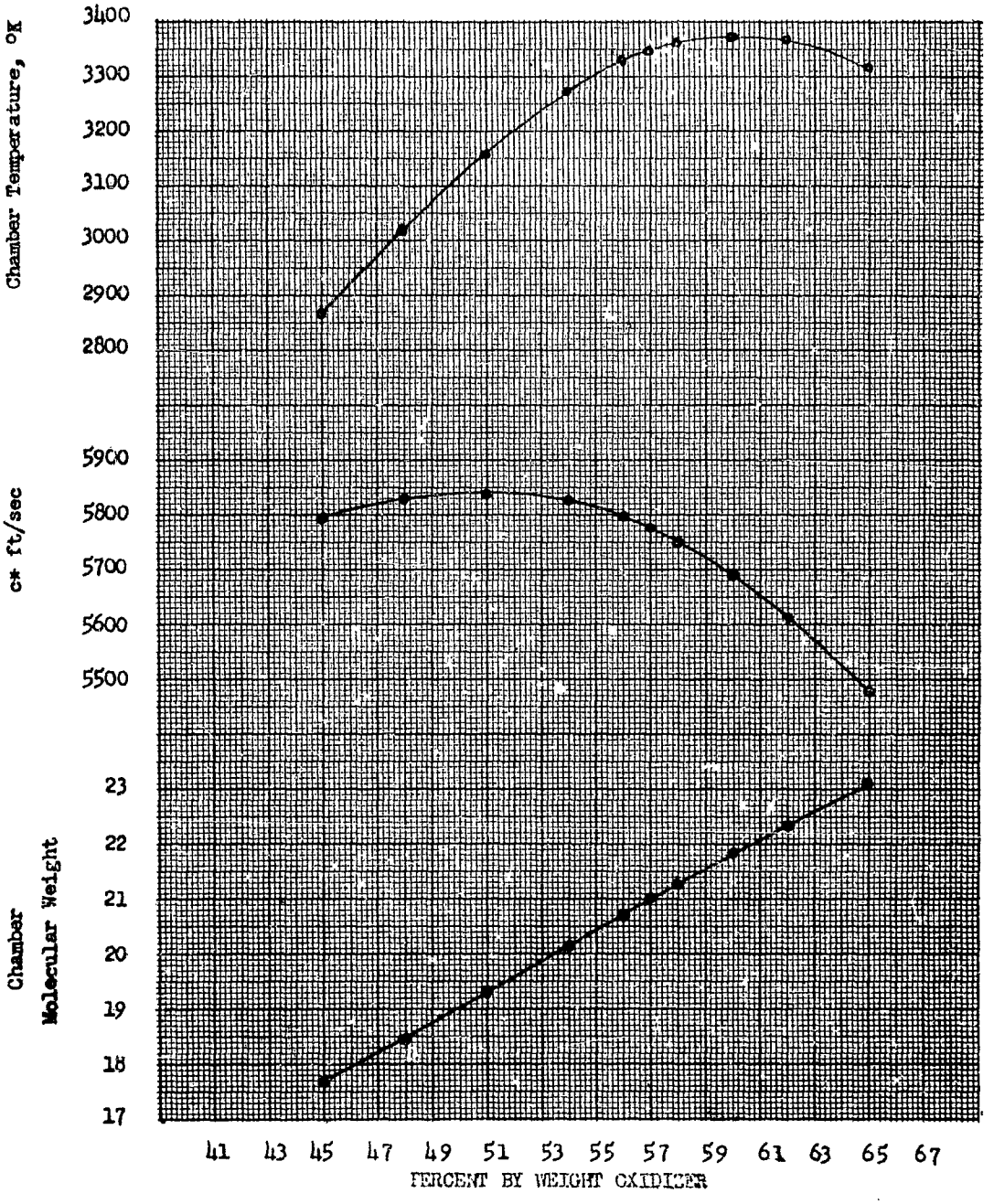


HYDRAZINE – [illegible] PERFORMANCE CURVES FIGURE 55




EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
2000
1800
1600
1400
1200
1000
800
600
400
1300
1200
1100
1000
900
800
700
600
500
400
300
41
43
45
47

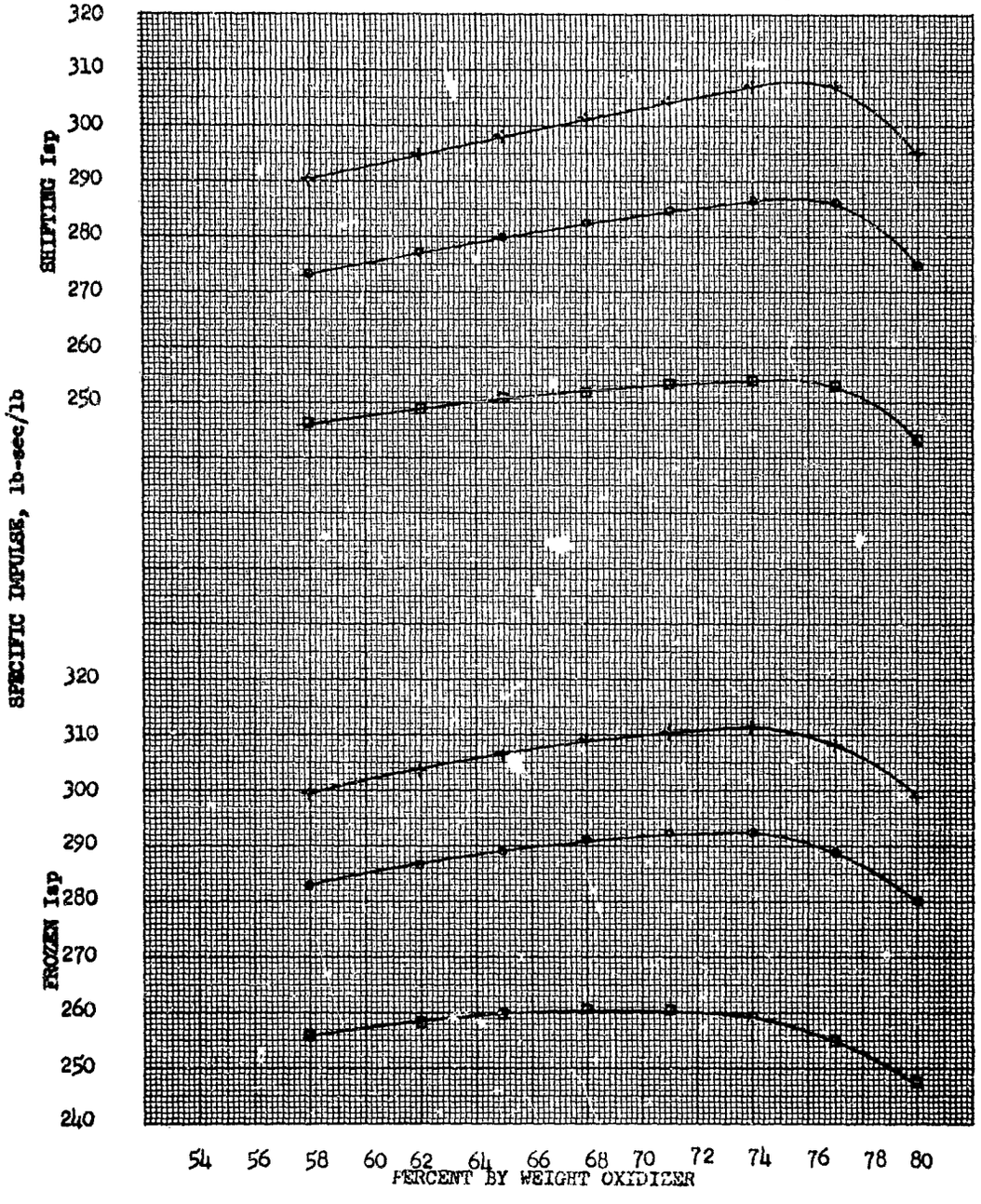
HYDRAZINE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 57

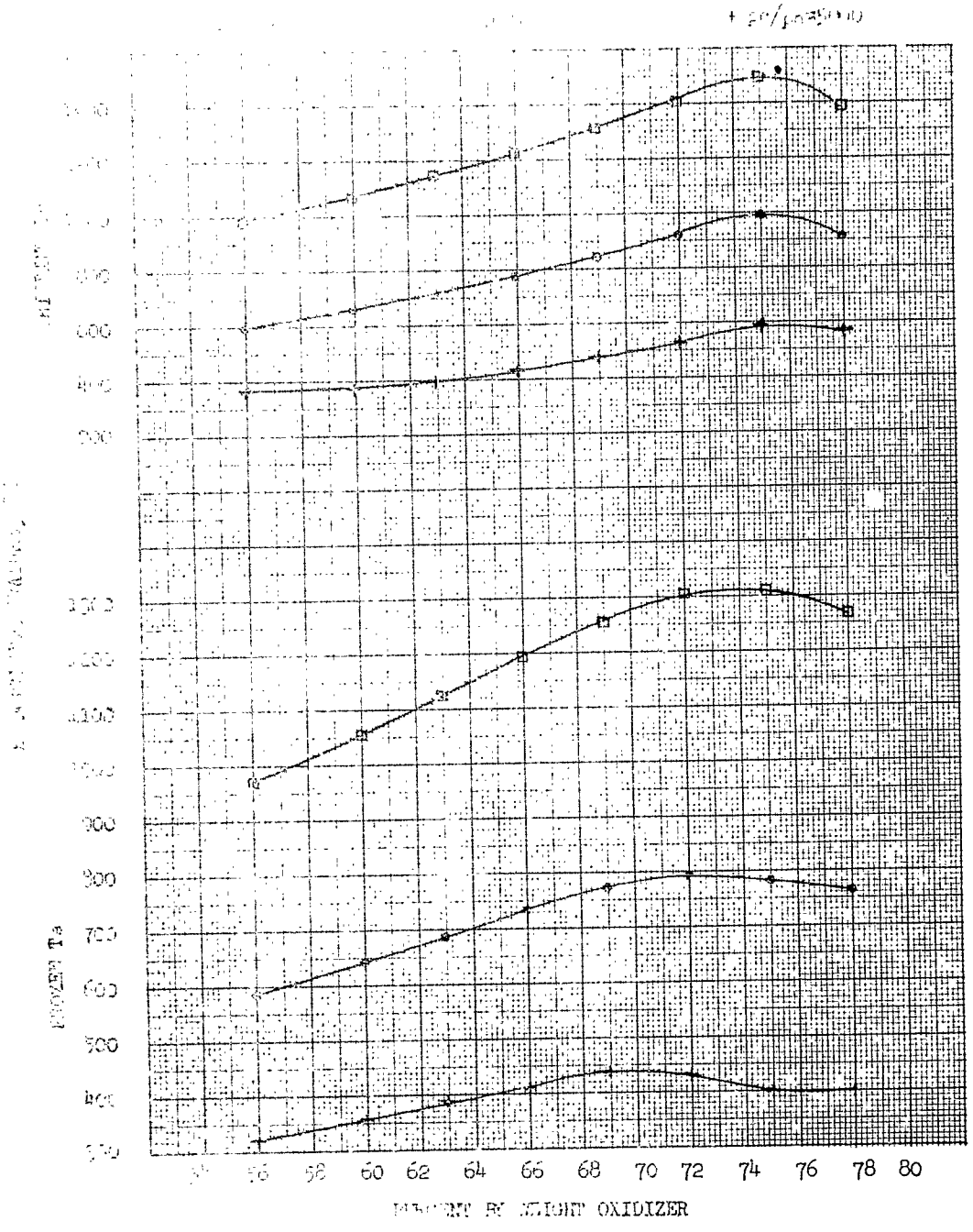


HYDRAZINE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 58

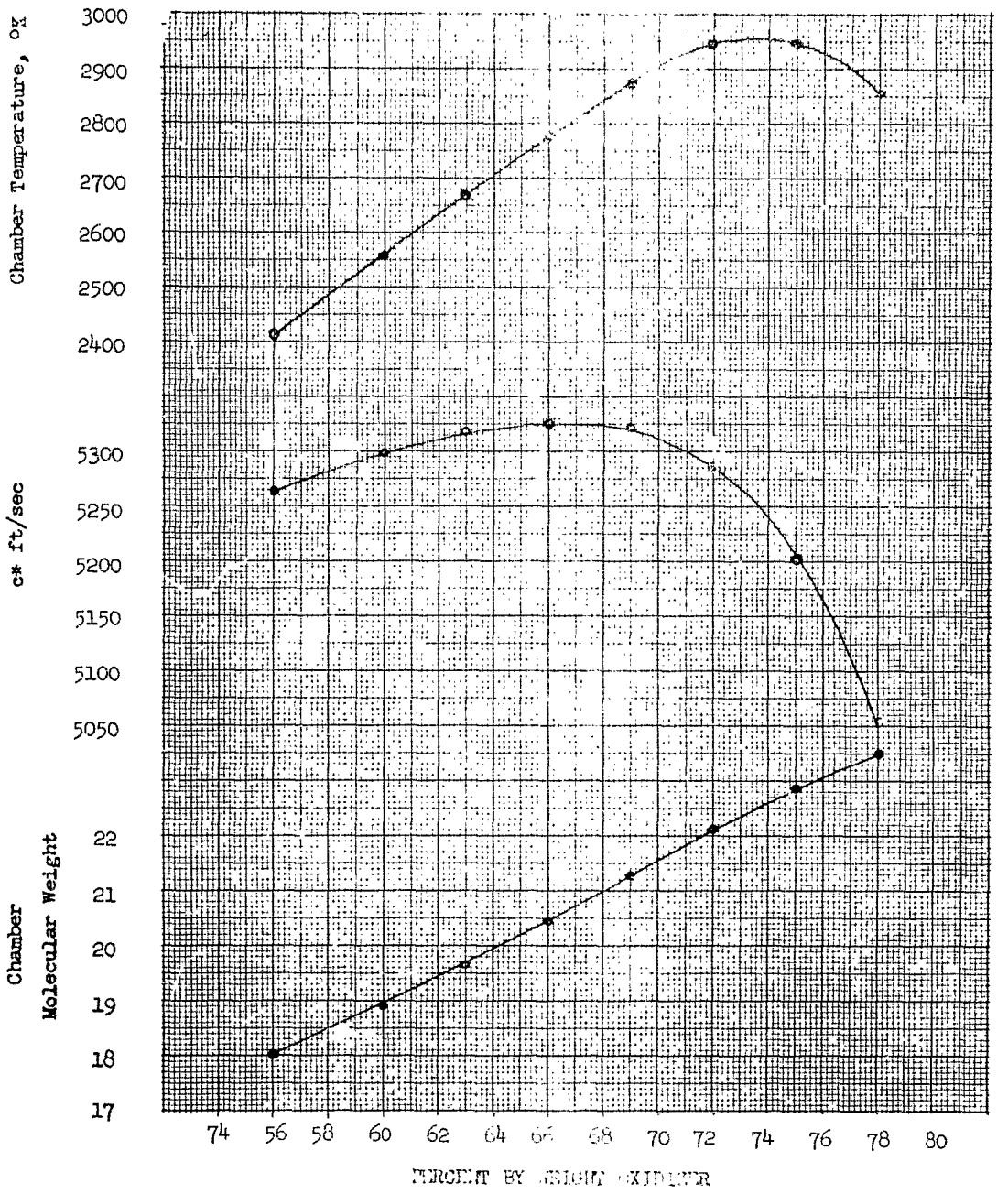
p_c = 1000 psi

□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000




56
58
60
62
64
66
68
70
72
74
76
78
80

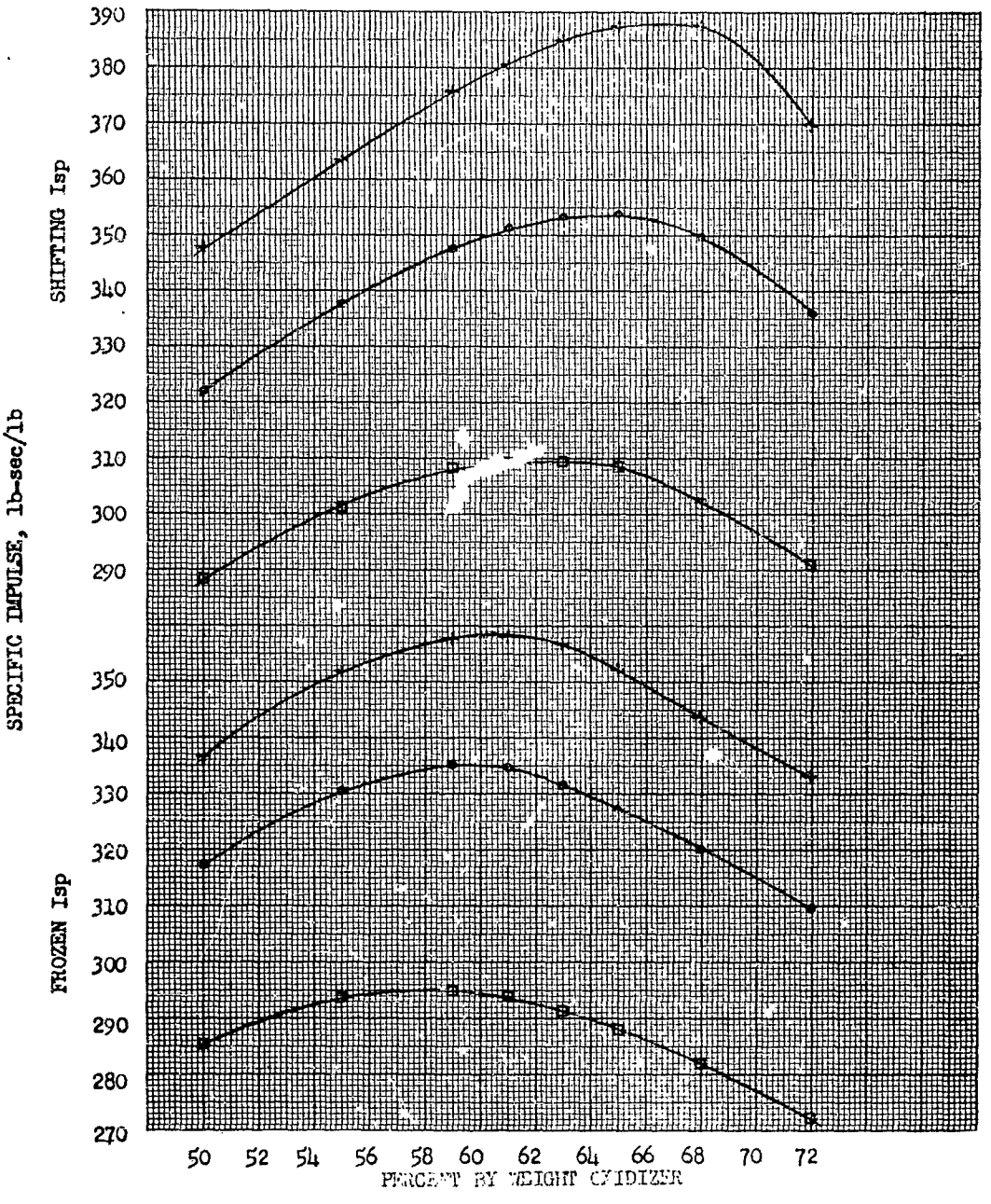
HYDRAZINE - [illegible]


Chamber Temperature, °K
3000
2900
2800
2700
2600
2500
2400
c* ft/sec
5300
5250
5200
5150
5100
5050
Chamber Molecular Weight
22
21
20
19
18
17
74
56
58
60
62
64
66
68
70
72
74
76
78
80
PERCENT BY WEIGHT OXIDIZER

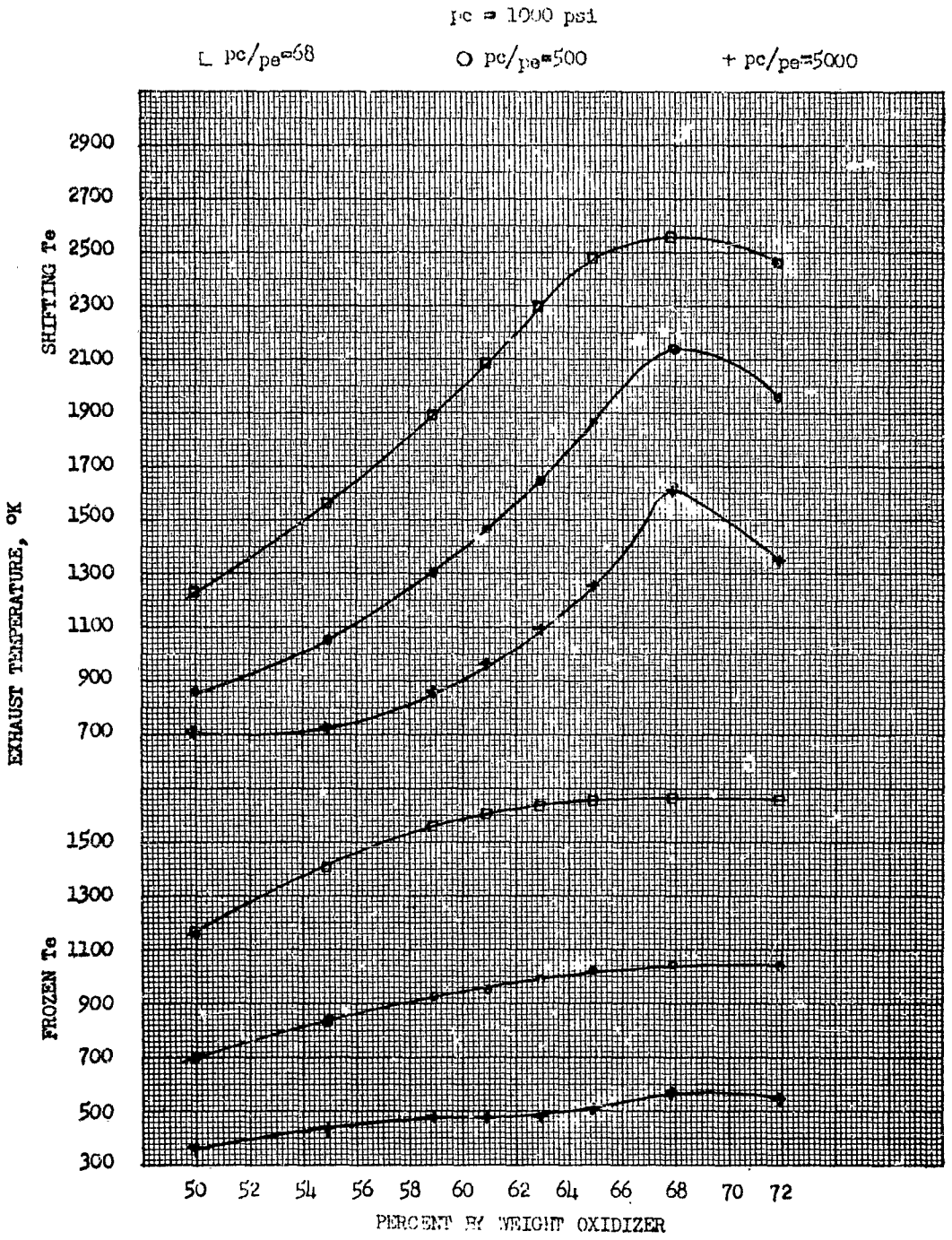
UDMH - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 61

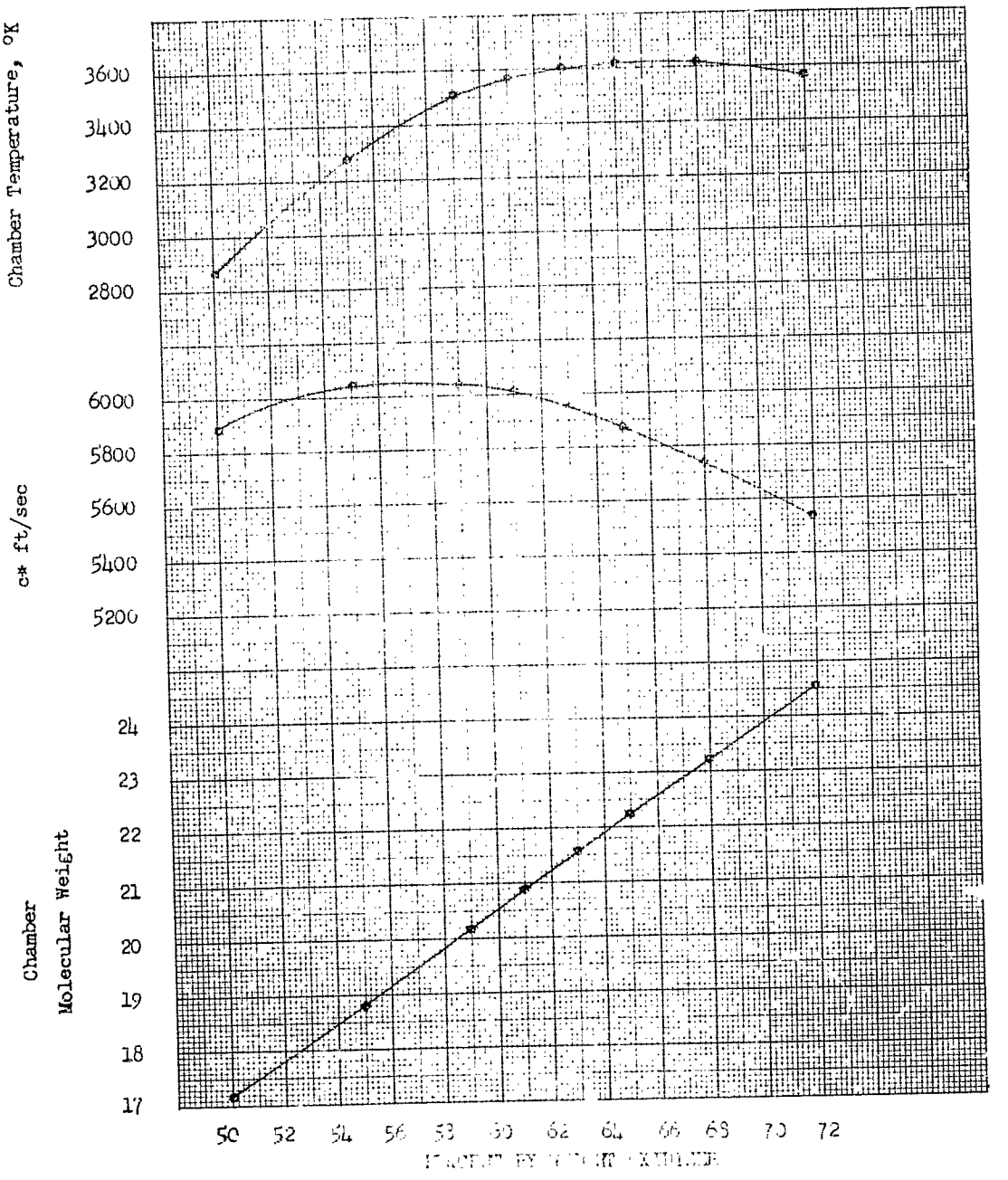
pc = 1000 psi

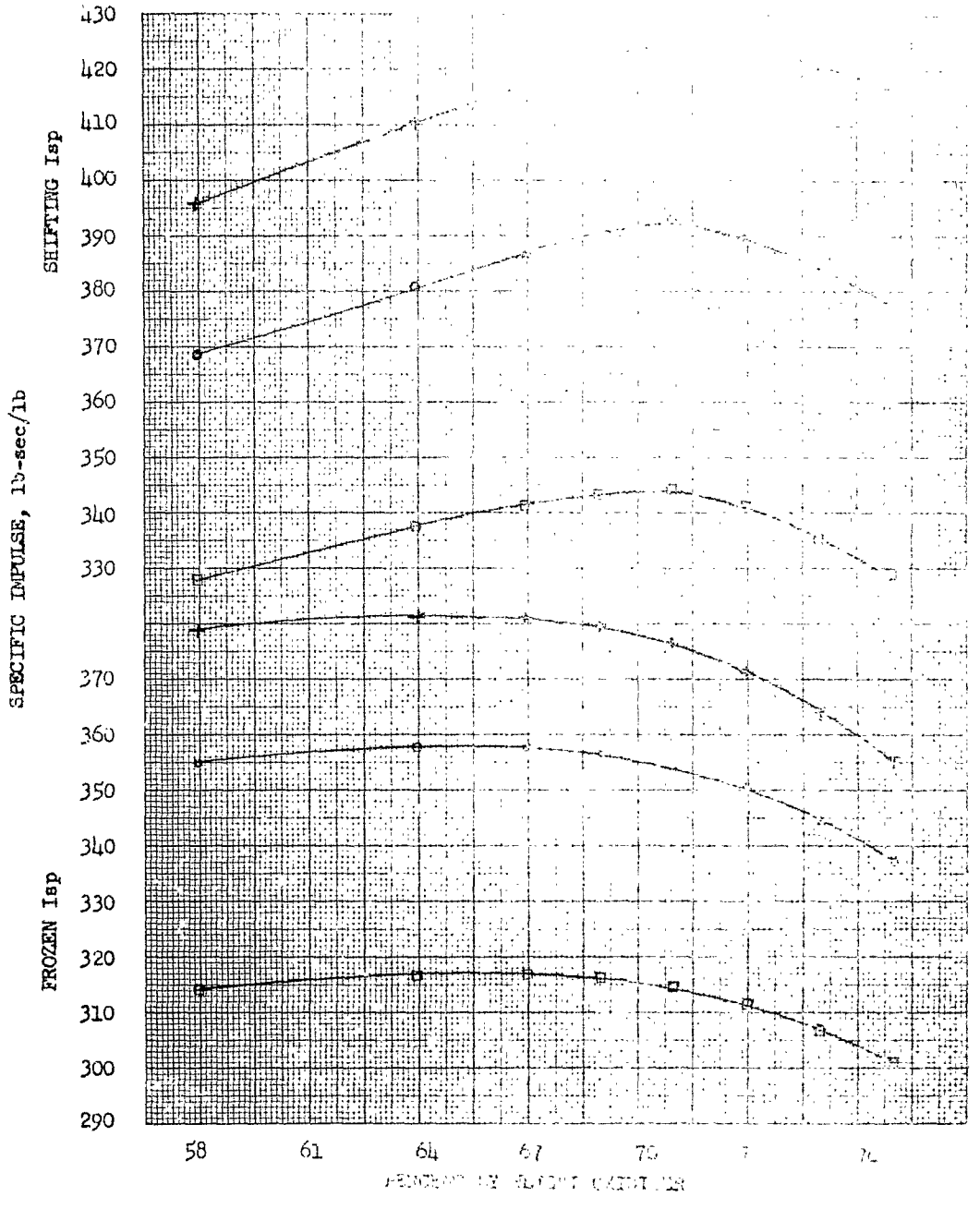
□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



UDMH - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 62



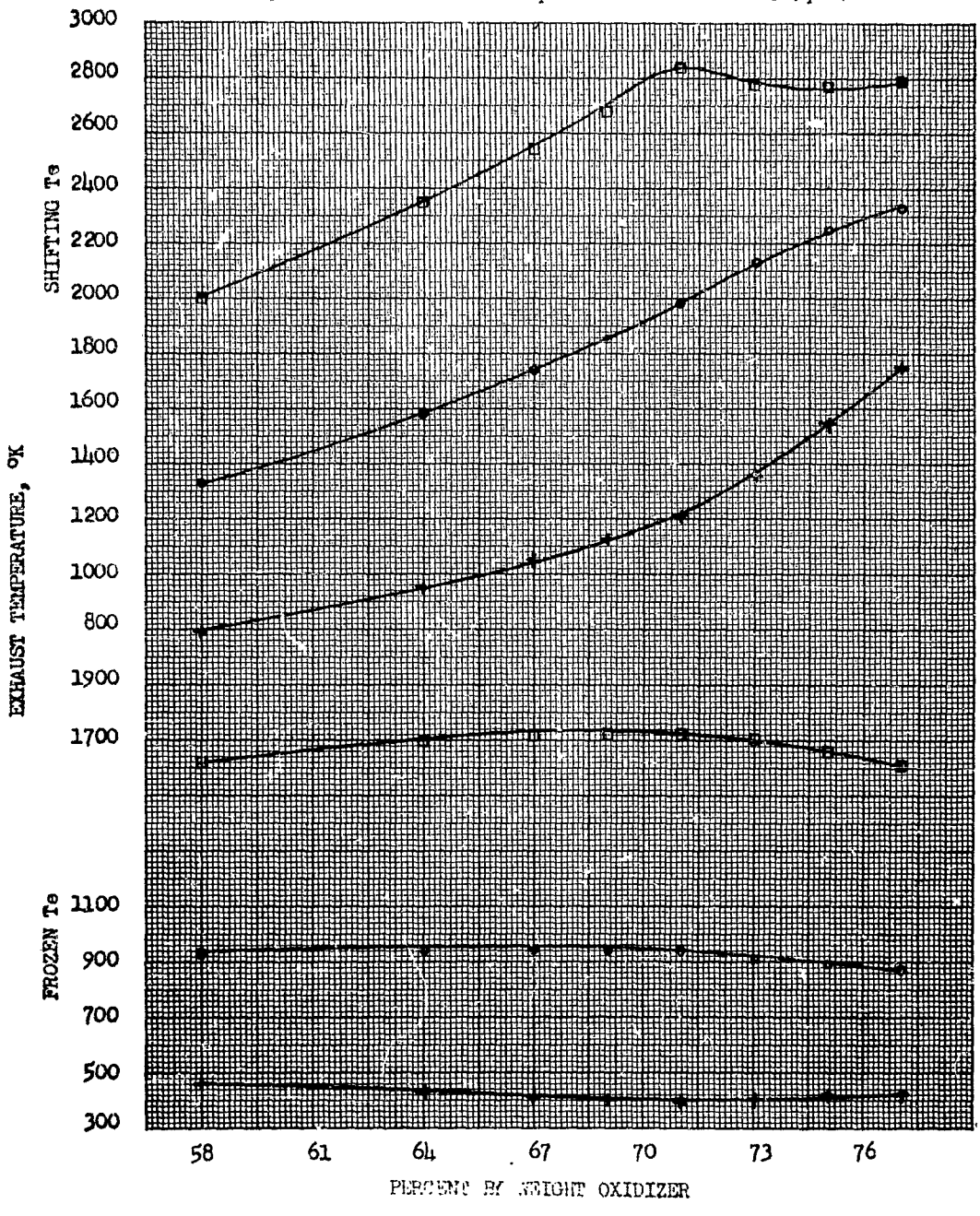

Chamber Temperature, °K
3600
3400
3200
3000
2800
c* ft/sec
6000
5800
5600
5400
5200
Chamber
Molecular Weight
24
23
22
21
20
19
18
17
50
52
54
56
58
60
62
64
66
68
70
72


SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
430
420
410
400
390
380
370
360
350
340
330
370
360
350
340
330
320
310
300
290
58
61
64
67
70

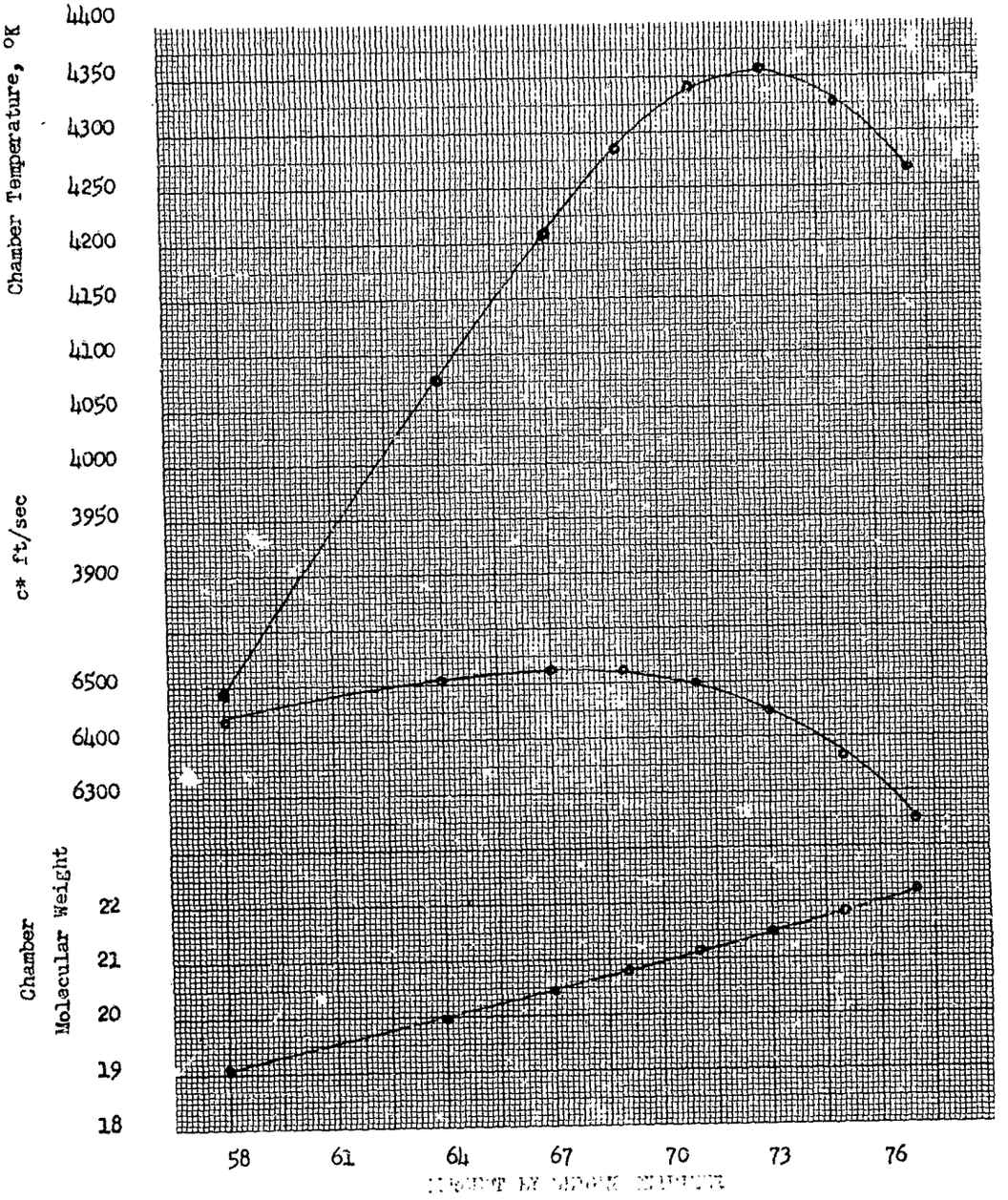
UDMH - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 65

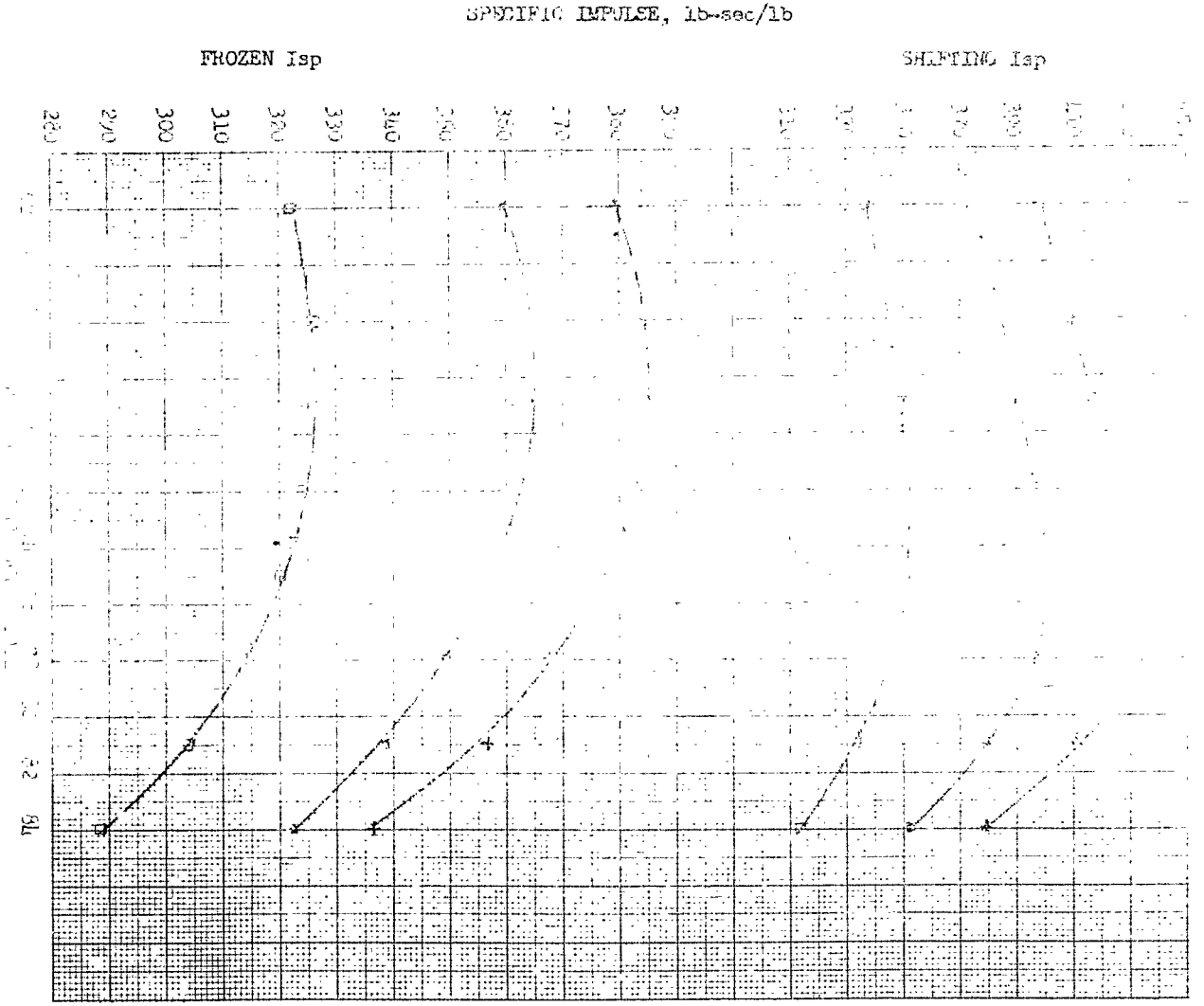
p_c = 1000 psi

△ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000

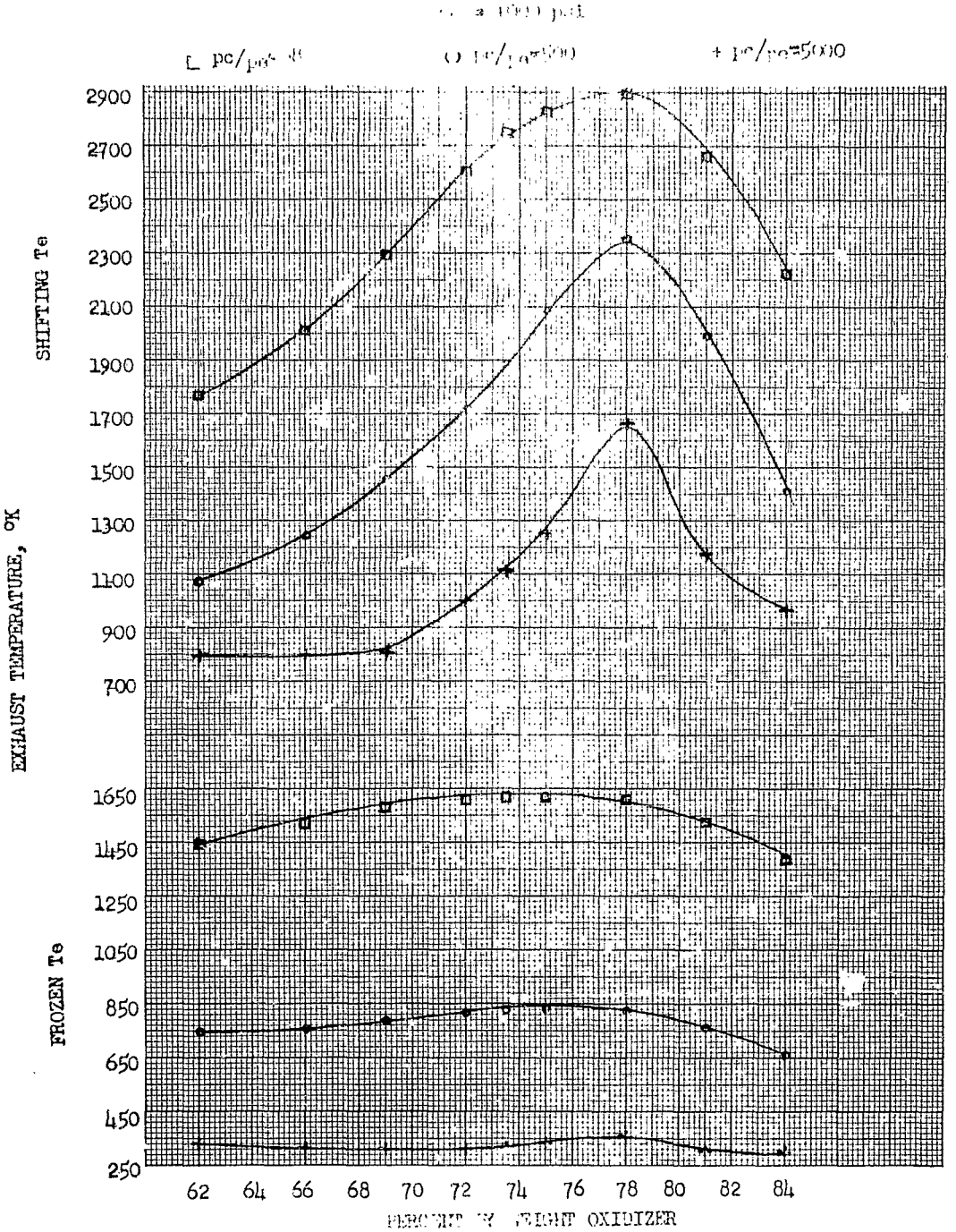


UDMH - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 66

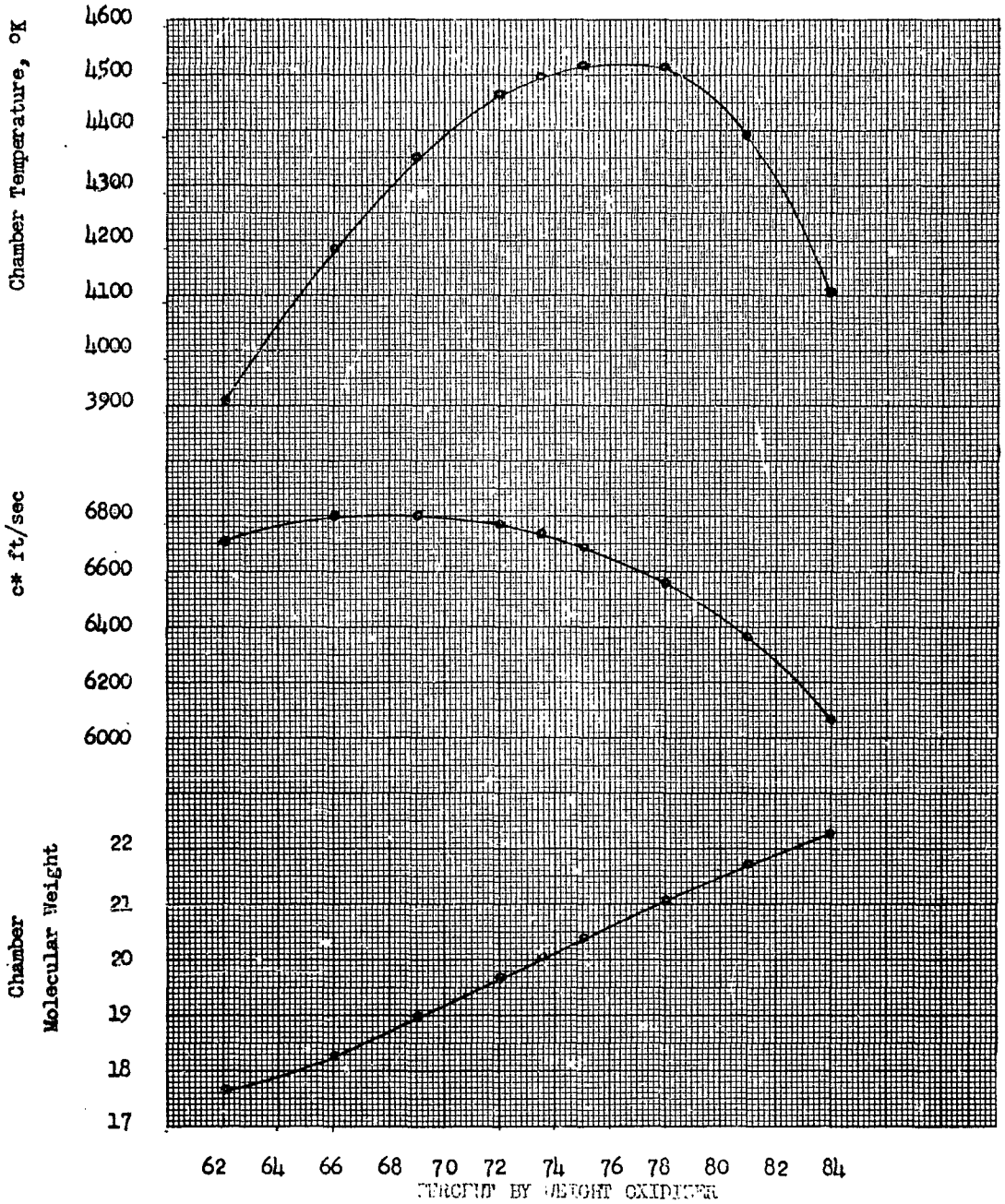



SPECIFIC IMPULSE, lb-sec/lb
FROZEN Isp
SHIFTING Isp
260
270
300
310
320
330
340
350
360
370
380
390
400

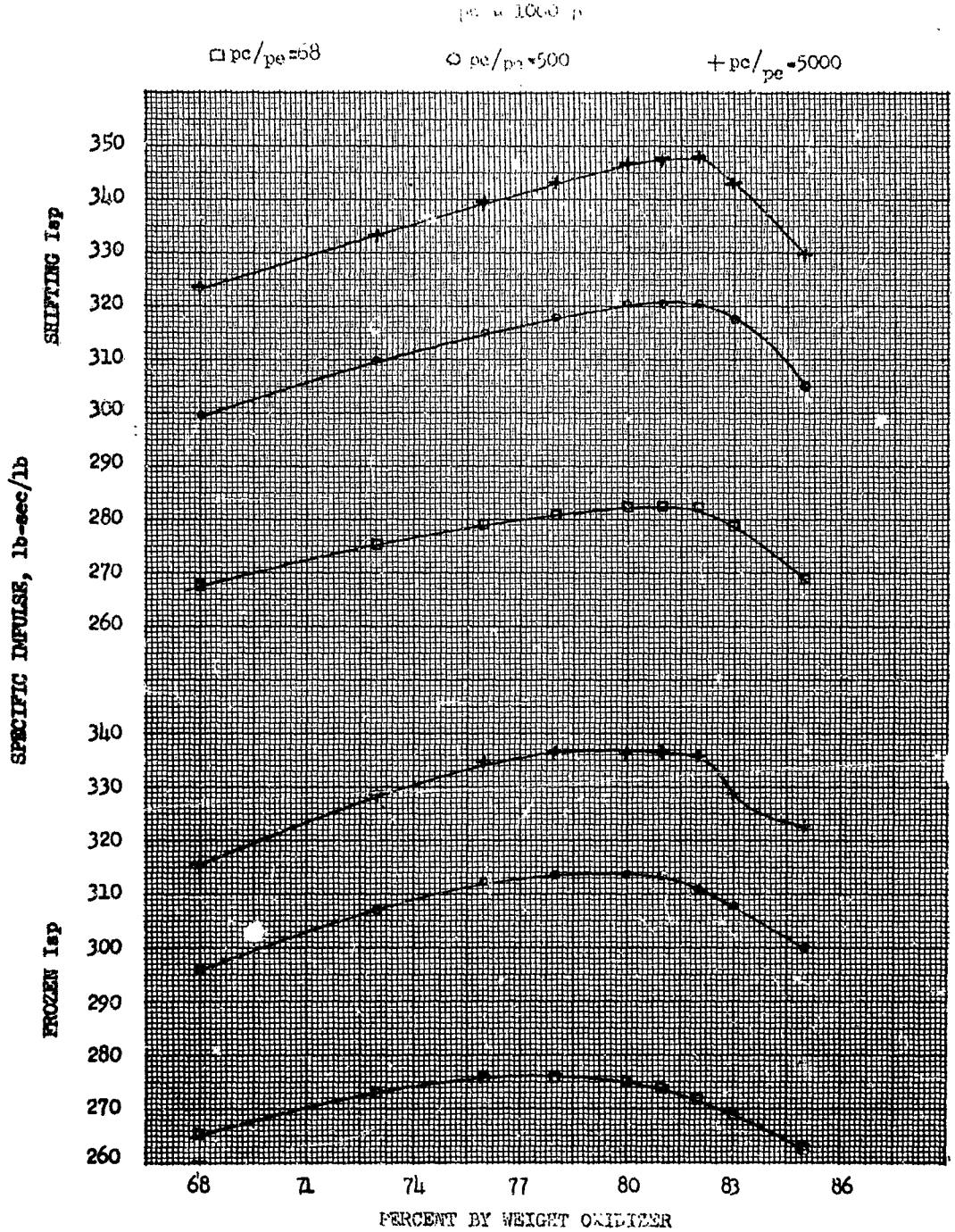
UDMH - OXYGEL DIFFUSION PERFORMANCE CURVES FIGURE 68



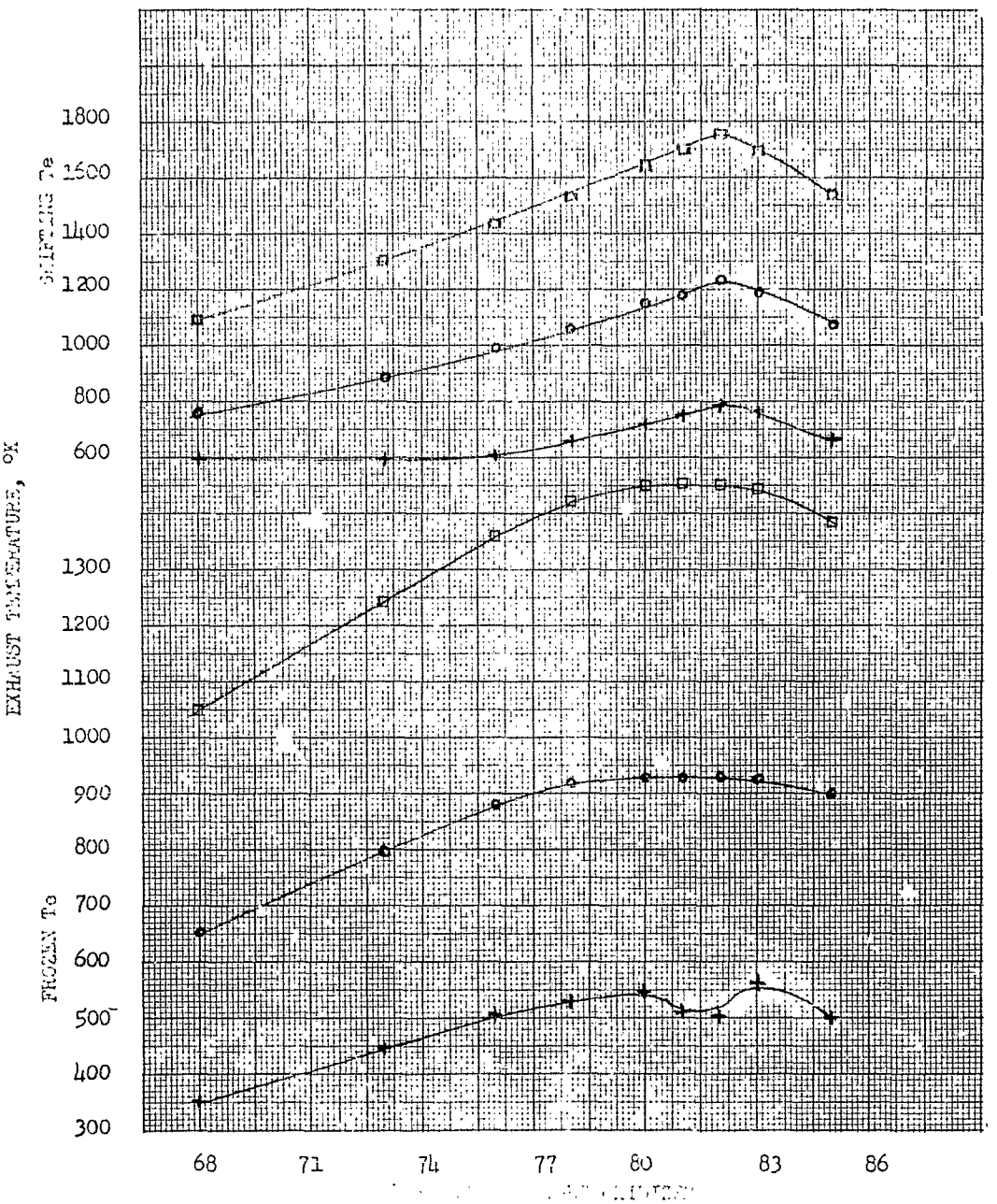
UDMH - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 69



UDMH - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 70

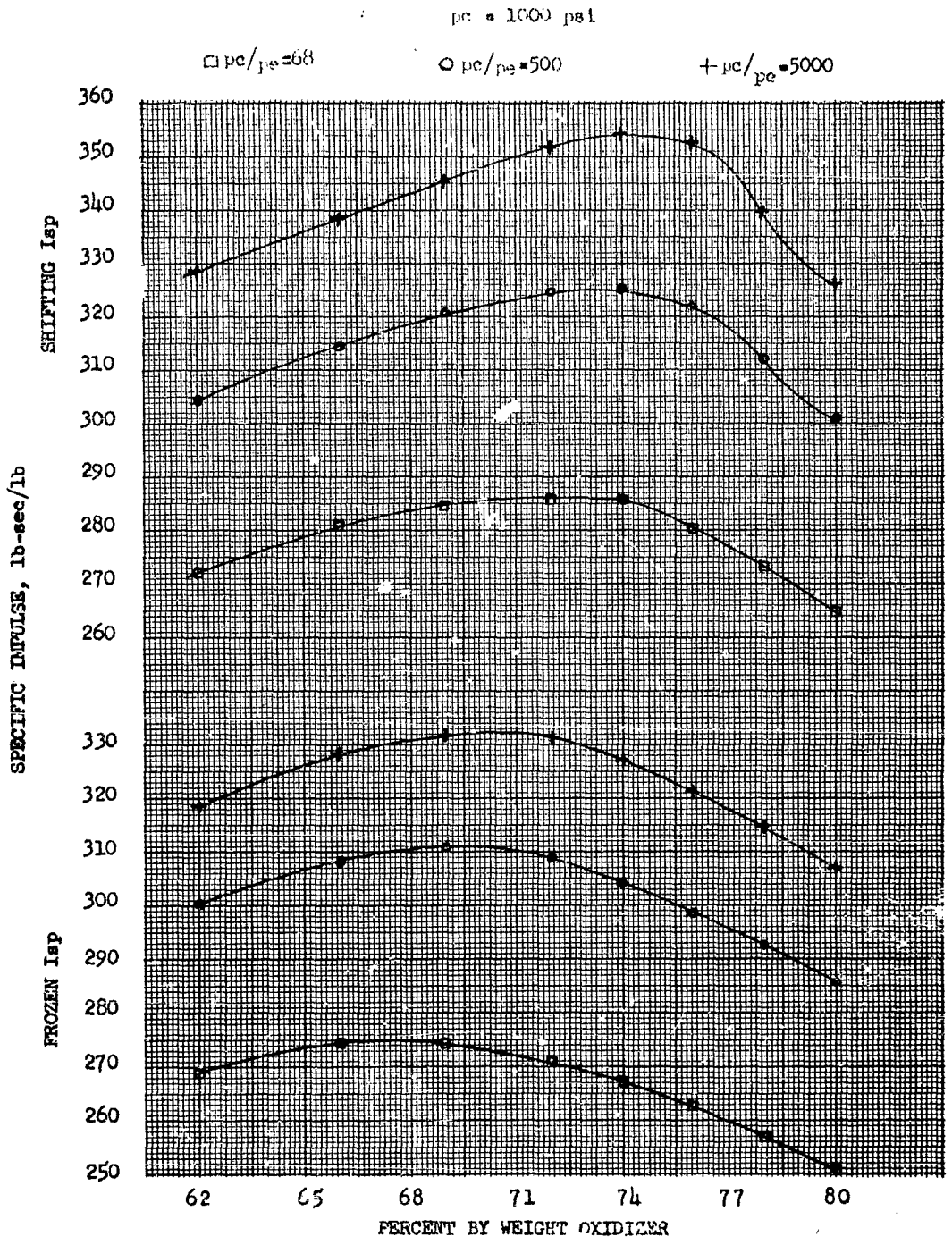


UDMH – HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 71

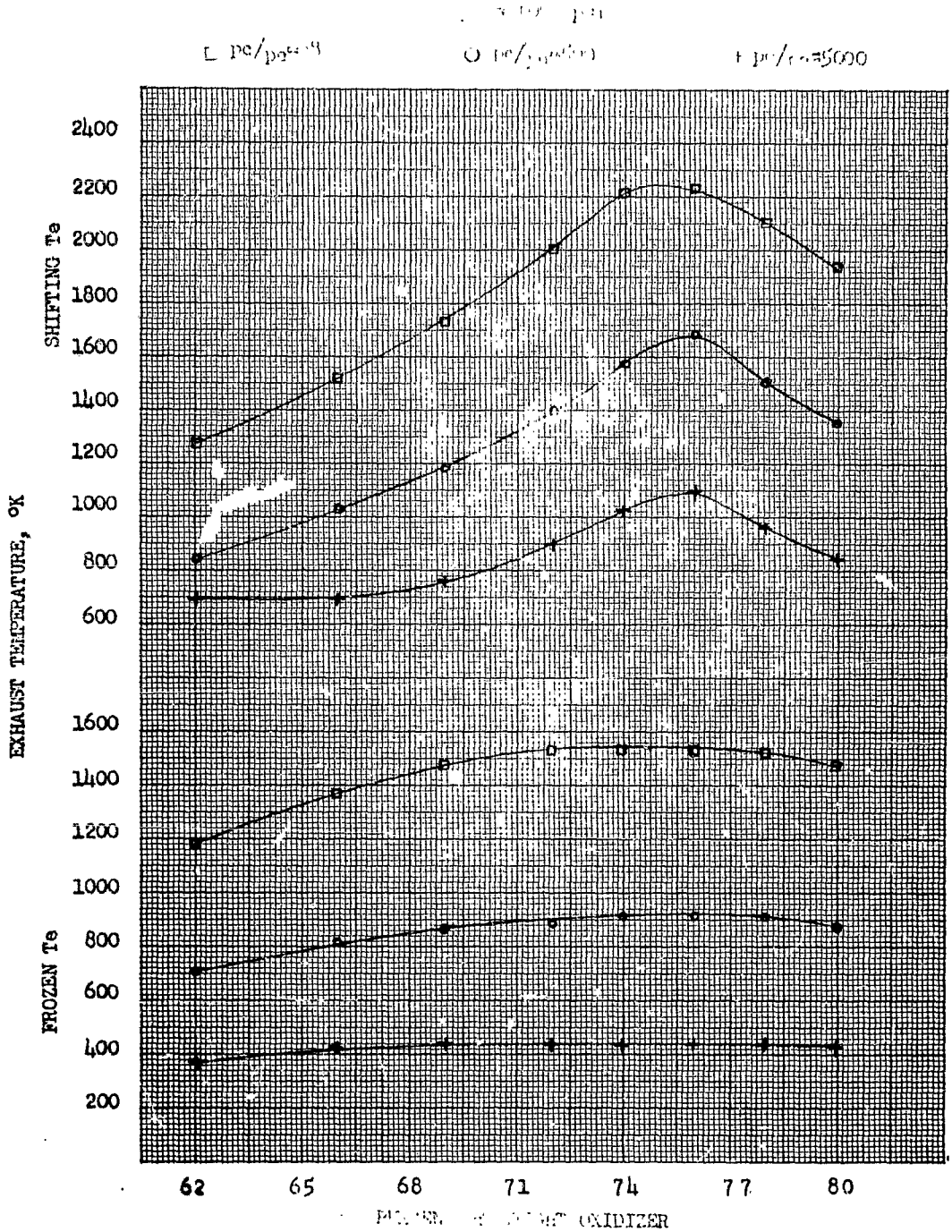


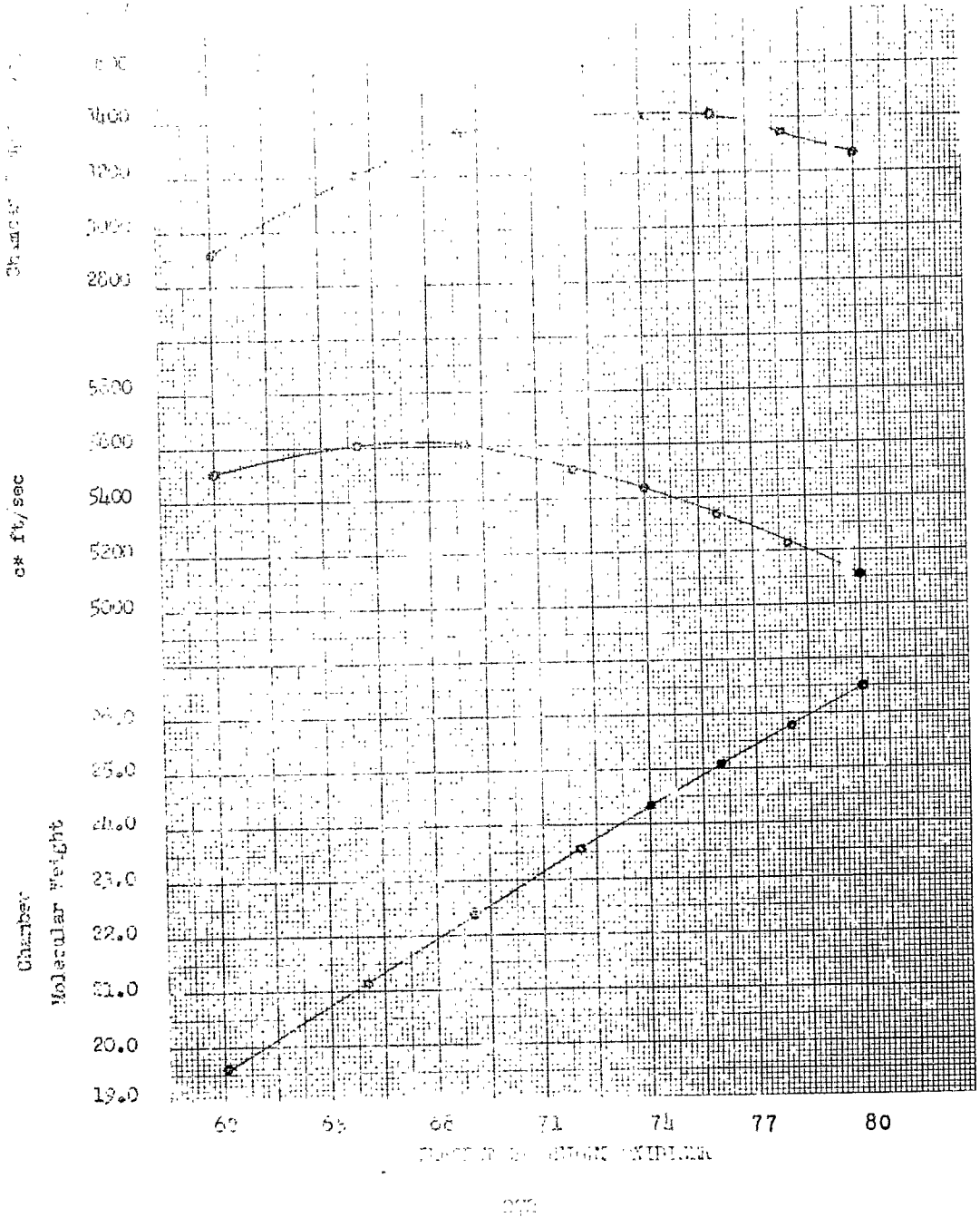
Chamber Temperature, °K
c* ft/sec
Chamber
Molecular Weight
3000
2900
2800
2700
2600
2500
5600
5500
5400
5300
21
20
19
18
17
68
72
74
86

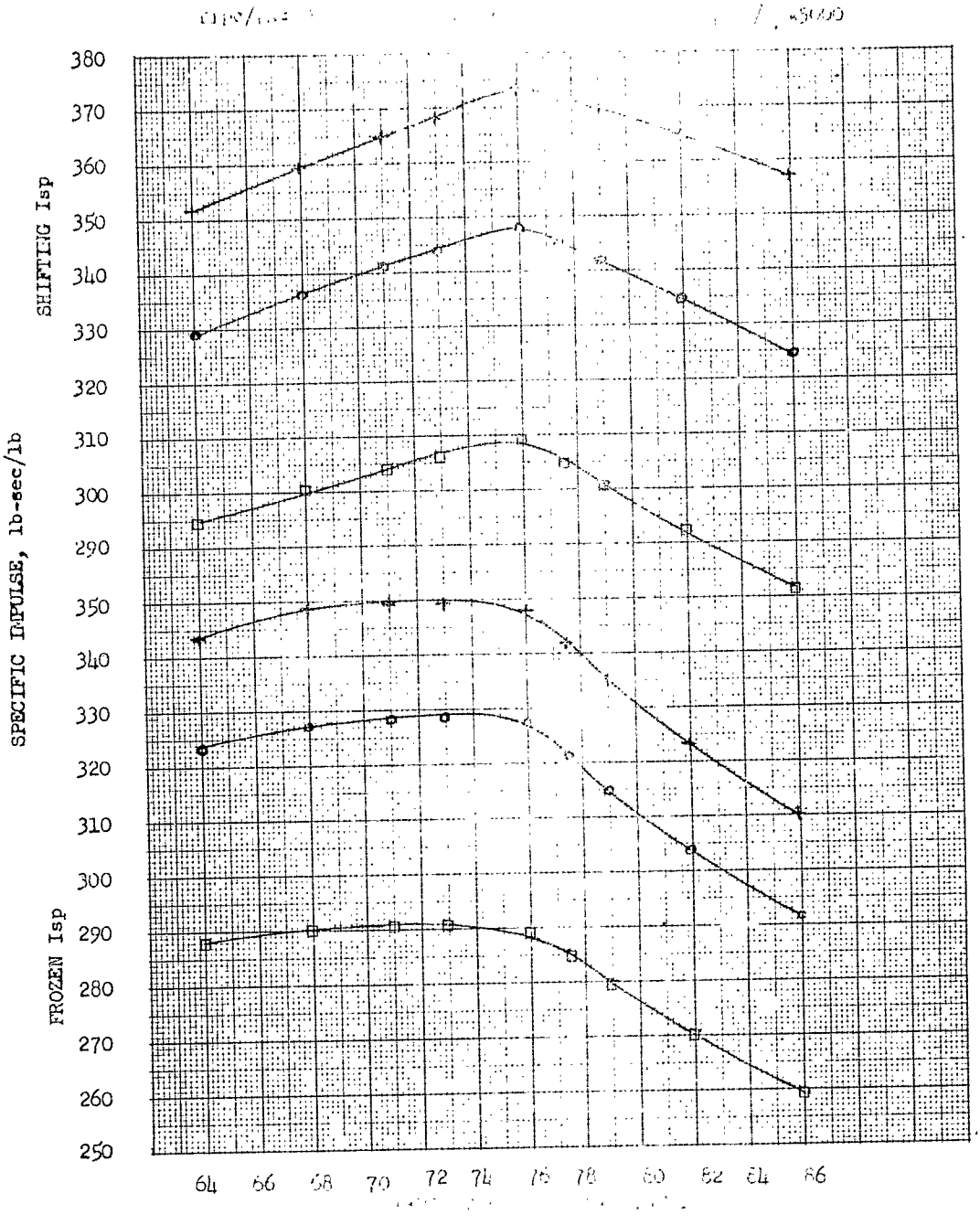
UDMH - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 73



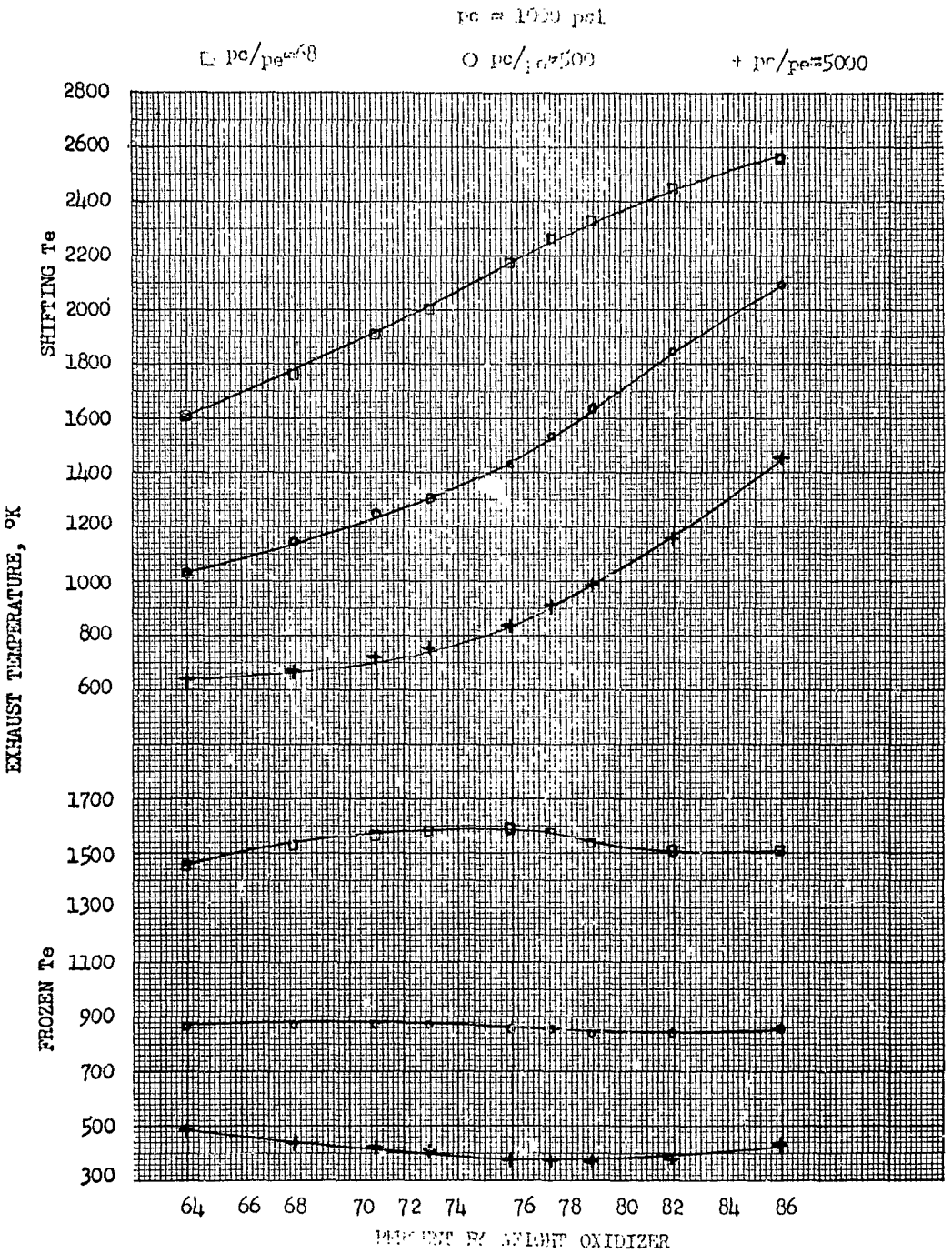
UDMH - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 74



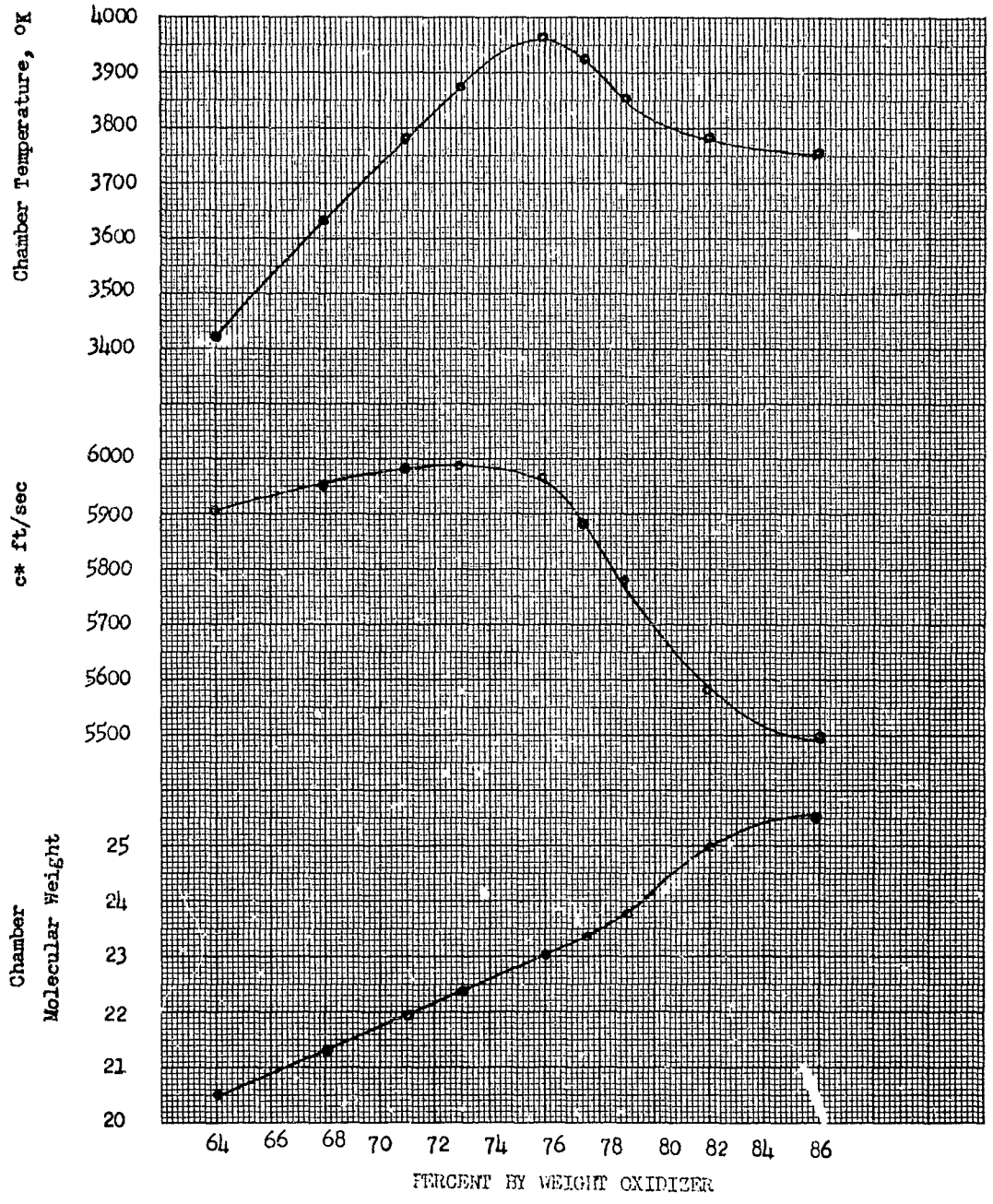

3000
2800
5600
5400
5200
5000
23.0
22.0
21.0
20.0
19.0
60
66
71
77
80

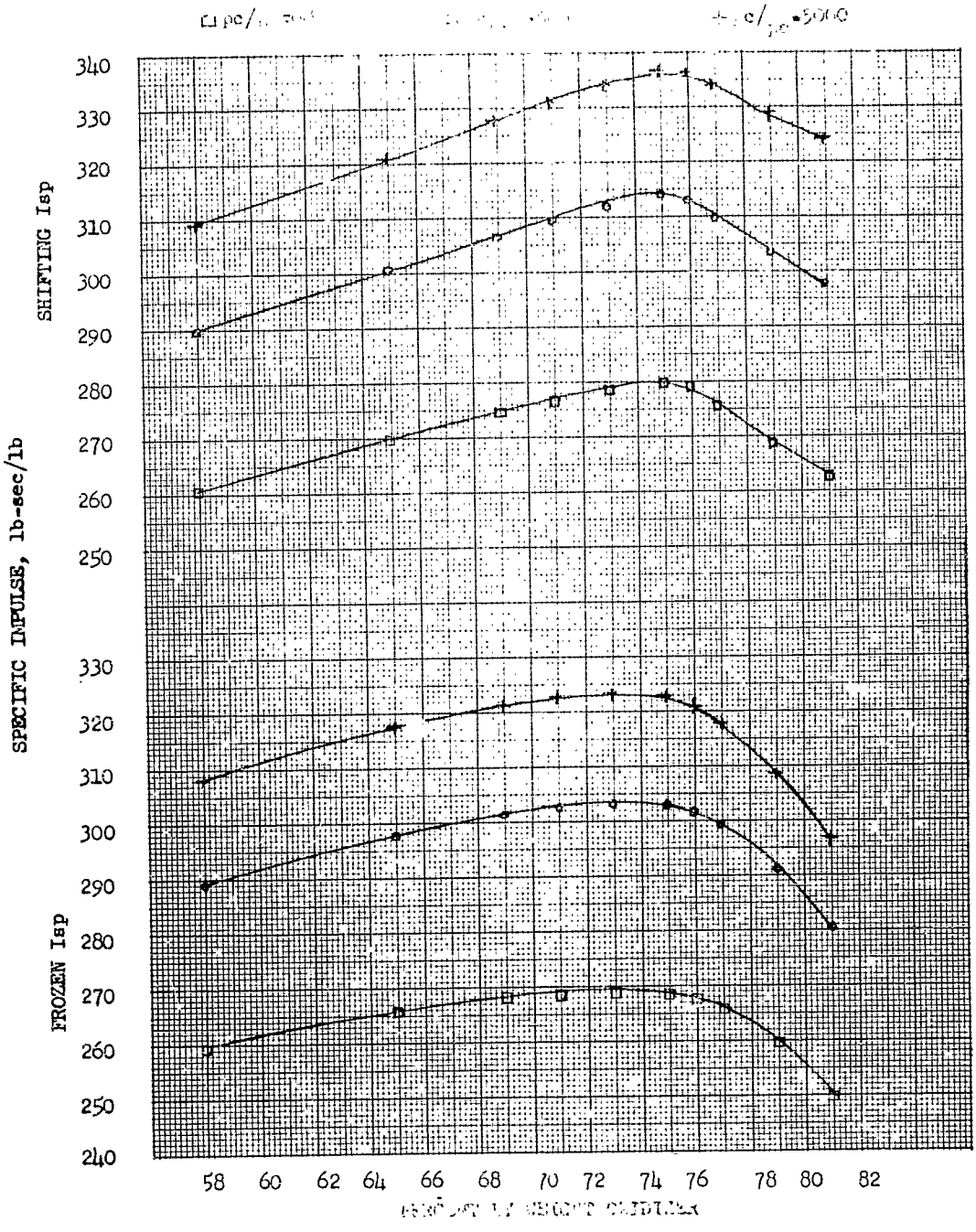

SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
380
370
360
350
340
330
320
310
300
290
350
340
330
320
310
300
290
280
270
260
250
64
66
68
70
72
74
76
78
80
82
84
86

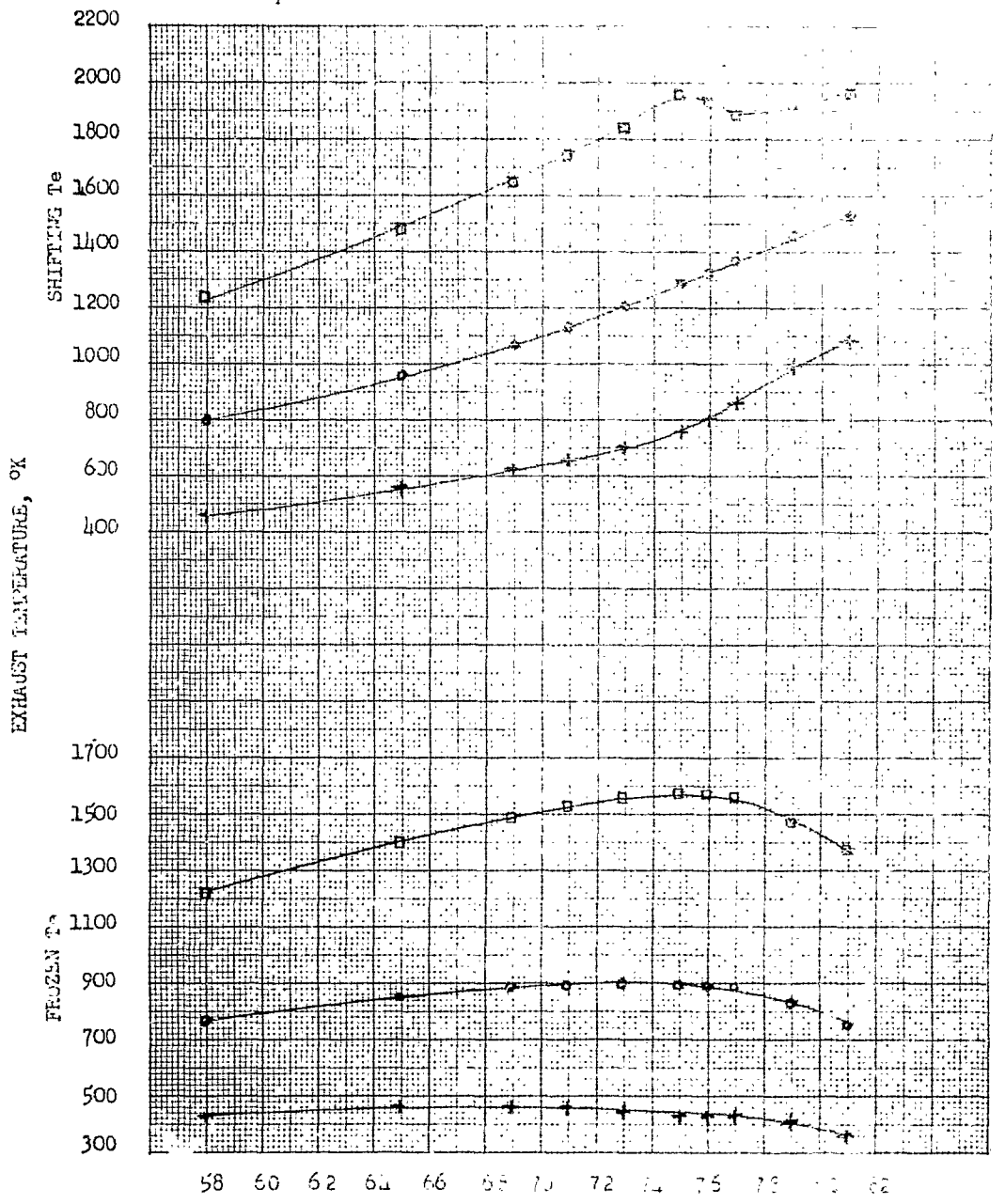
UDMH - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 77



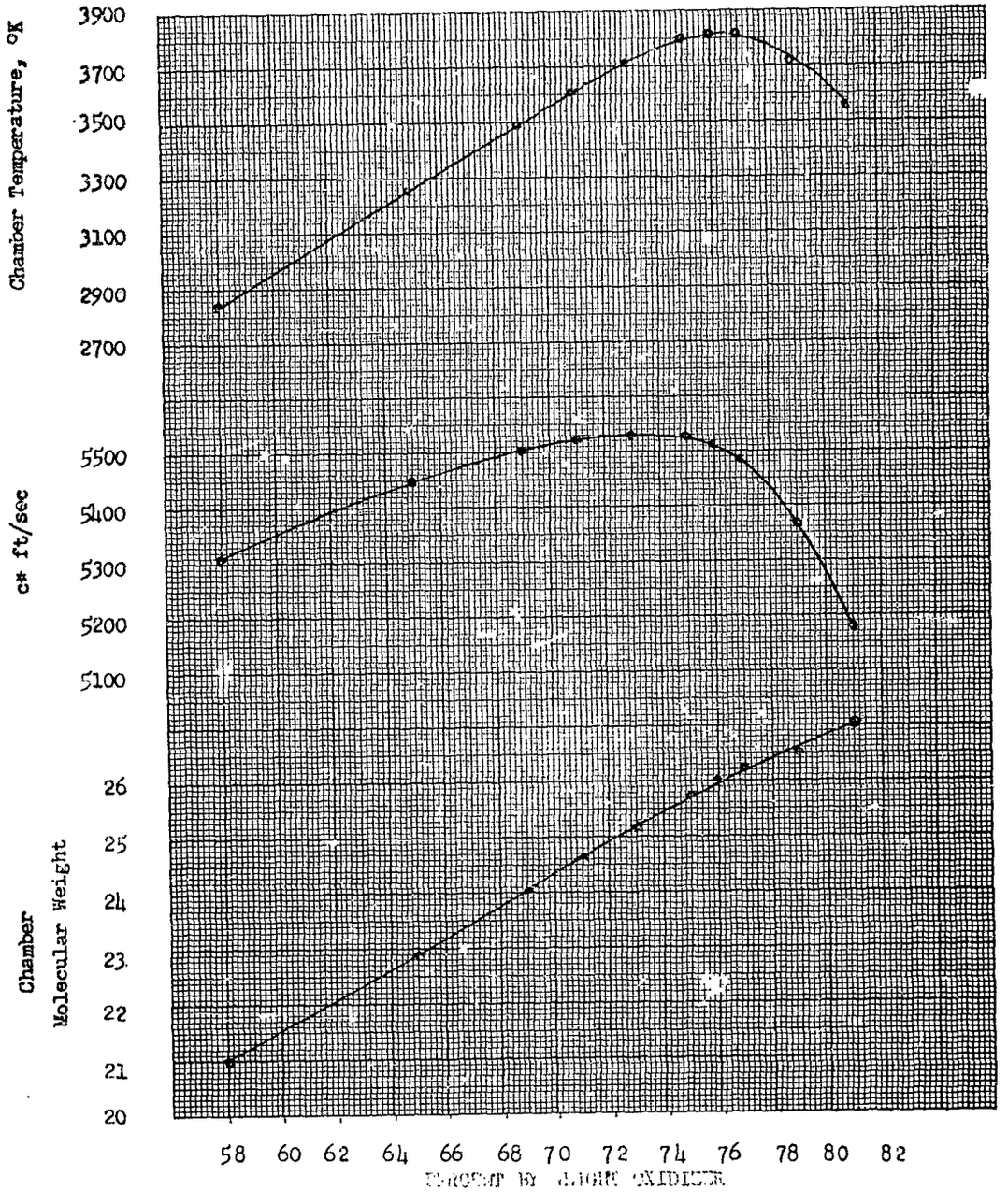
UDMH - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 78



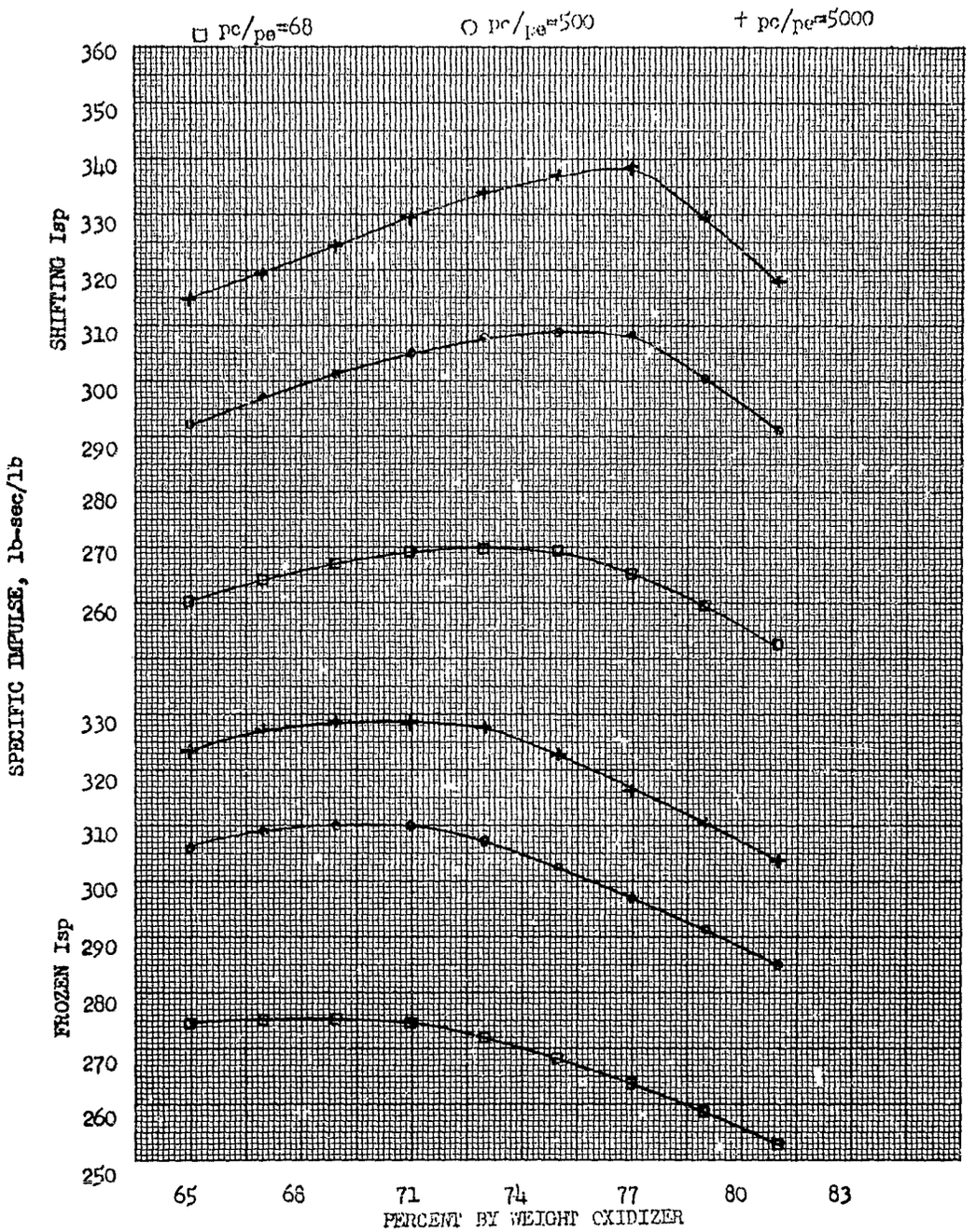

SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
340
330
320
310
300
290
280
270
260
250
240
58
60
62
64
66
68
70
72
74
76
78
80
82

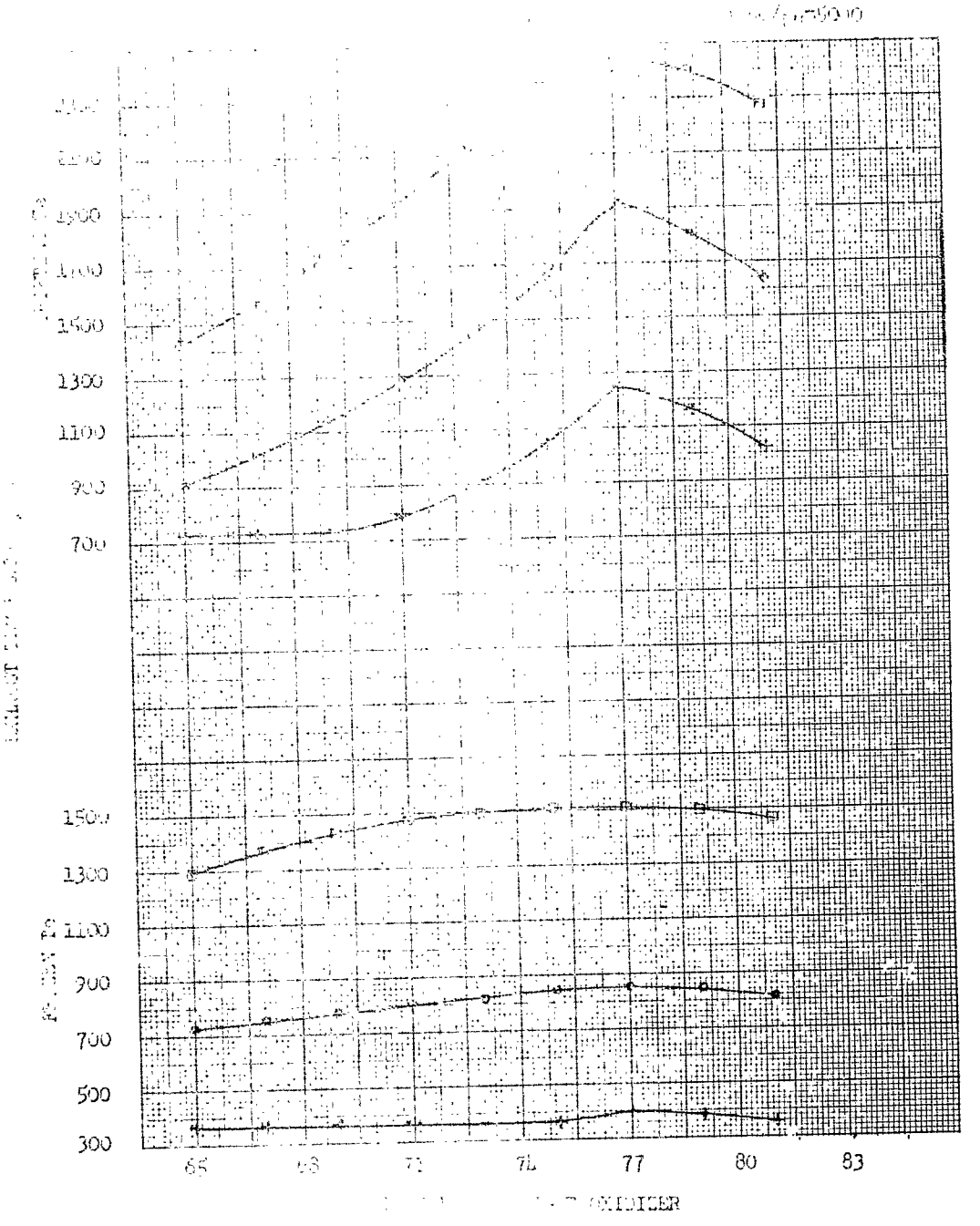

EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
2200
2000
1800
1600
1400
1200
1000
800
600
400
1700
1500
1300
1100
900
700
500
300
58
60
62
64
66
68
70
72
74
76
78
80
82

UDMH – CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 81

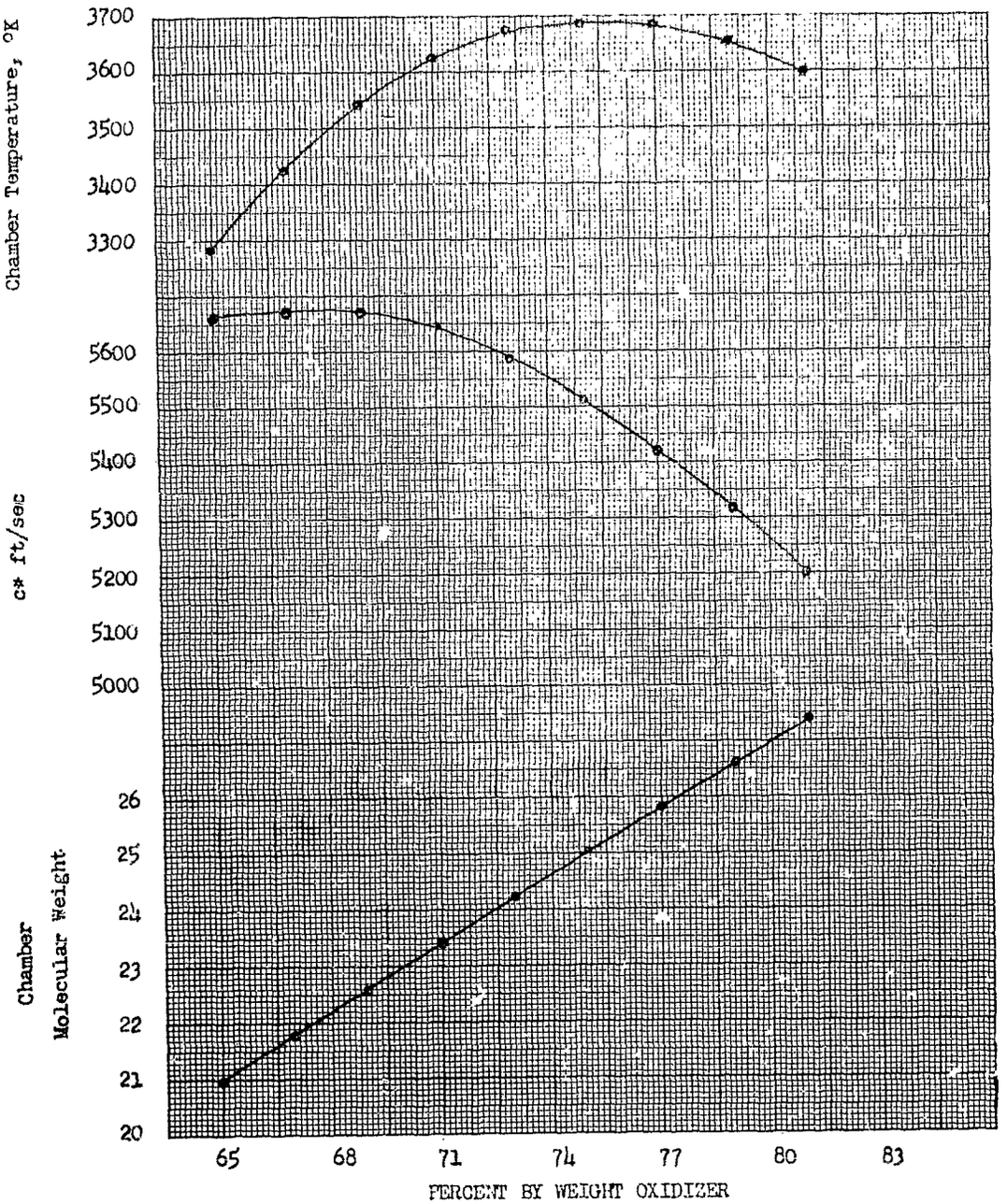


UDMH - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 82




1500
1300
1100
900
700
1500
1300
1100
900
700
500
300
65
68
71
74
77
80
83

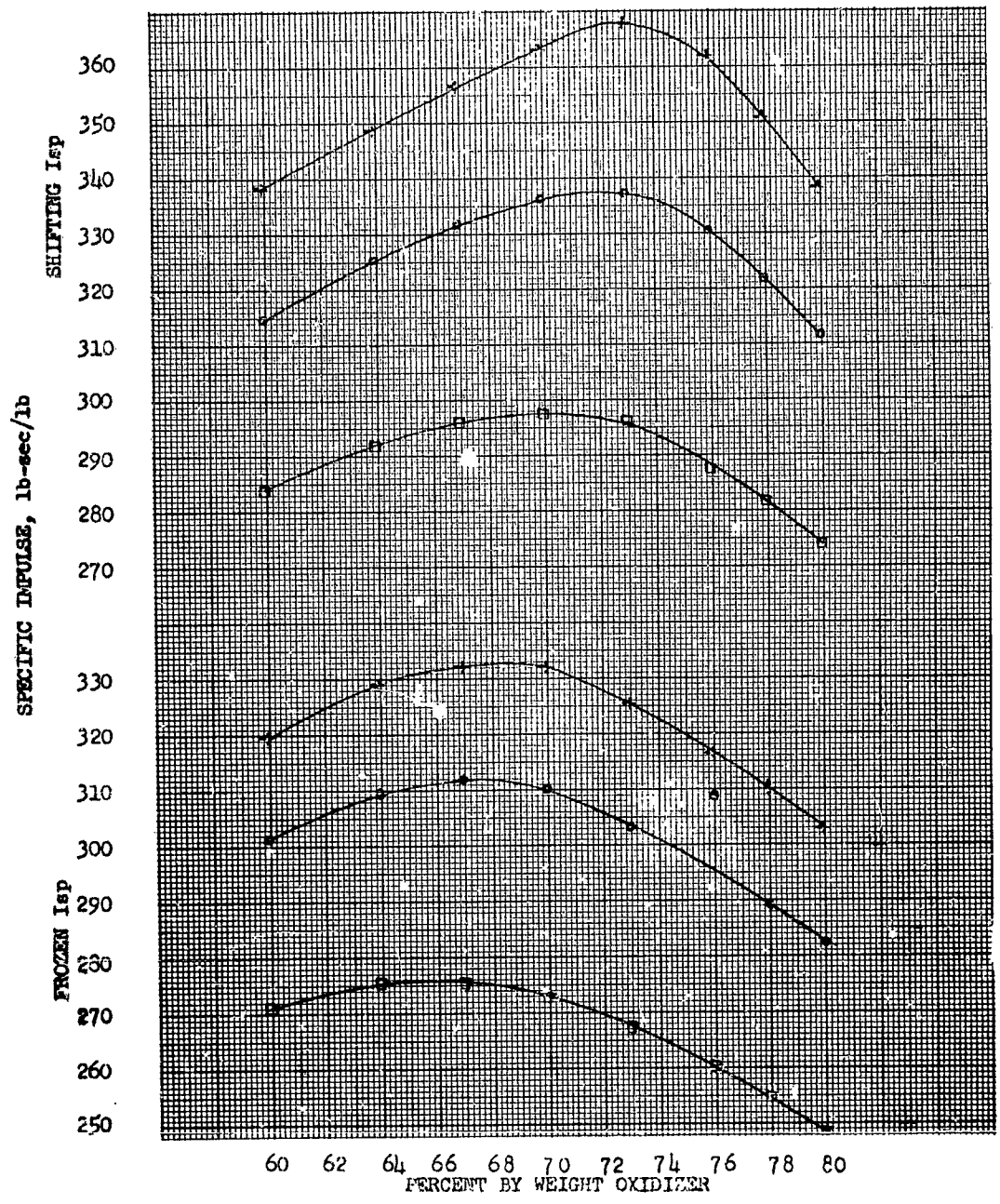
UDMH - PERCHLORYL FLUORIDE PERFORMANCE CURVES



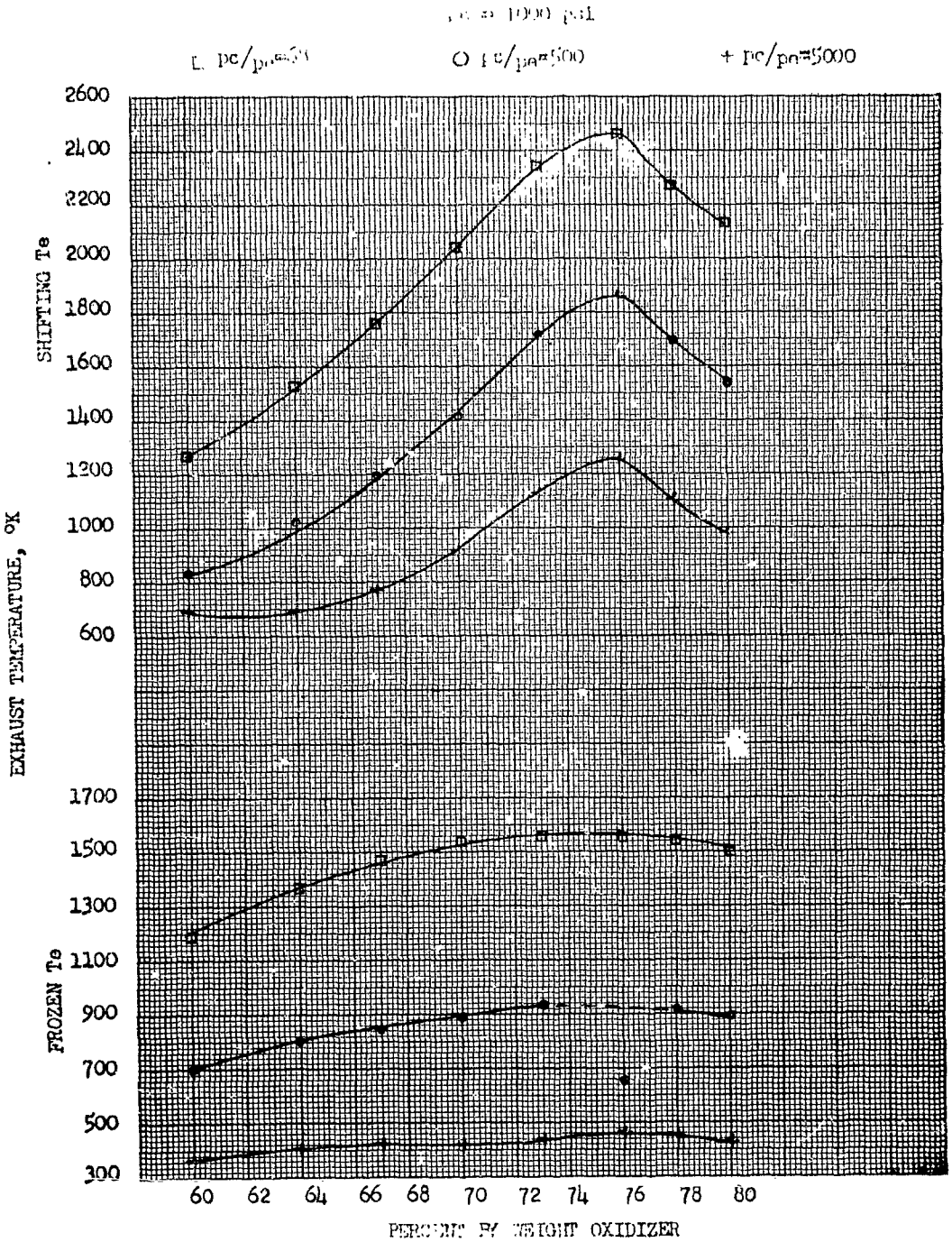
UDMH - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 85

p_c = 1000 psi

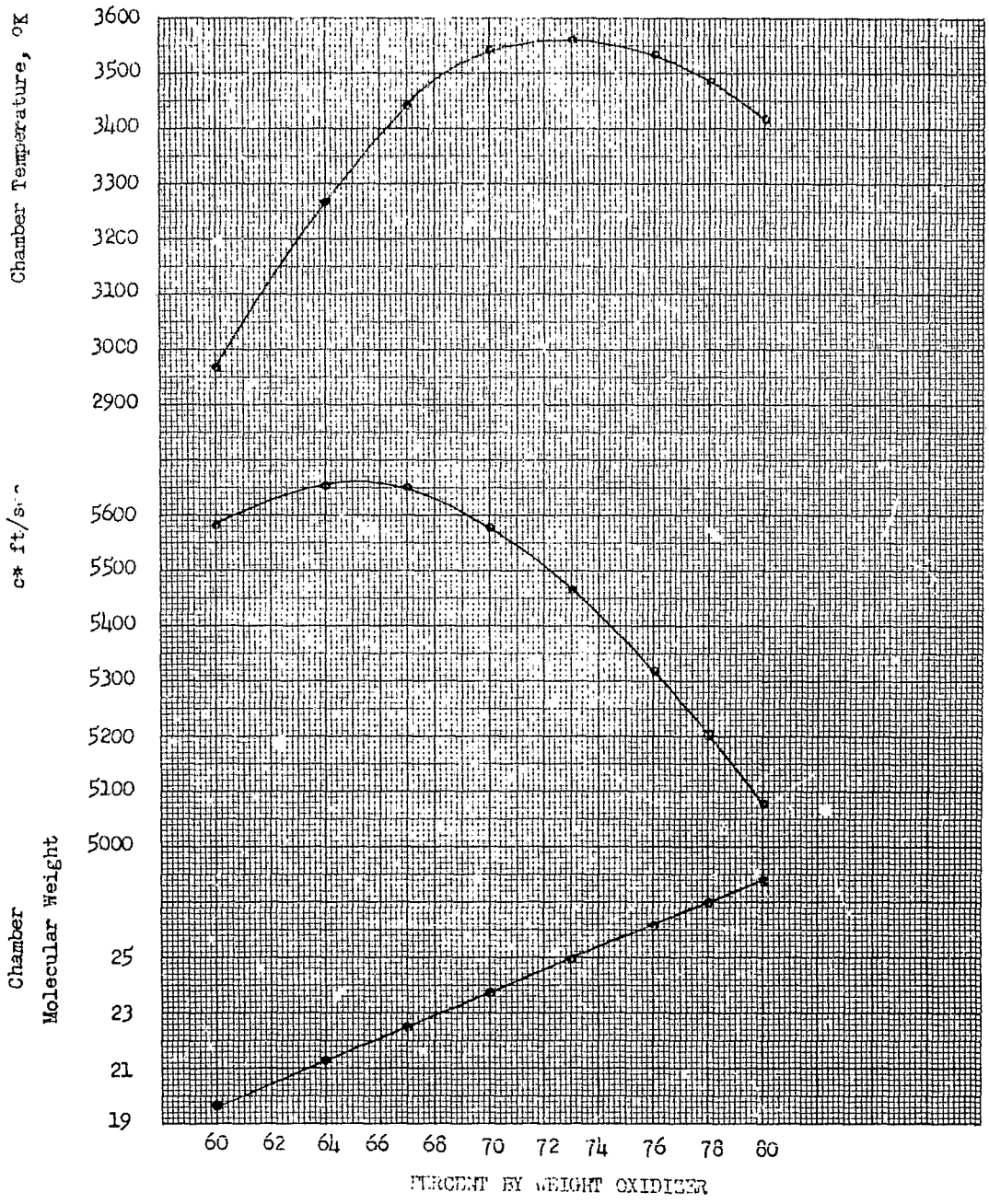
□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



UDMH - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 86

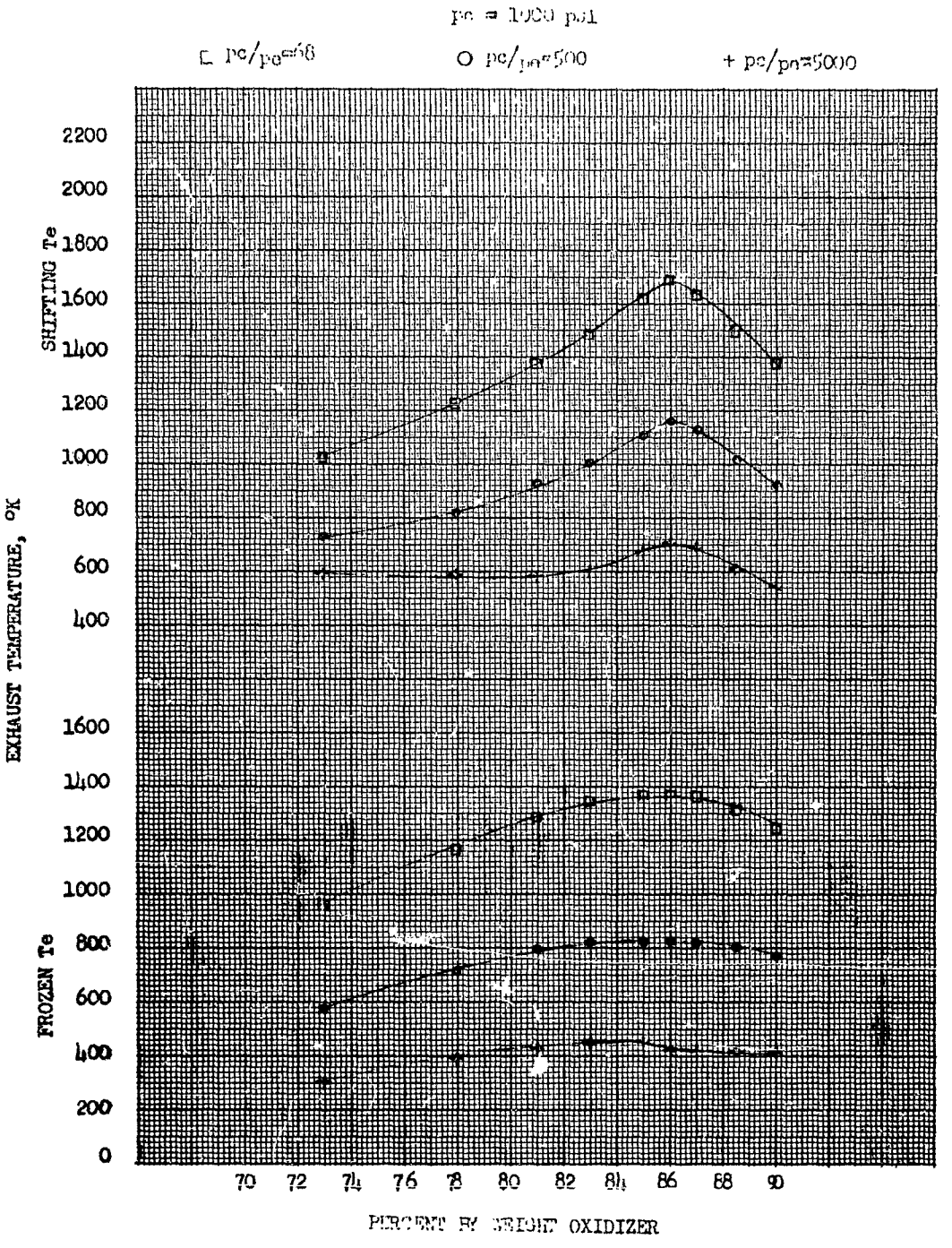


UDMH - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 87

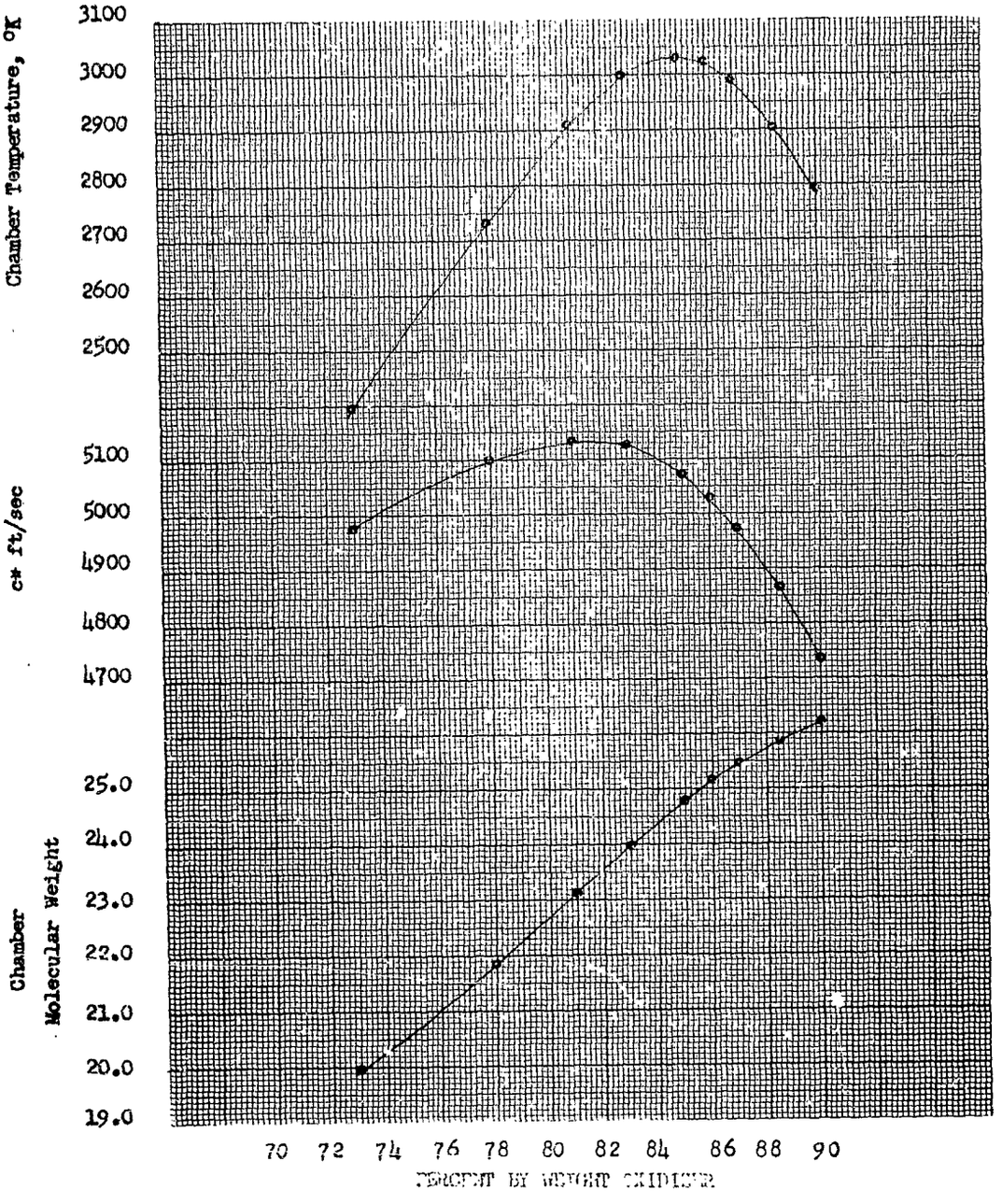


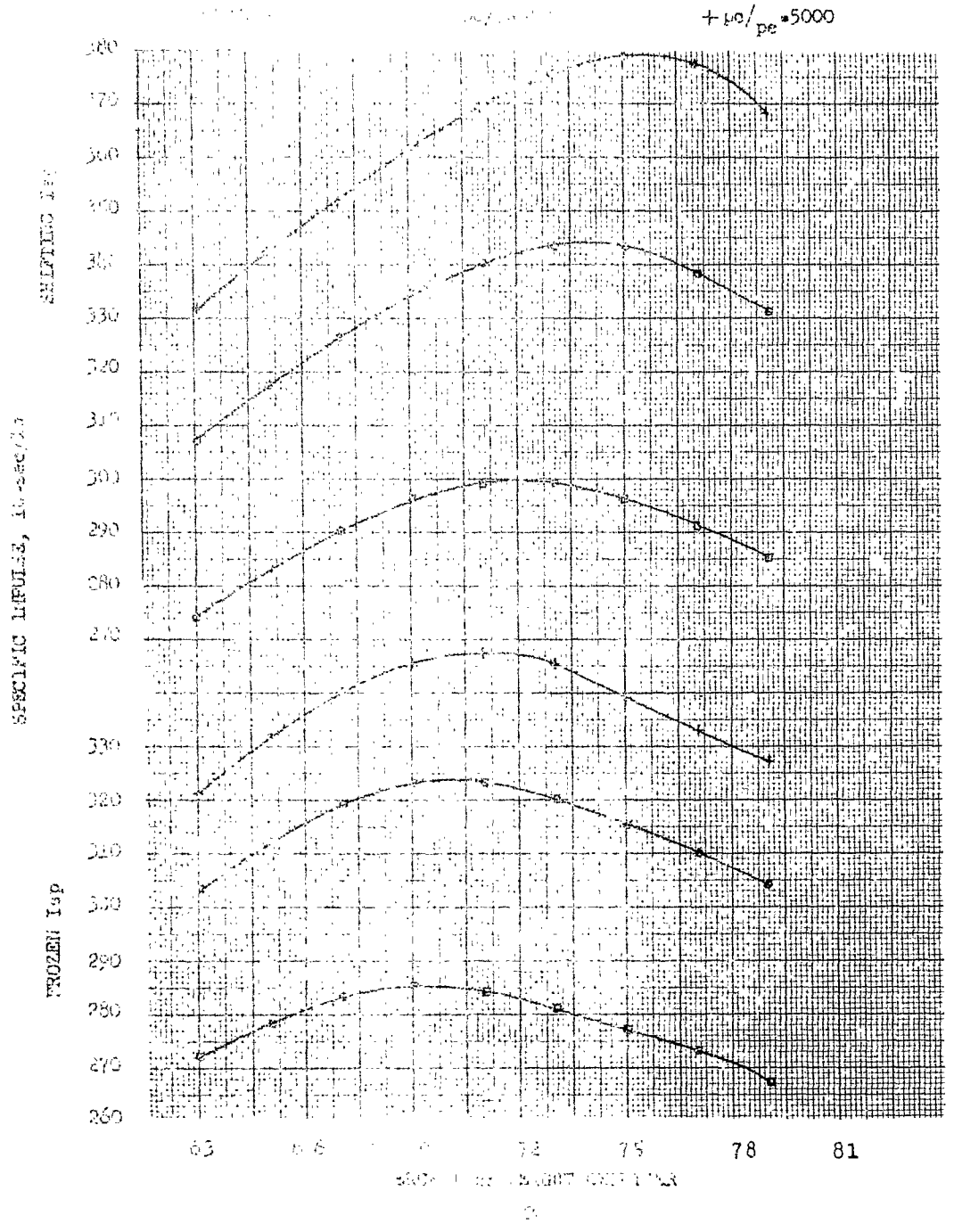
SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
320
310
300
290
280
270
260
250
240
230
FROZEN Isp
310
300
290
280
270
260
250
240
230

UDHM - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 89

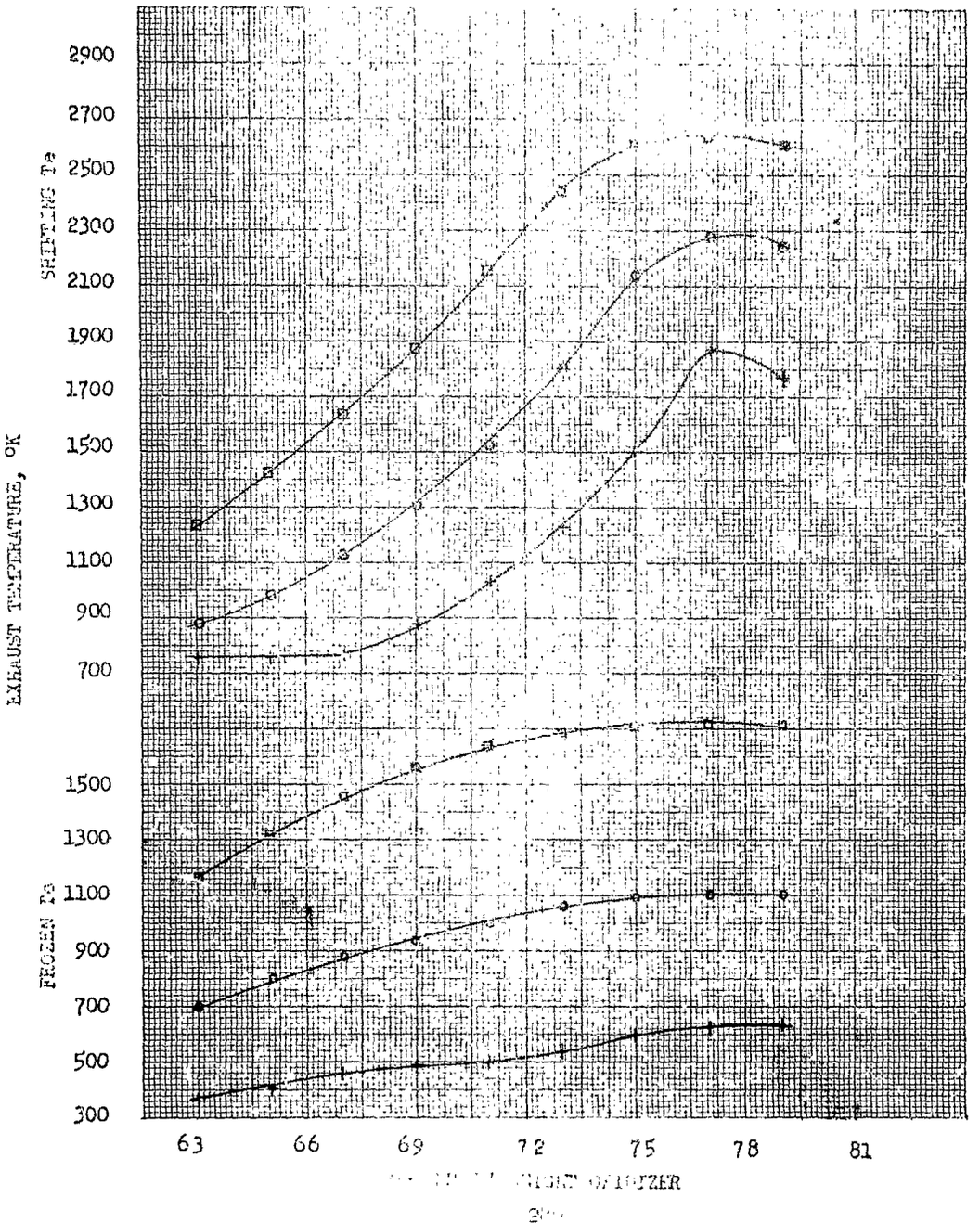


UDMH - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 90

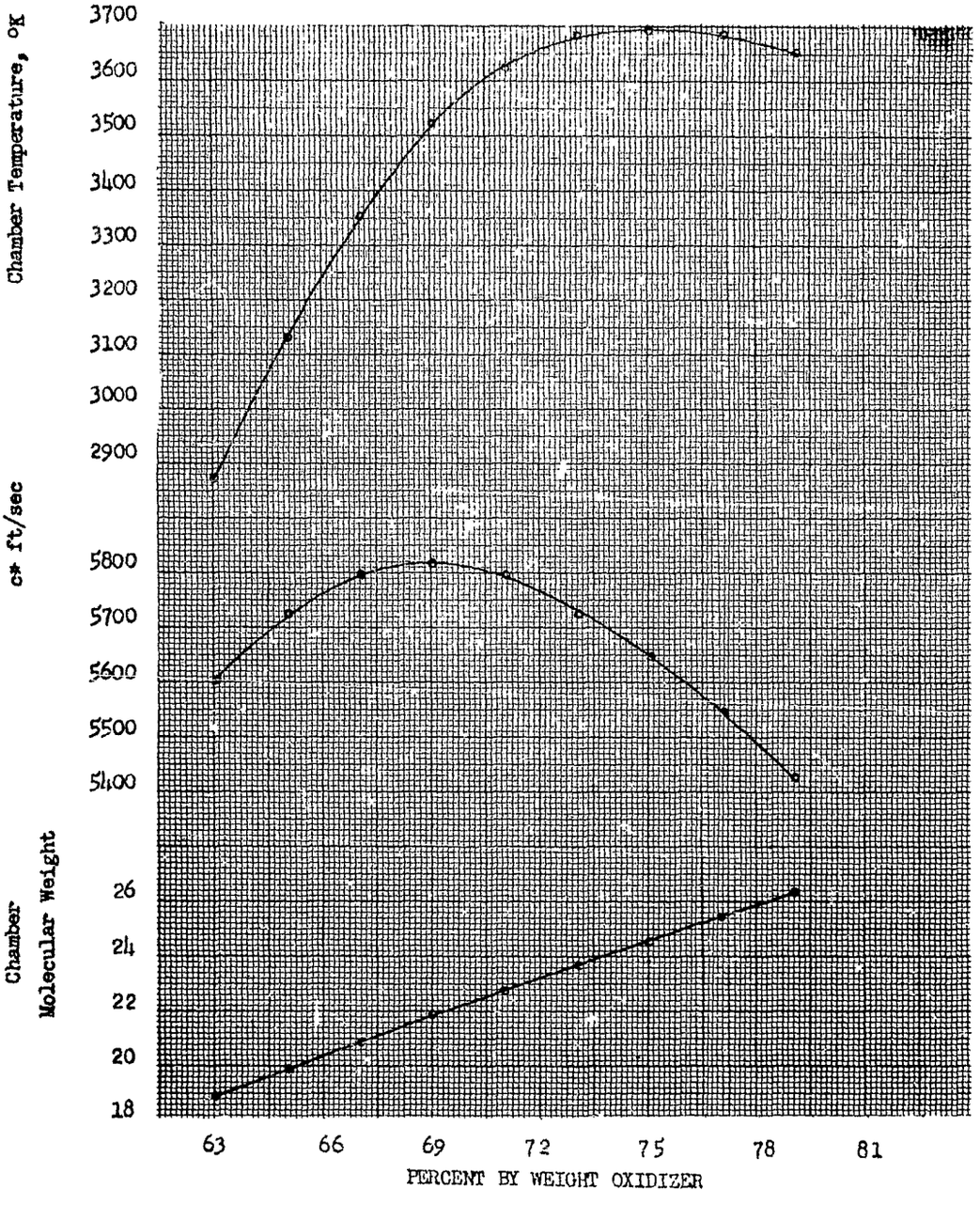



$+\mu o/_{pe}$=5000
SPECIFIC IMPULSE, lbf-sec/lb
FROZEN Isp
380
370
360
350
340
330
320
310
300
290
280
270
260
63
78
81

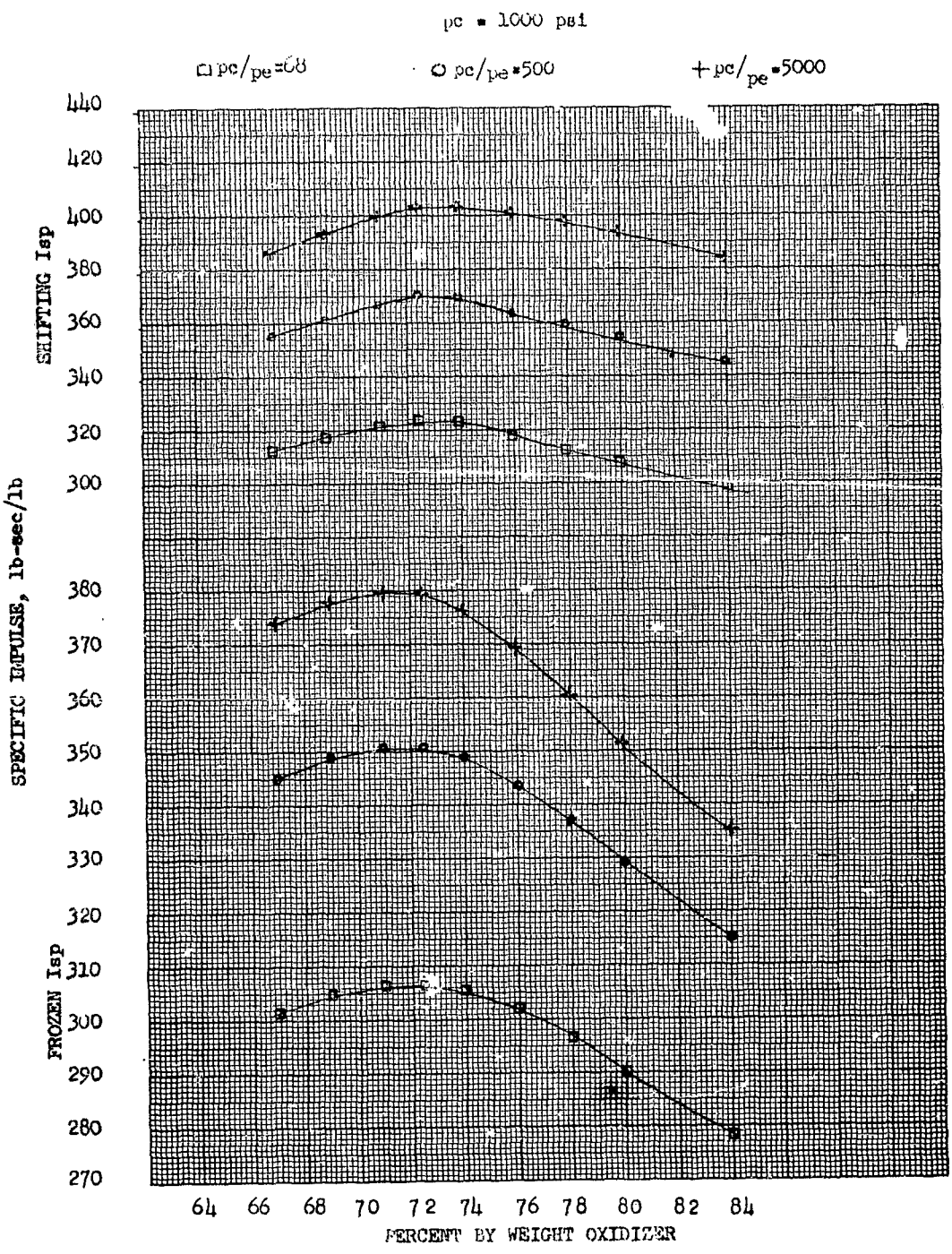
POLYETHYLENE -

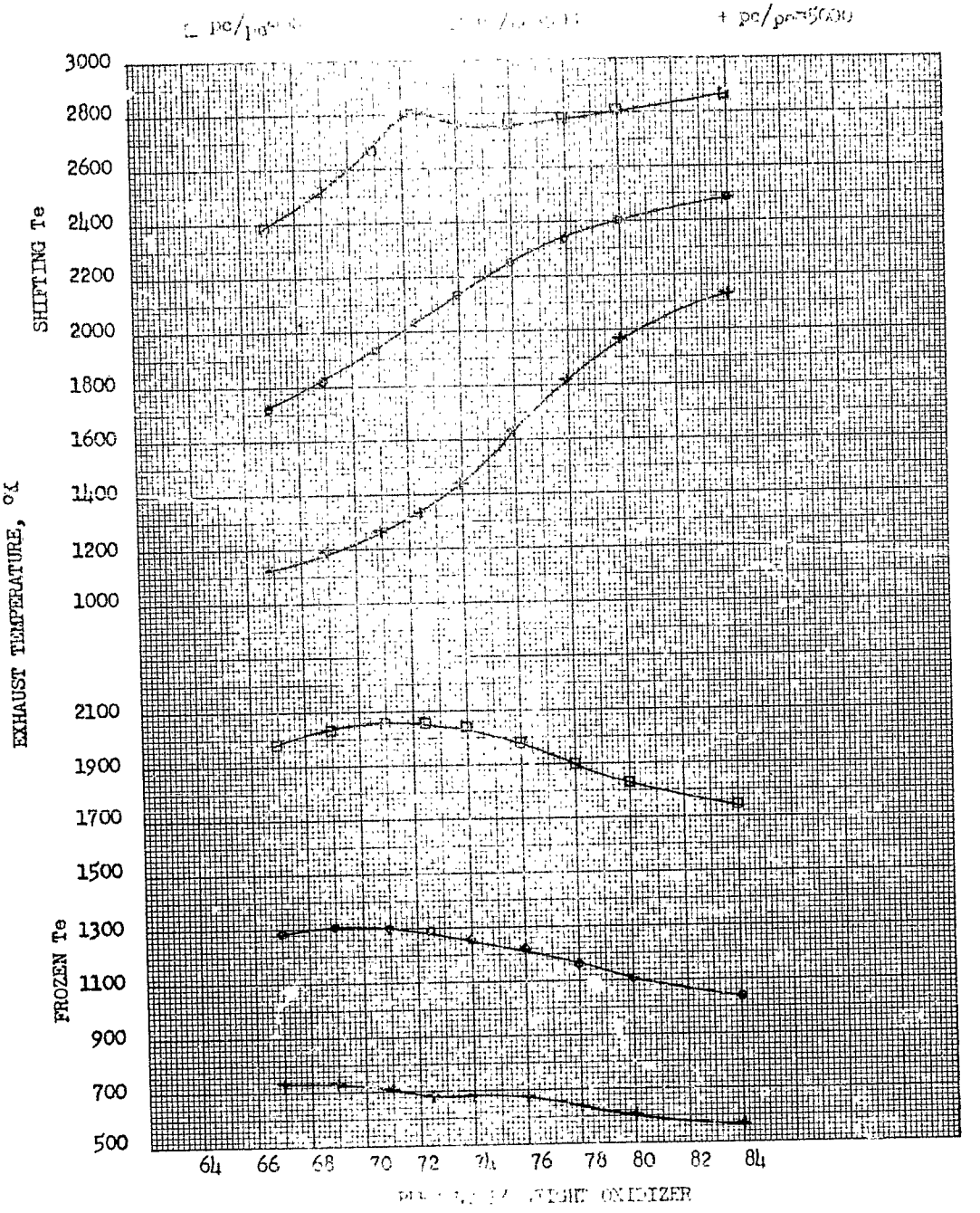


POLYETHYLENE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 93

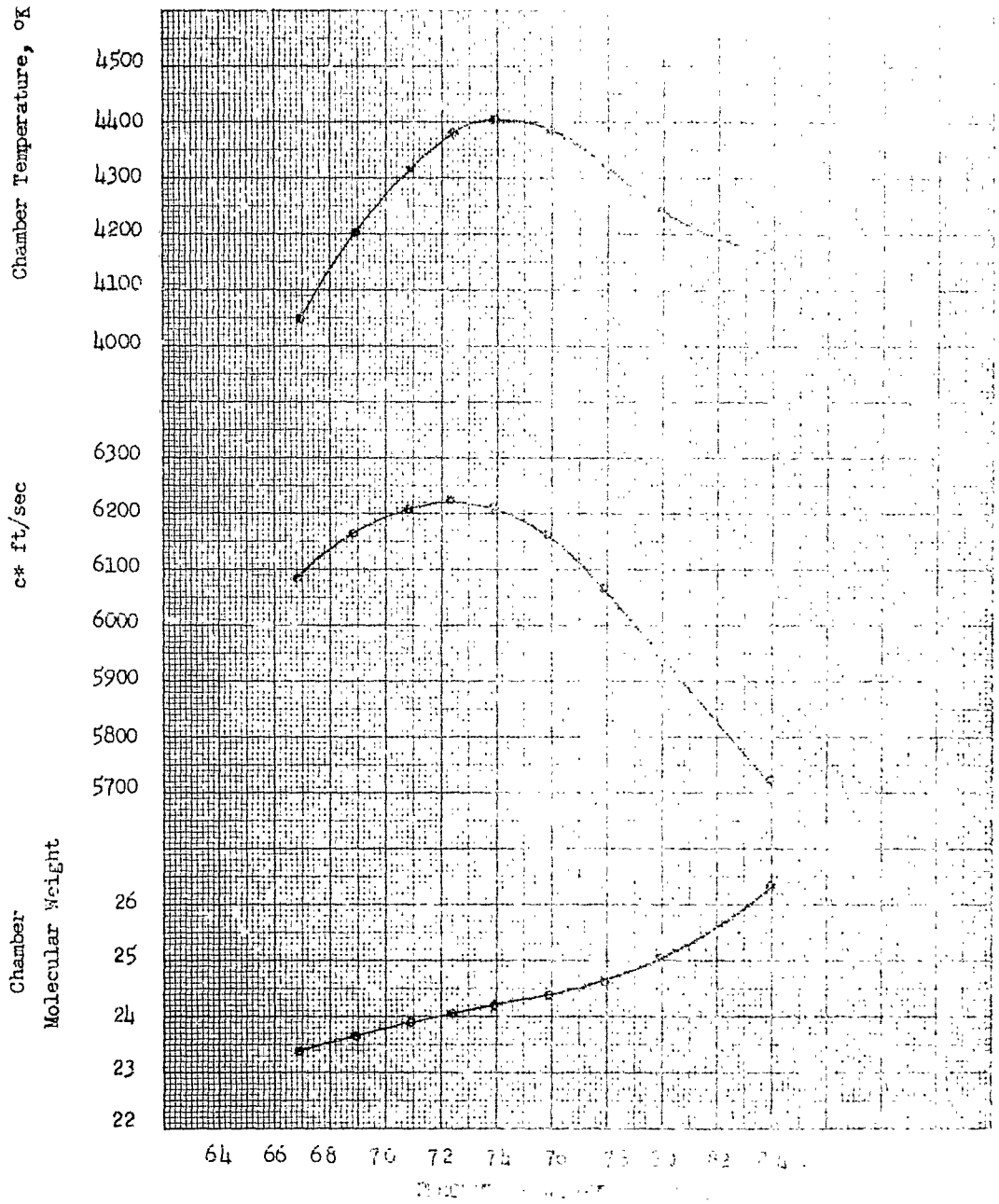


POLYETHYLENE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 94




EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
2100
1900
1700
1500
1300
1100
900
700
500
64
66
68
70
72
74
76
78
80
82
84

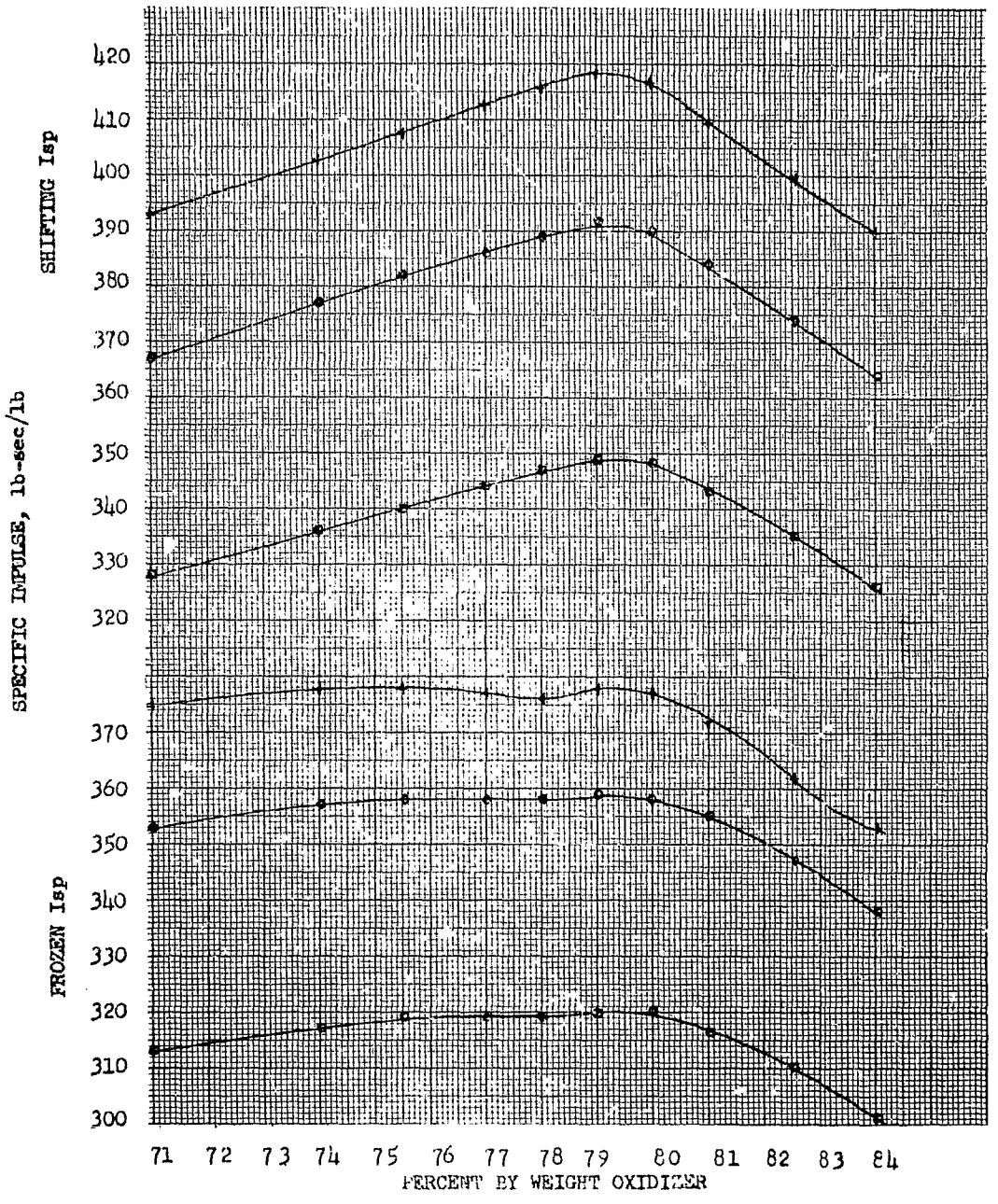
POLYETHYLENE - LIQUID [illegible]



POLYETHYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 97

p_c = 1000 psi

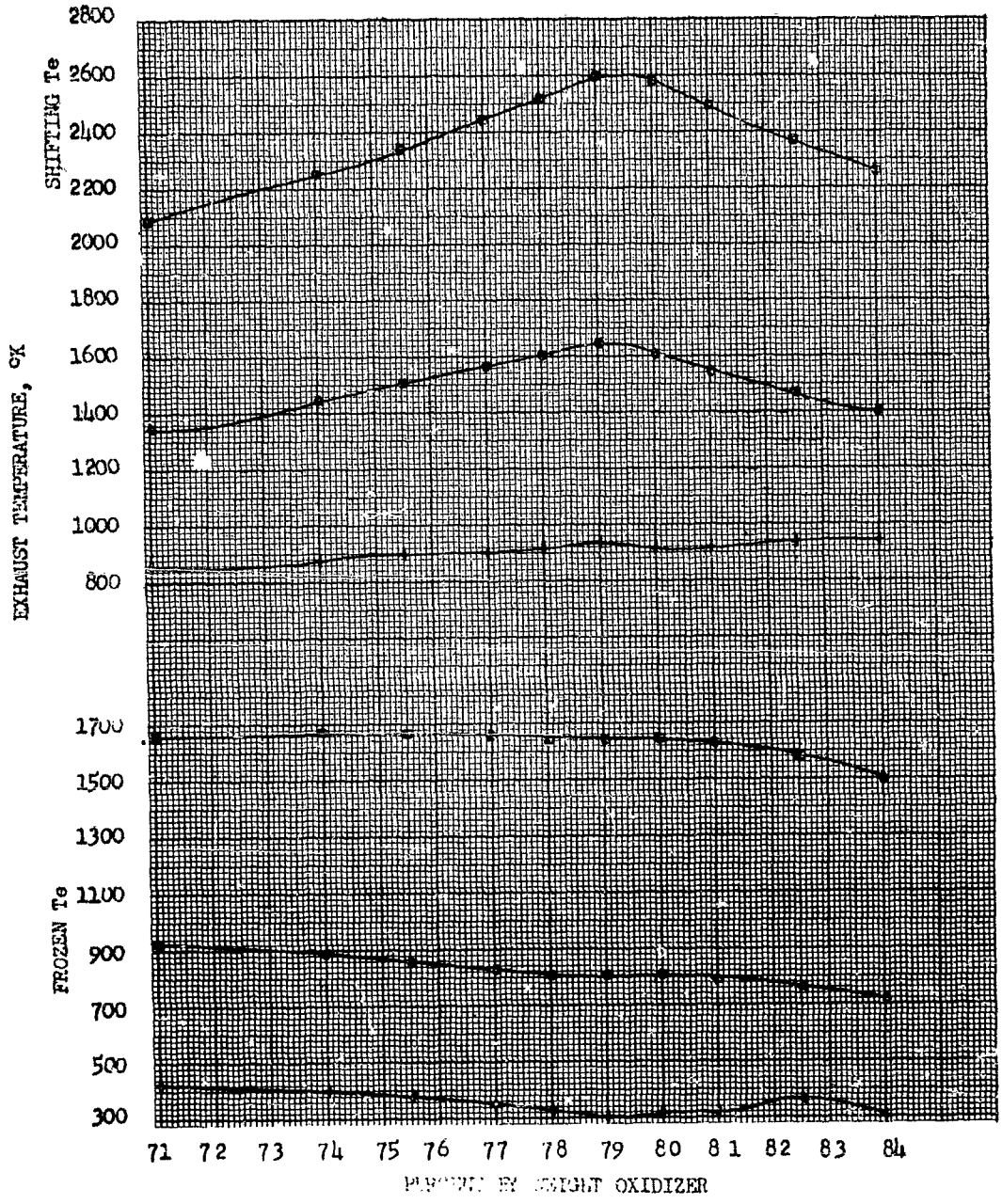
□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000

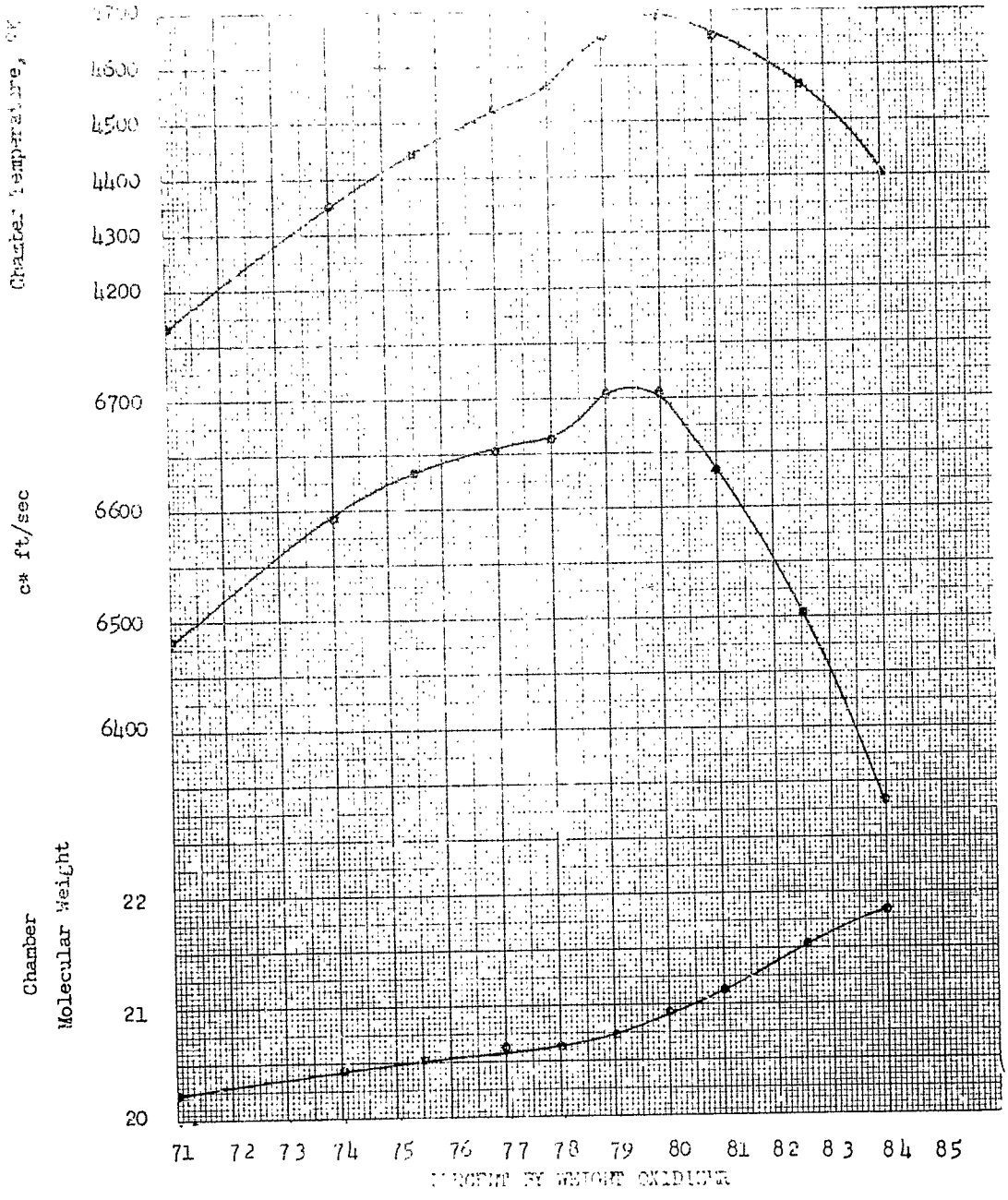


POLYETHYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 98

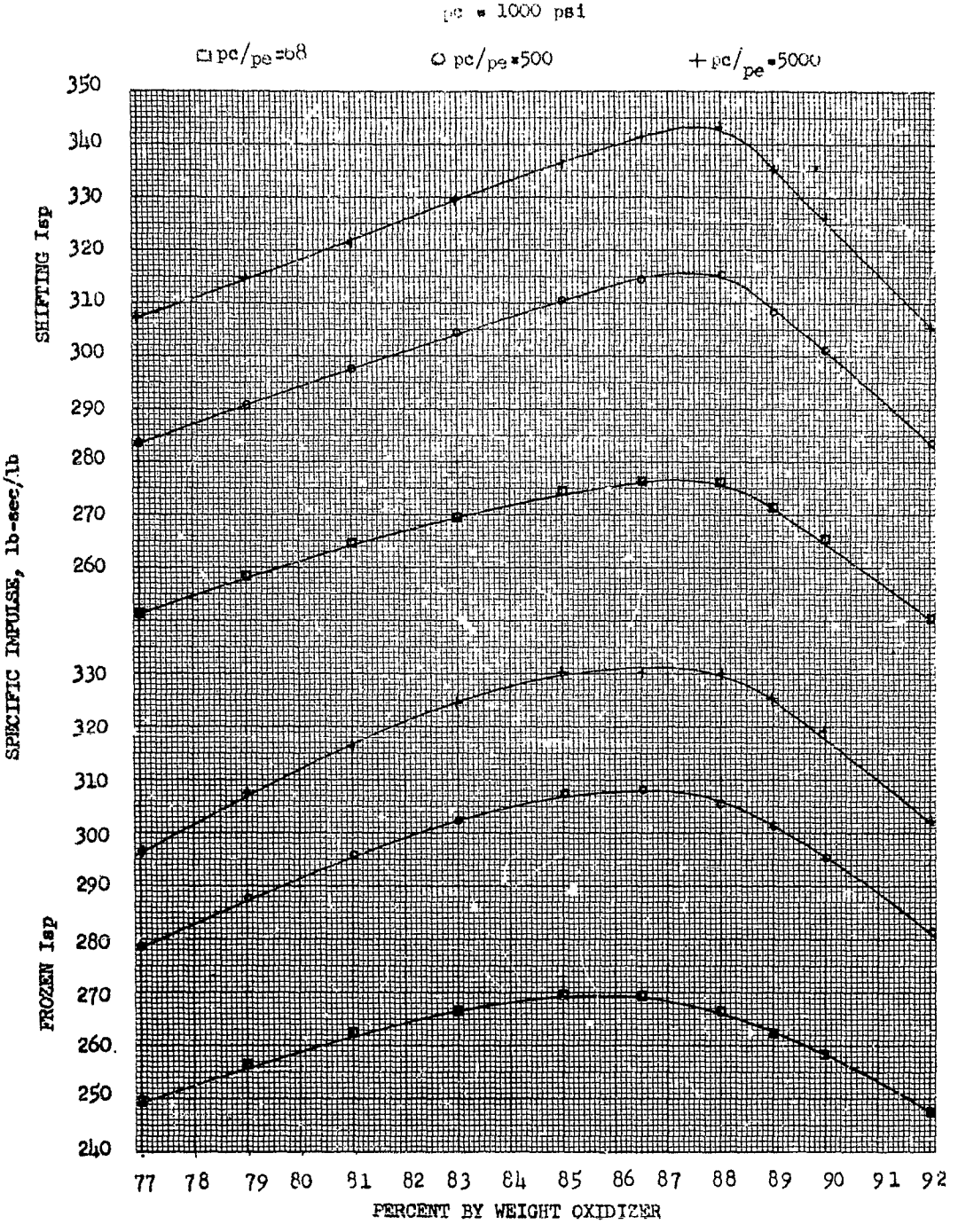
pc = 1000 psi

L p_c/p_e=68 O p_c/p_e=500 + p_c/p_e=5000

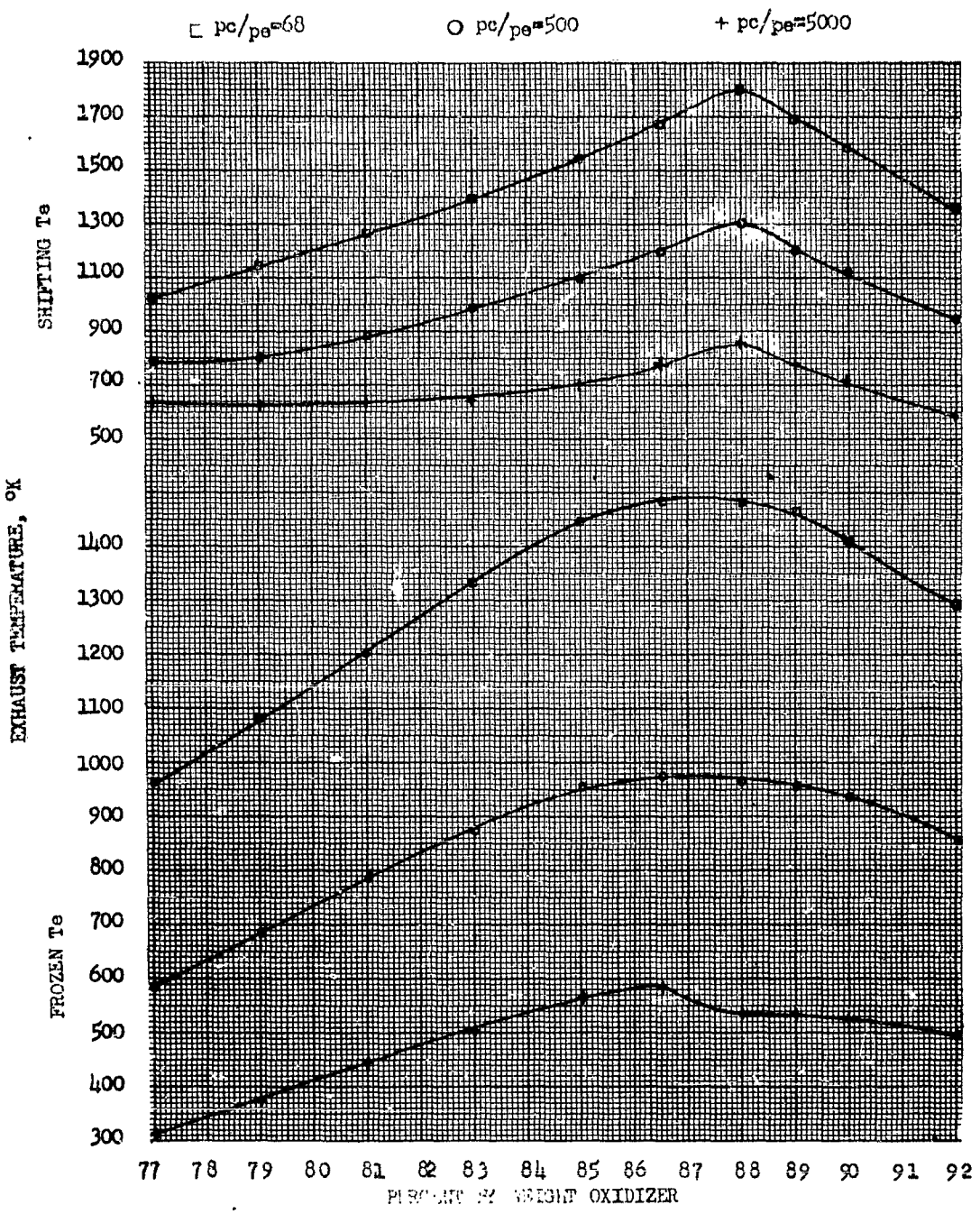



Chamber Temperature, °K
4600
4500
4400
4300
4200
c* ft/sec
6700
6600
6500
6400
Chamber
Molecular Weight
22
21
20
71 72 73 74 75 76 77 78 79 80 81 82 83 84 85

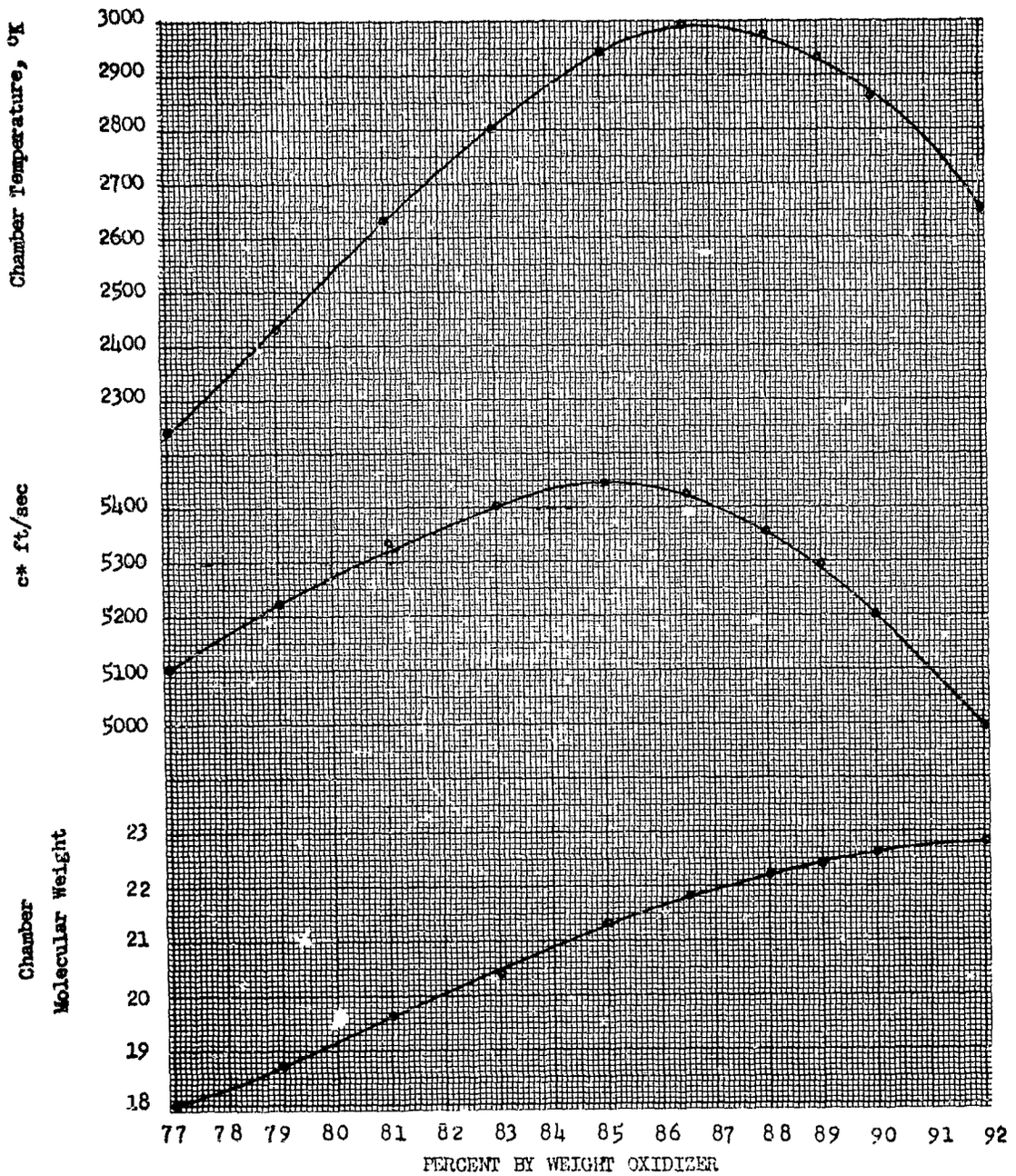
POLYETHYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 100



POLYETHYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 101

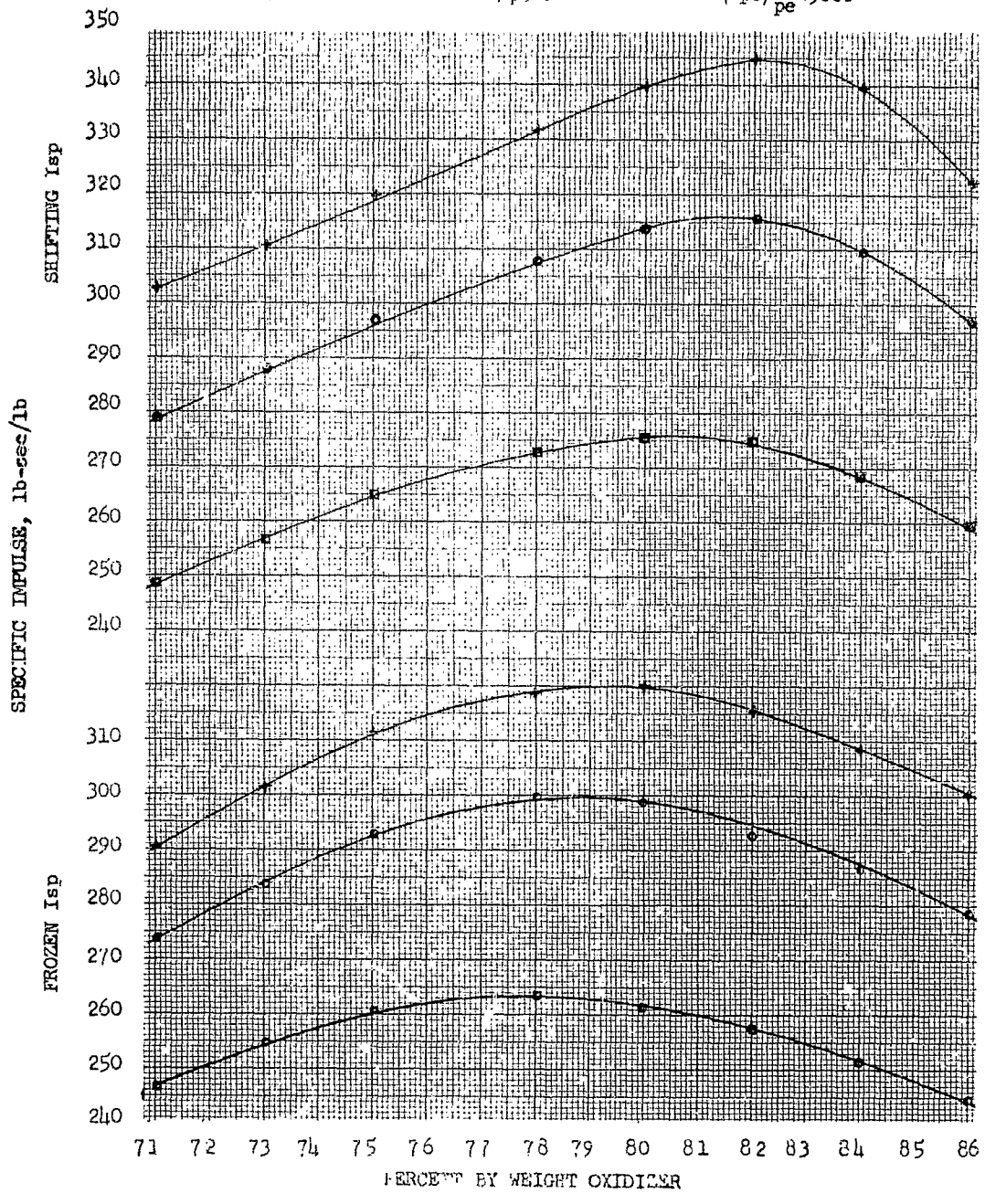


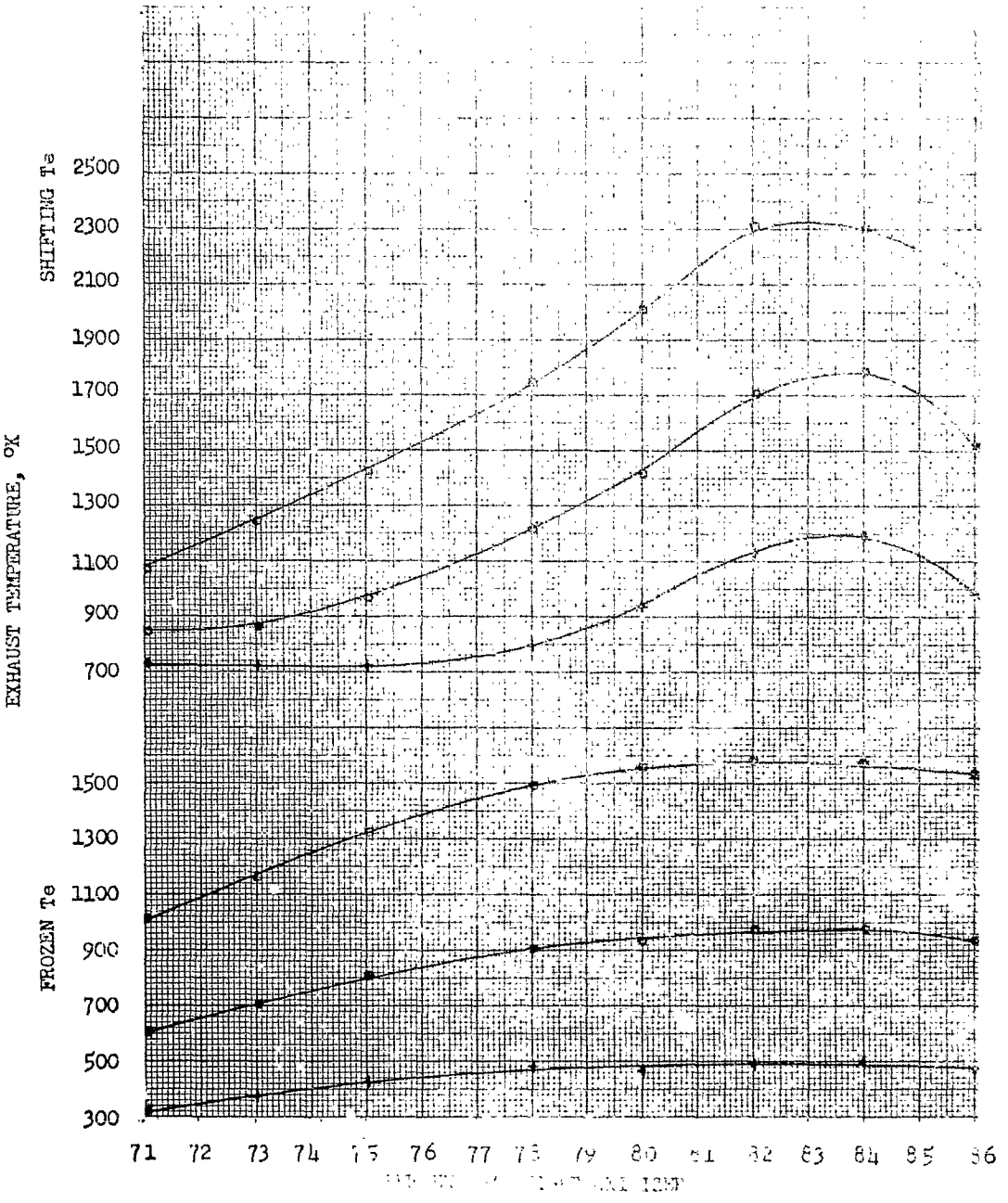
POLYETHYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 102



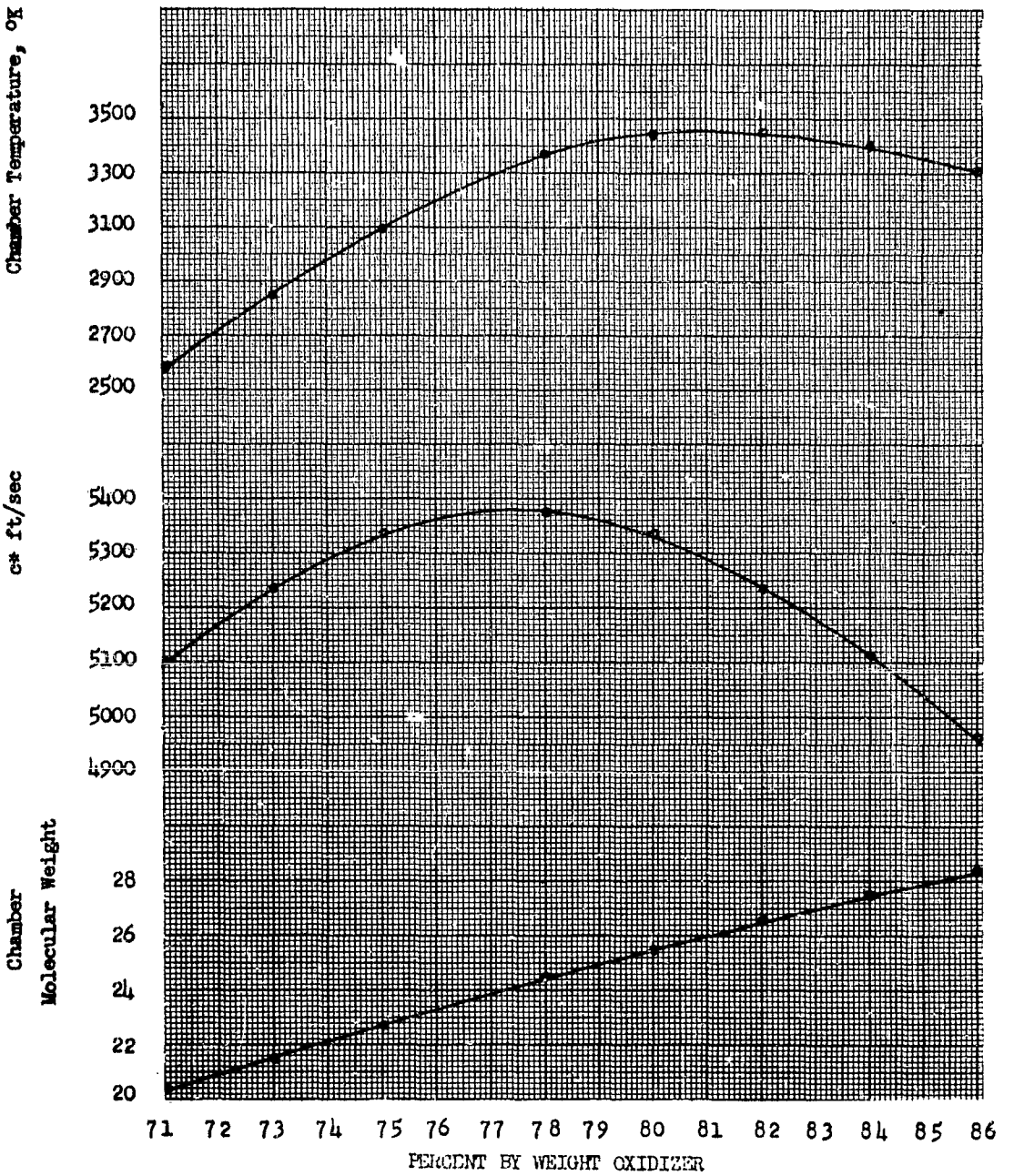
POLYETHYLENE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 103

p_c = 1000 psi

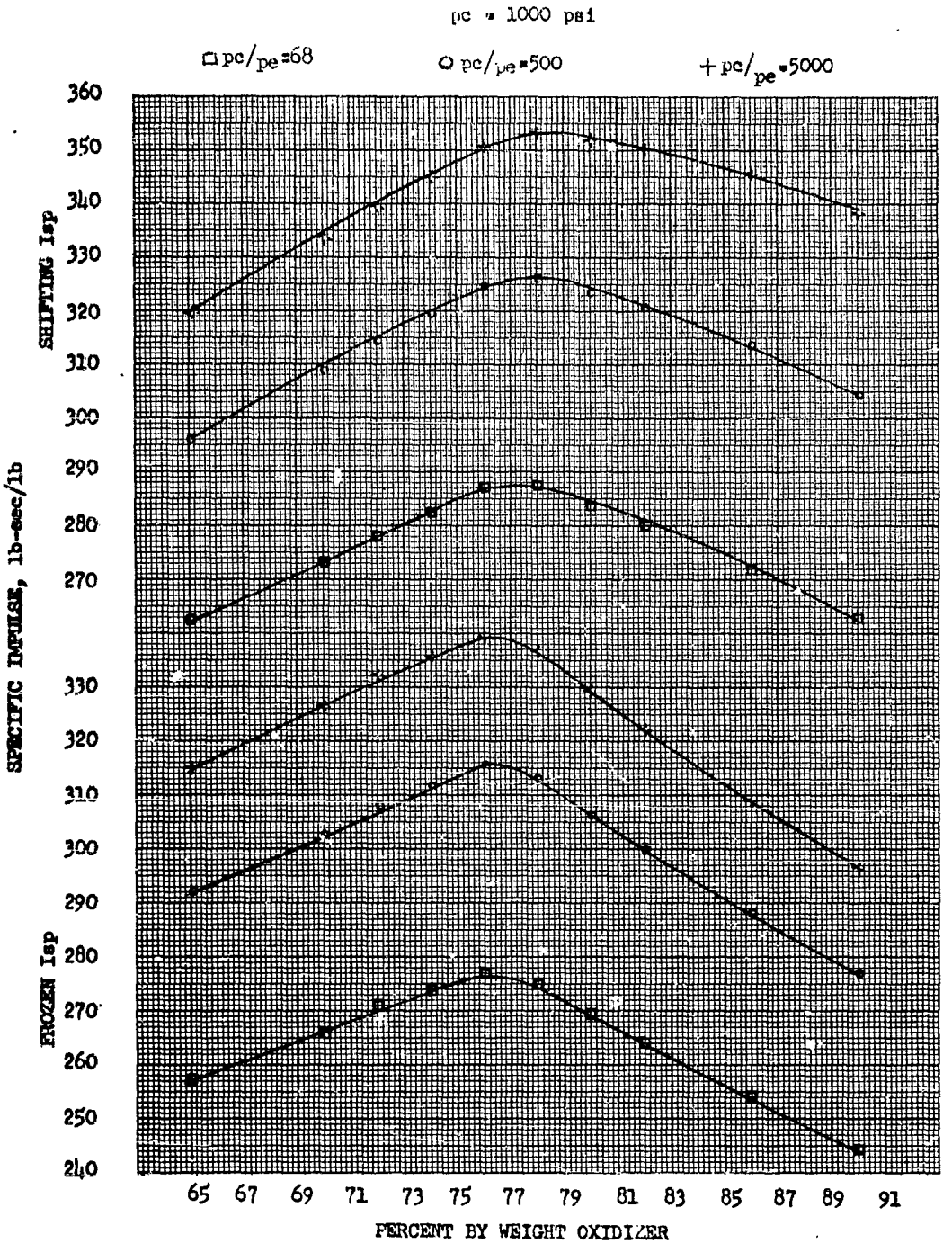


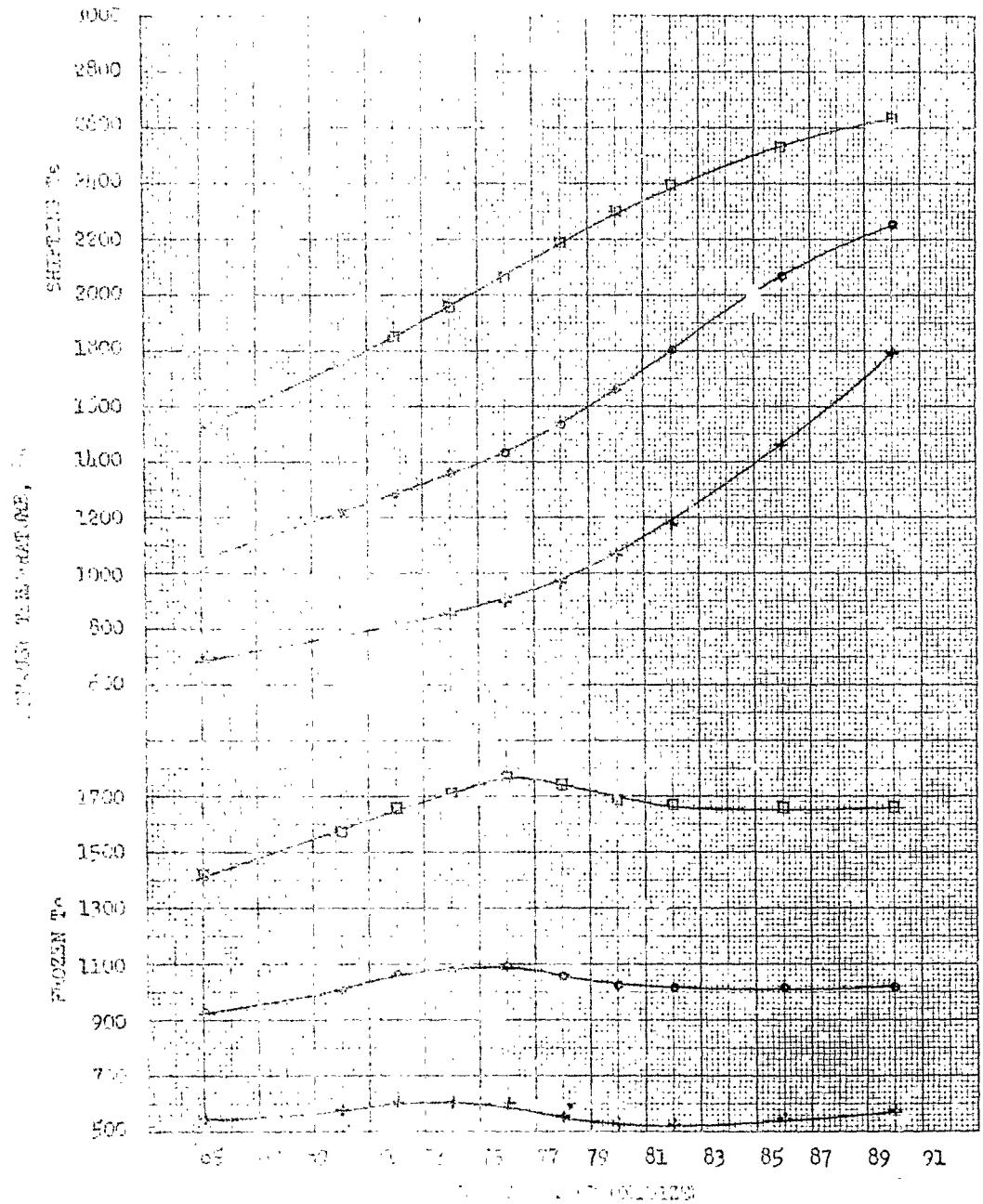

EXHAUST TEMPERATURE, °K
SHIFTING Te
2500
2300
2100
1900
1700
1500
1300
1100
900
700
FROZEN Te
1500
1300
1100
900
700
500
300
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86

POLYETHYLENE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 105

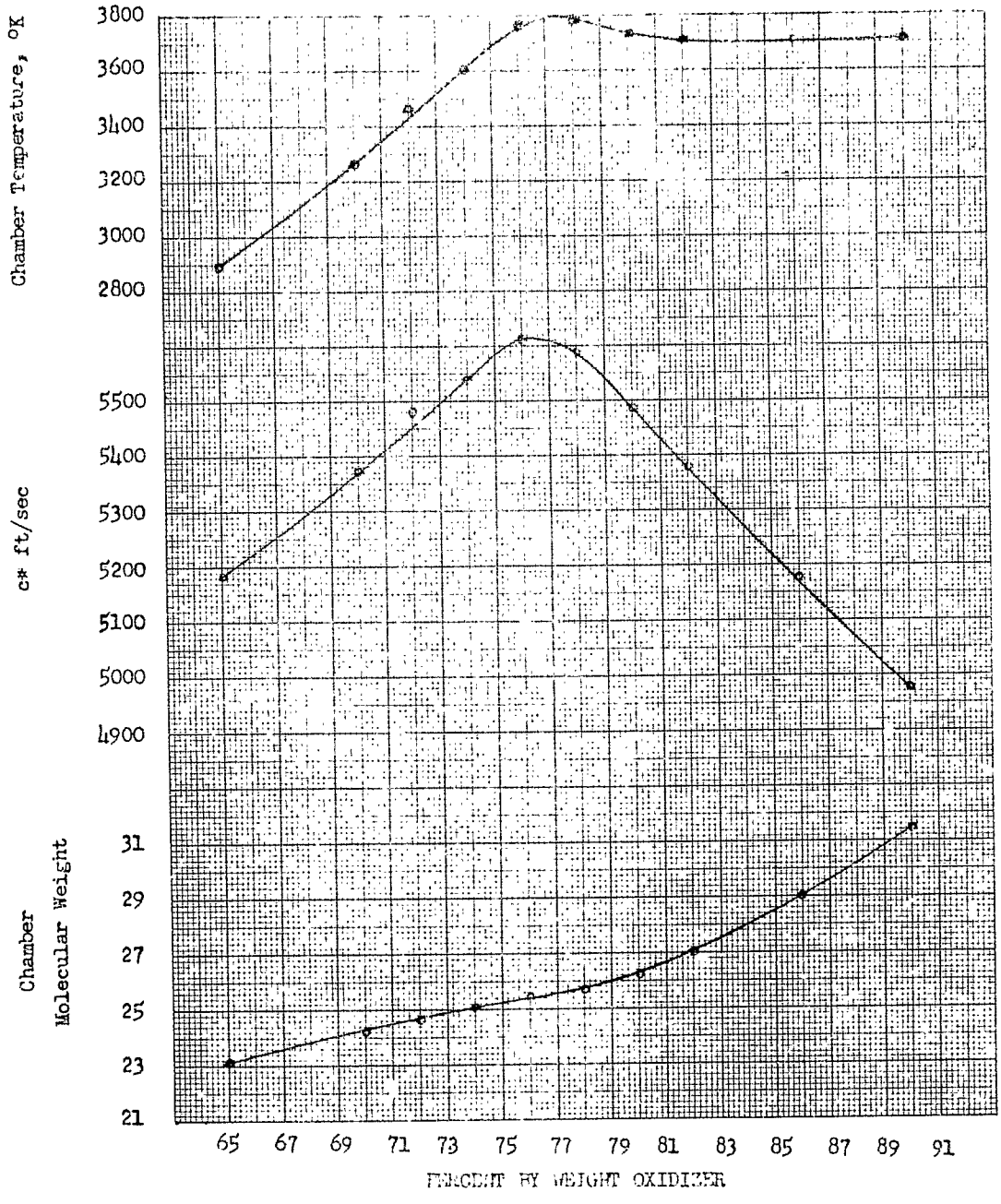


POLYETHYLENE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 106

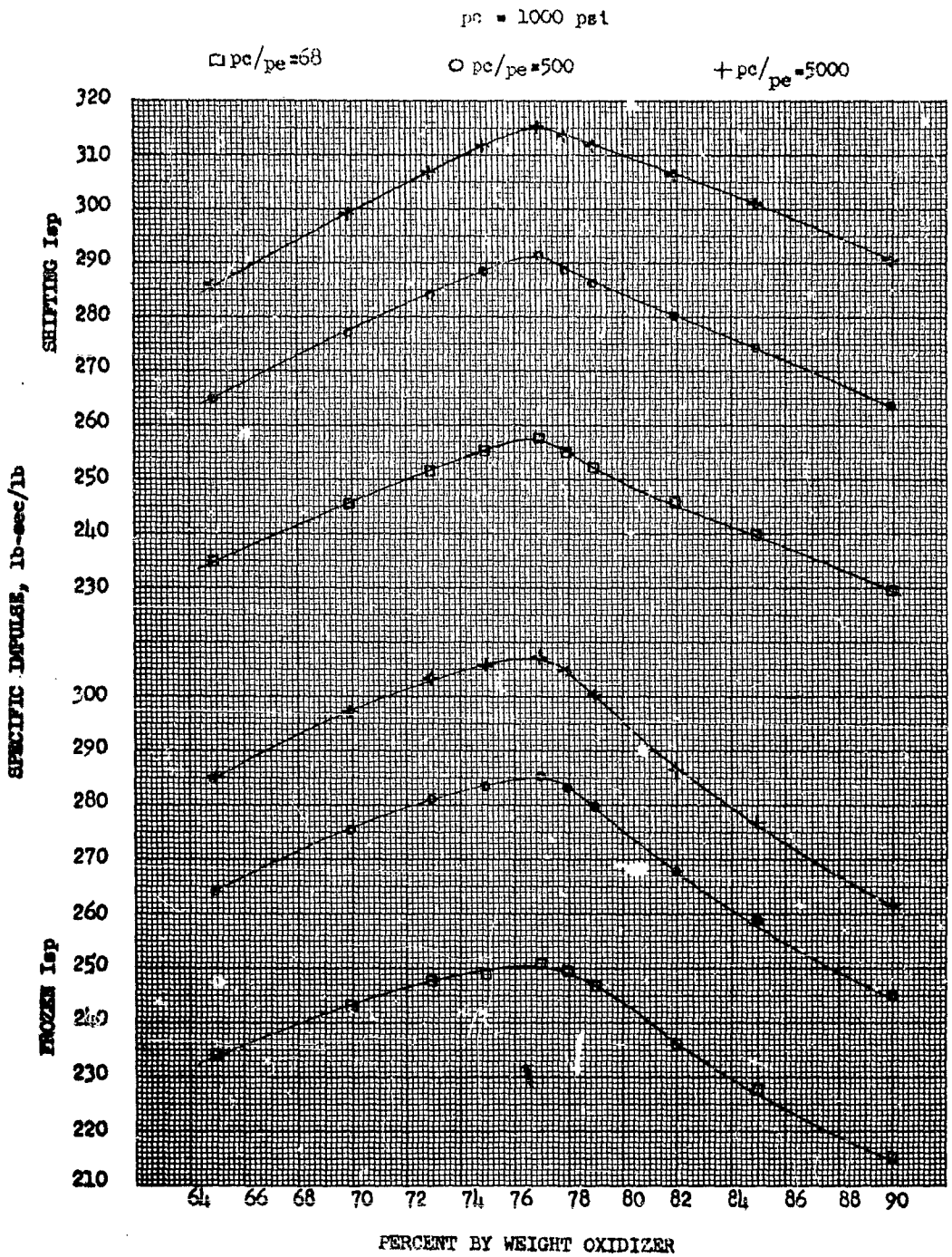



2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
1700
1500
1300
1100
900
500
79
81
83
85
87
89
91

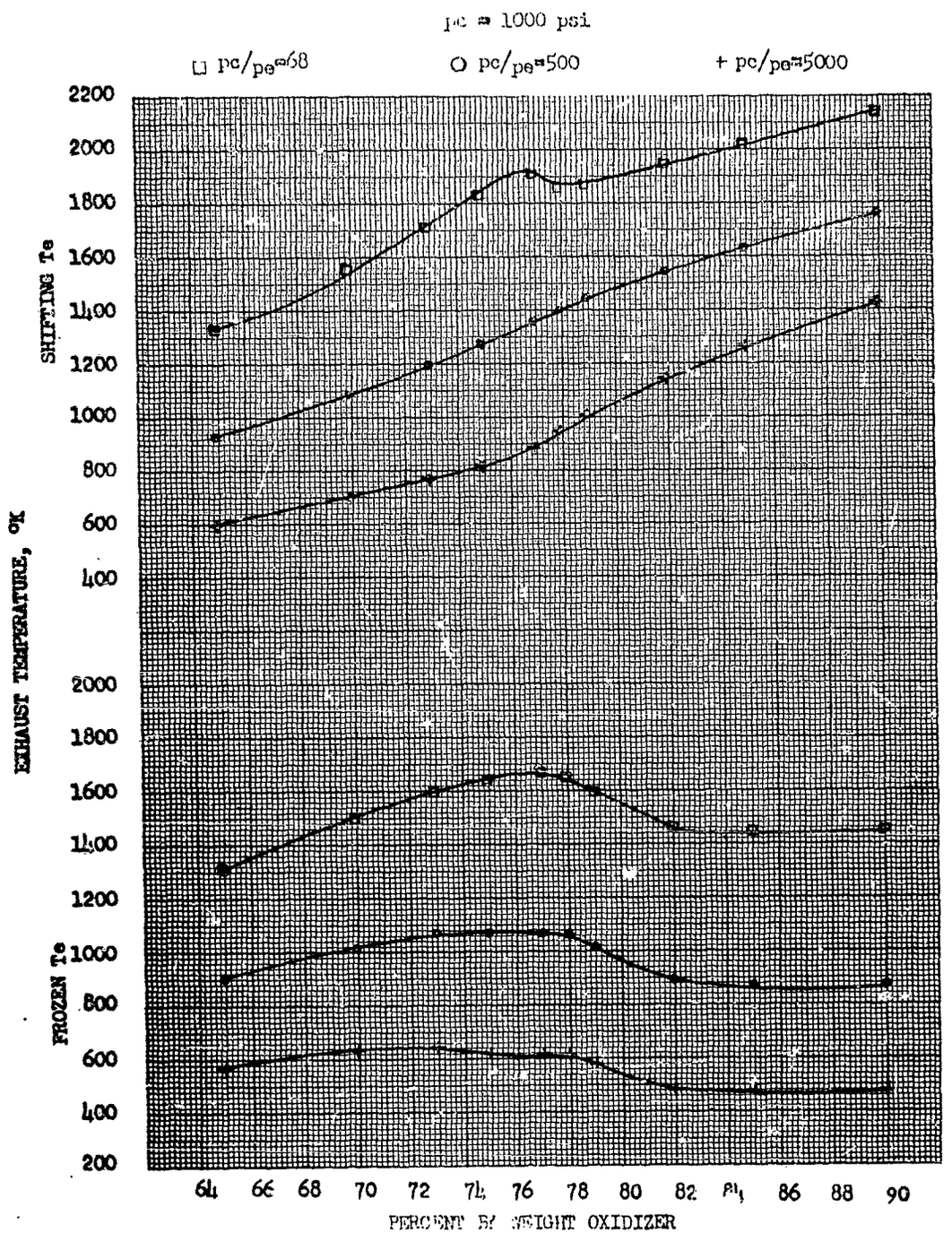
POLETHYLENE - [illegible] PROPELLANT CURVES FIGURE 108



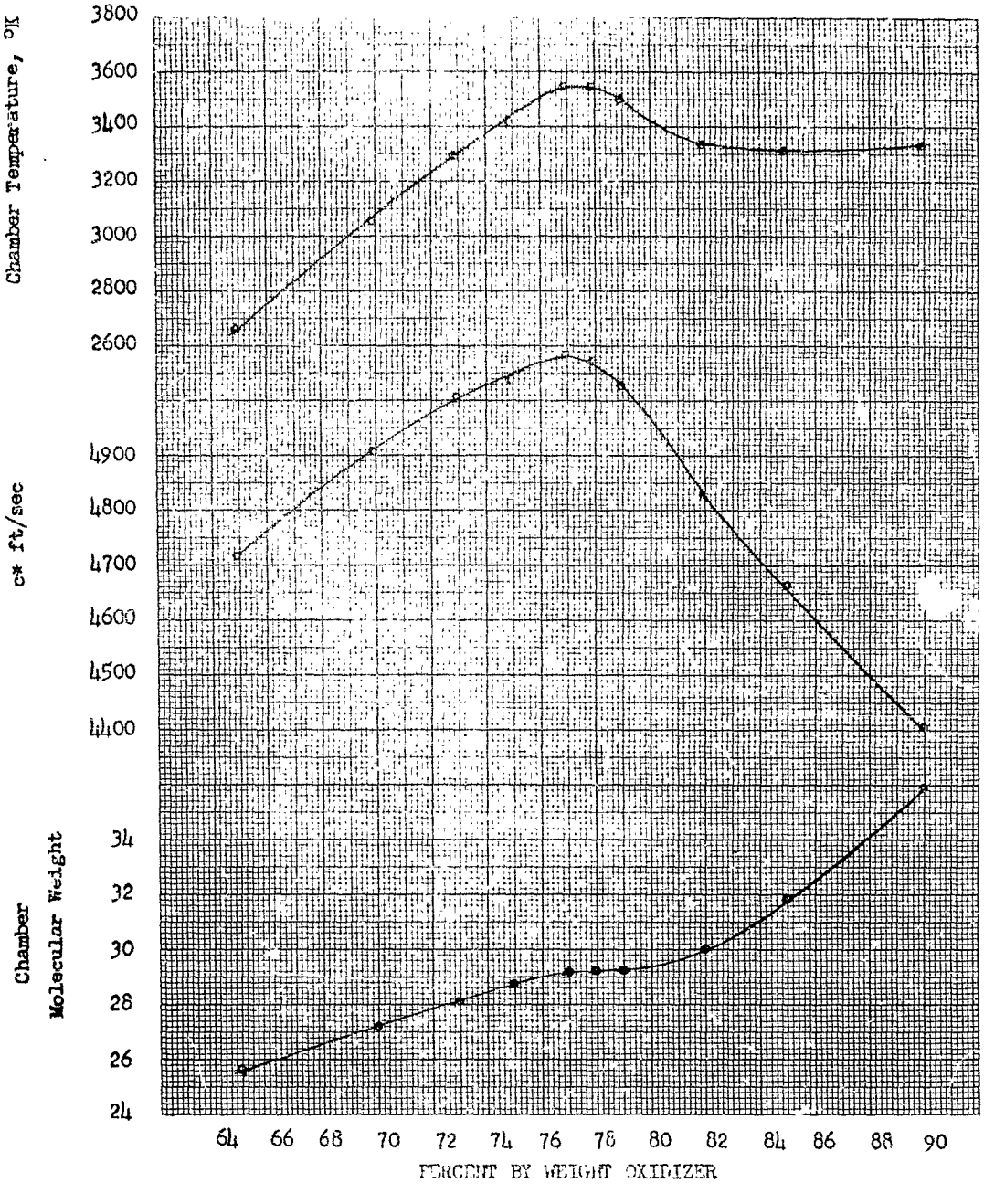
POLYETHYLENE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 109

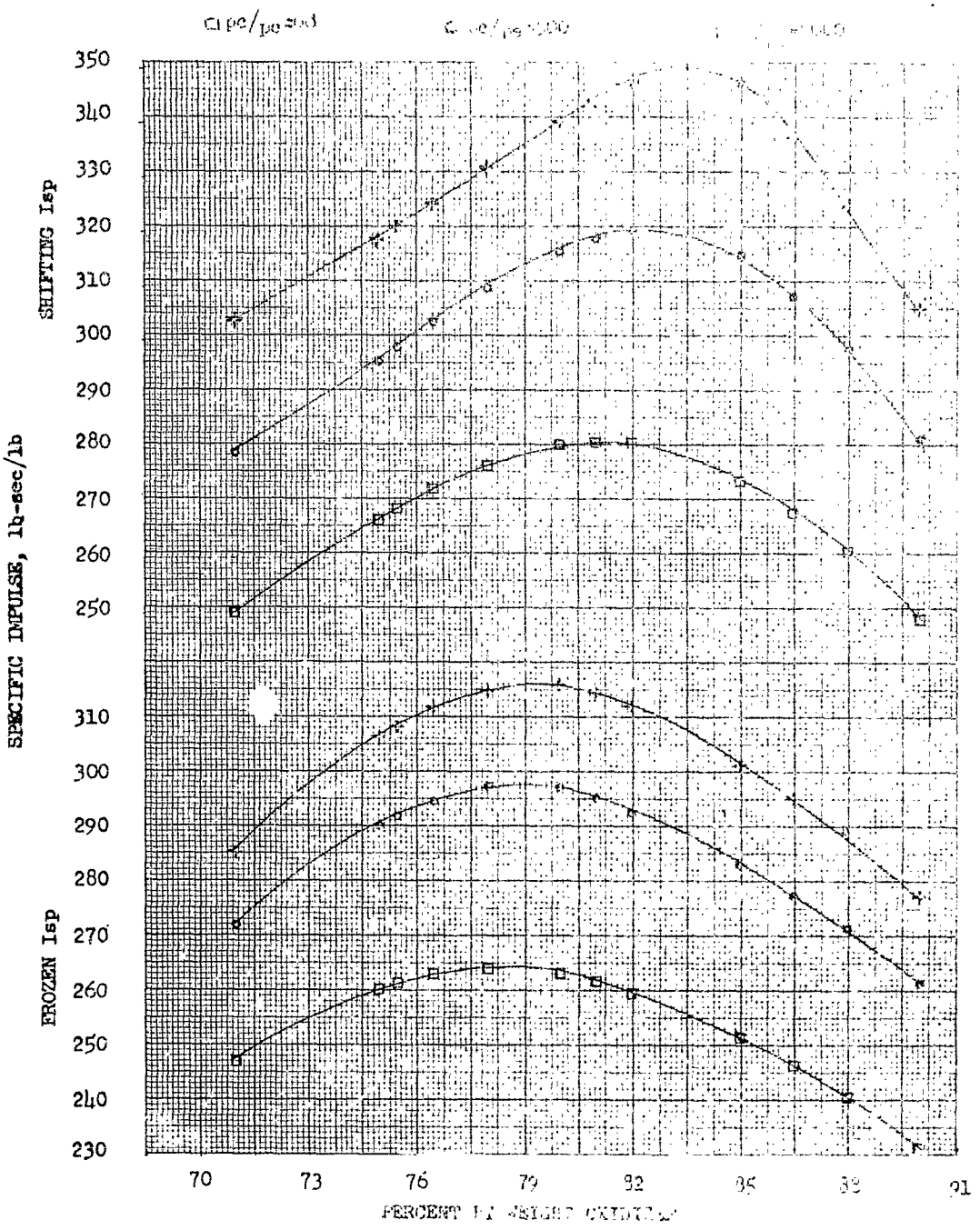


POLYETHYLENE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 110

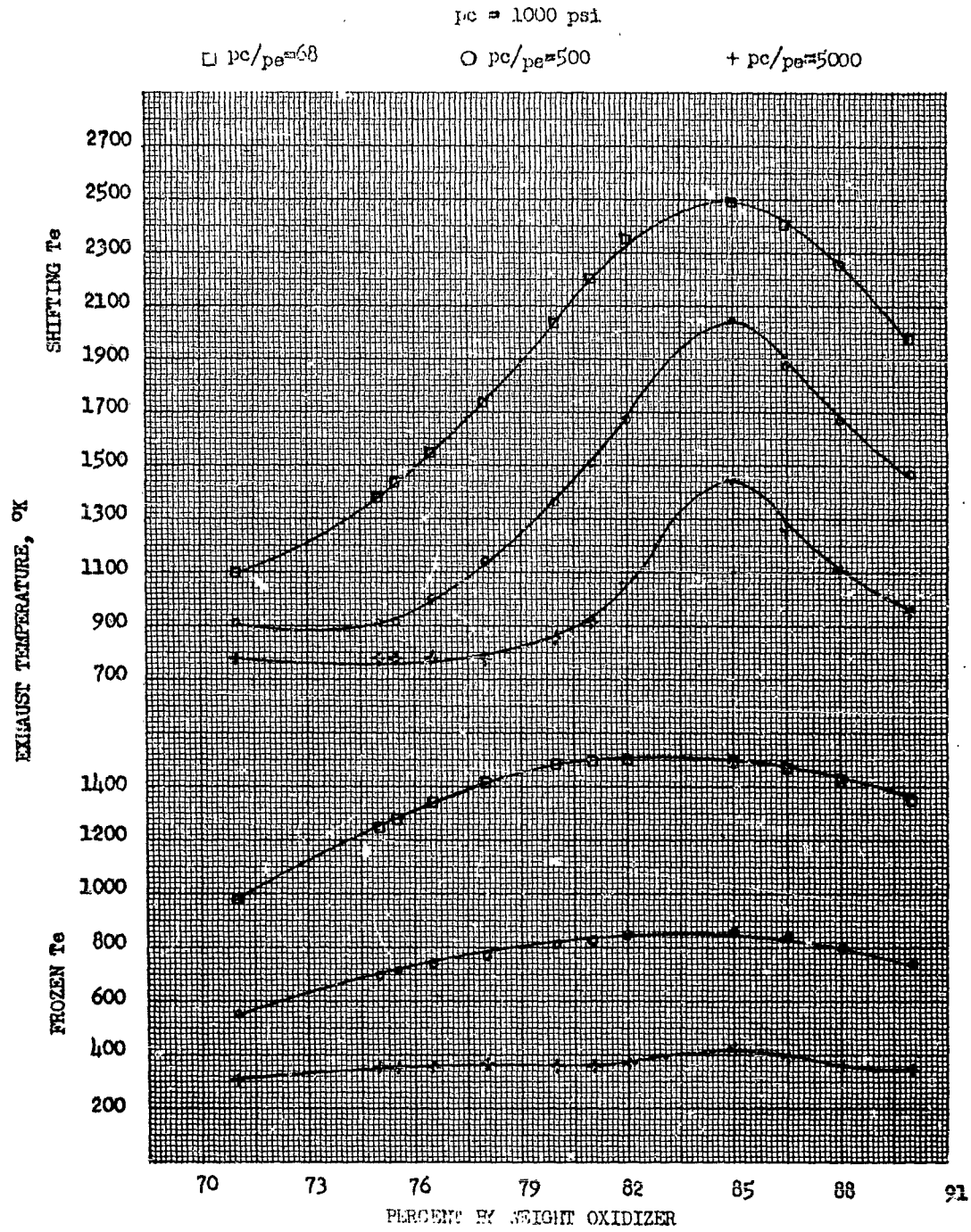


POLYETHYLENE [illegible] PERFORMANCE CURVES FIGURE III

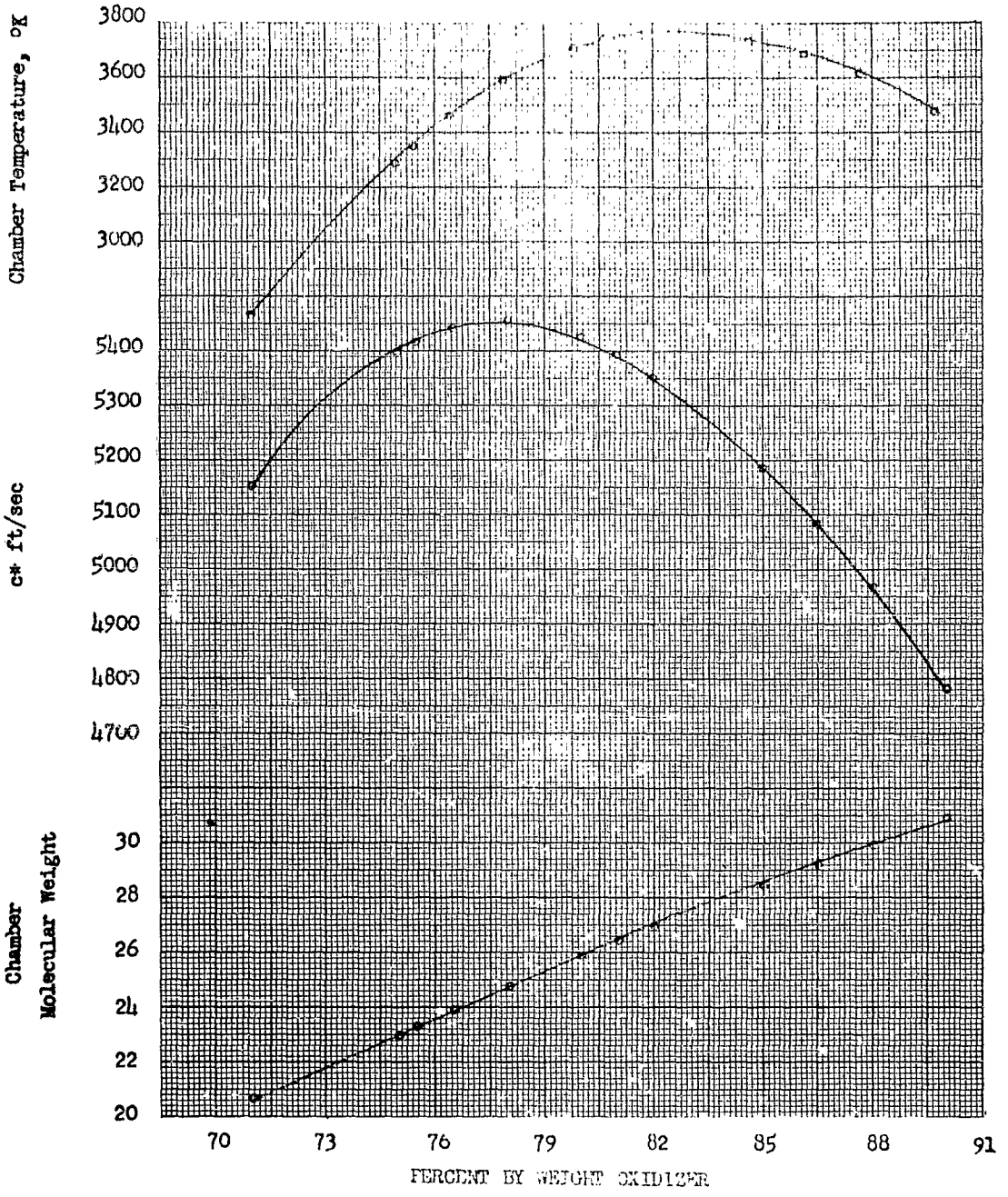



SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
350
340
330
320
310
300
290
280
270
260
250
310
300
290
280
270
260
250
240
230
70
73
76
79
92
85
88
91

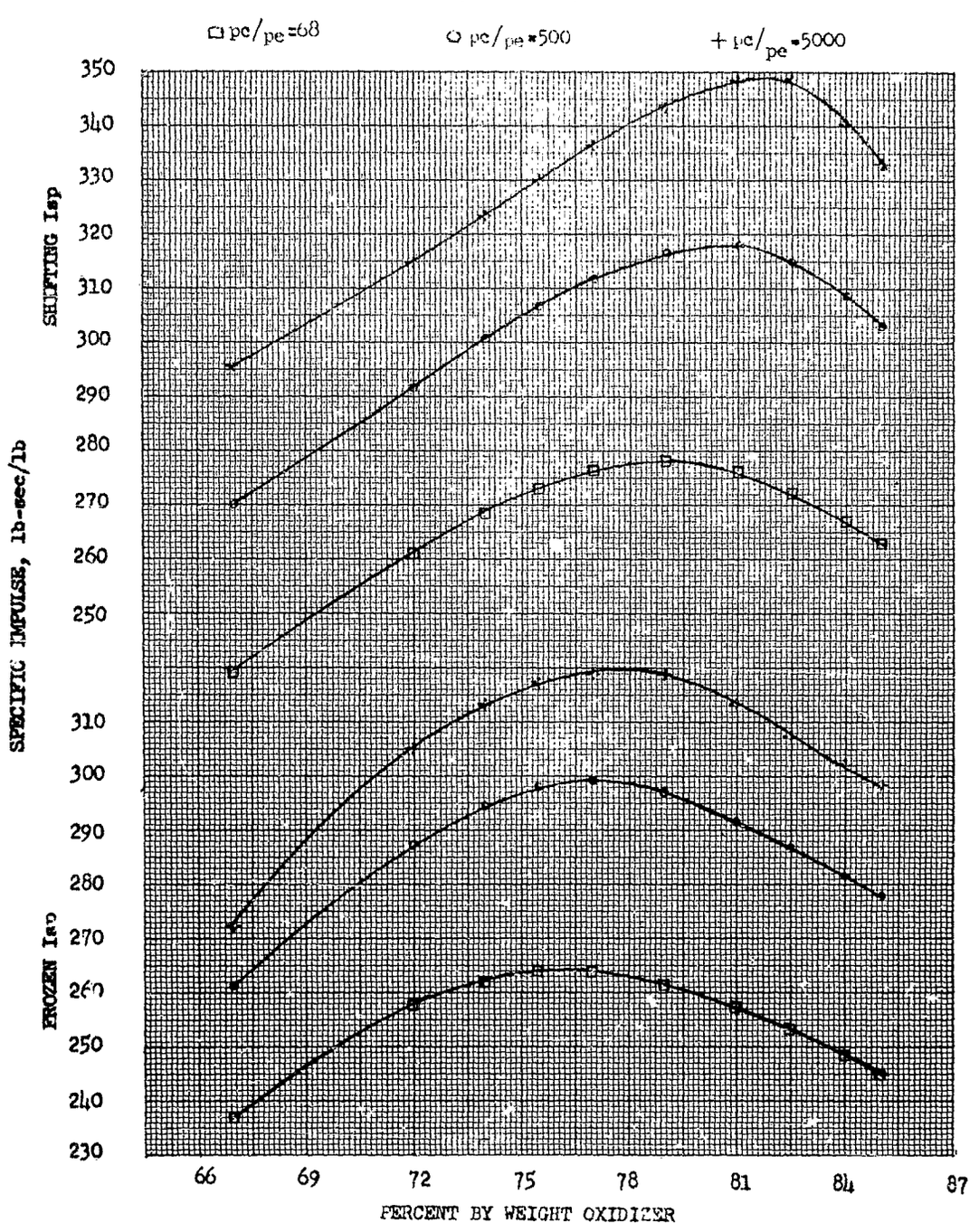
POLYETHYLENE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 113



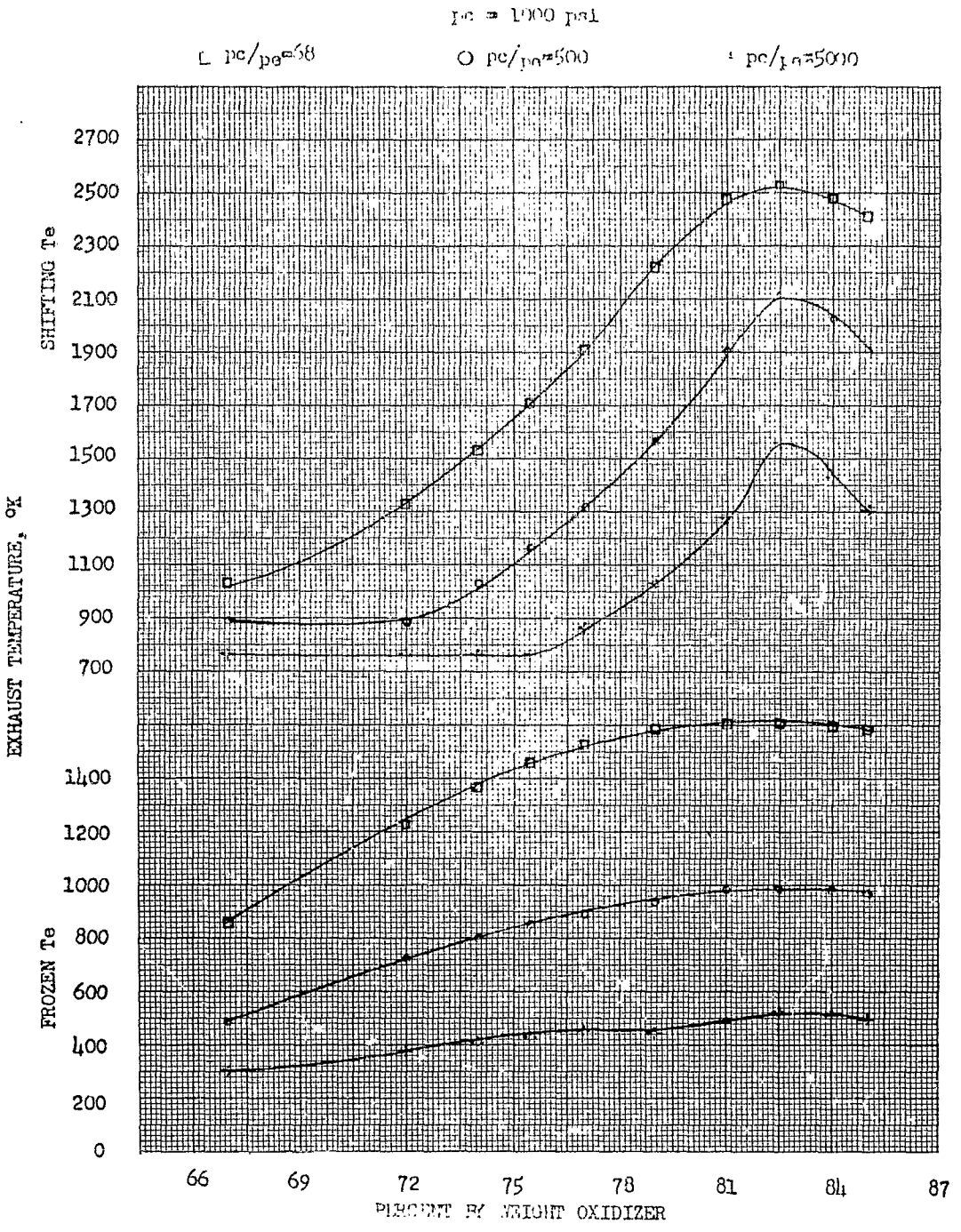
POLYETHYLENE – PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 11L



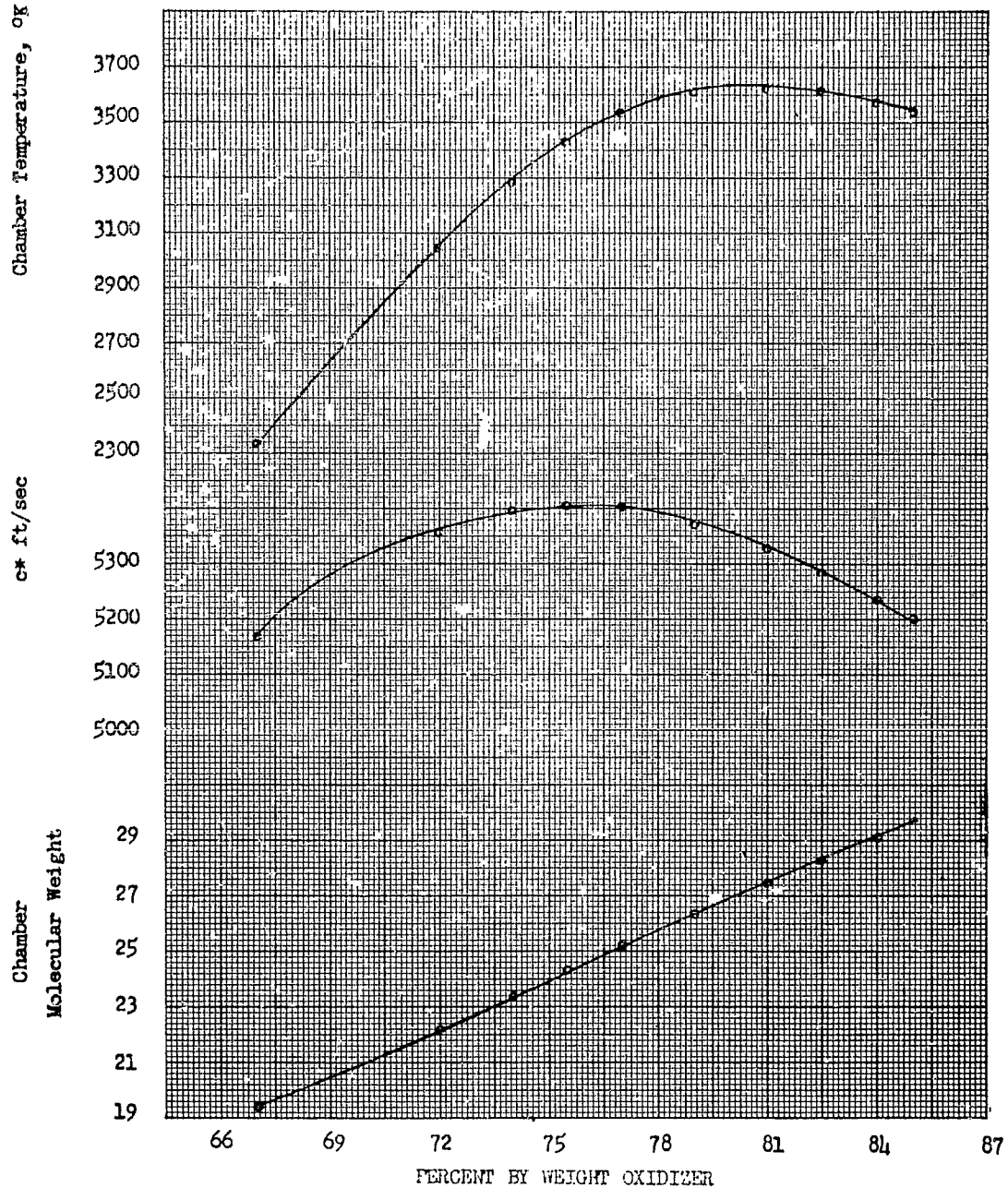
POLYETHYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 115



POLYETHYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 116



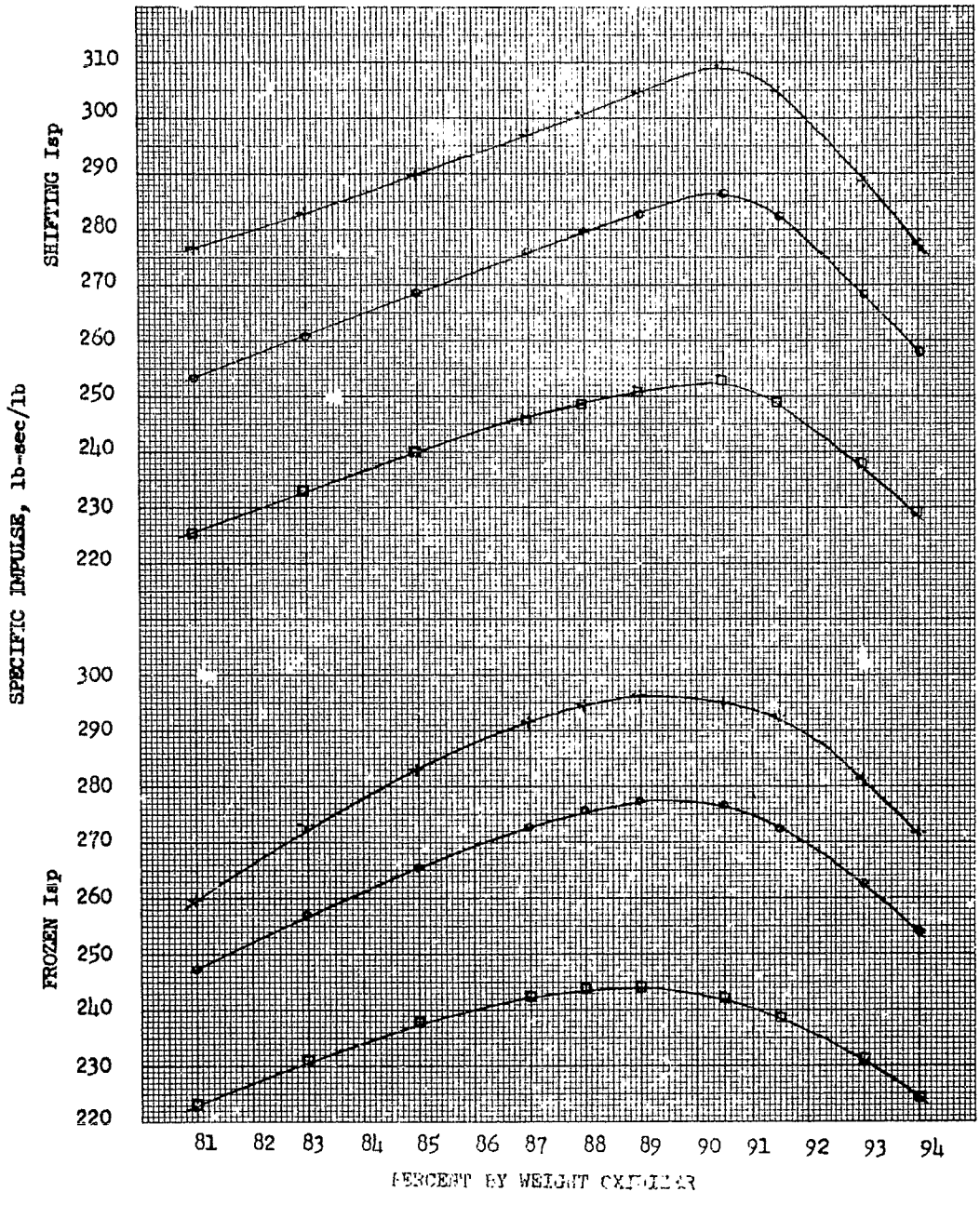
POLYETHYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 117



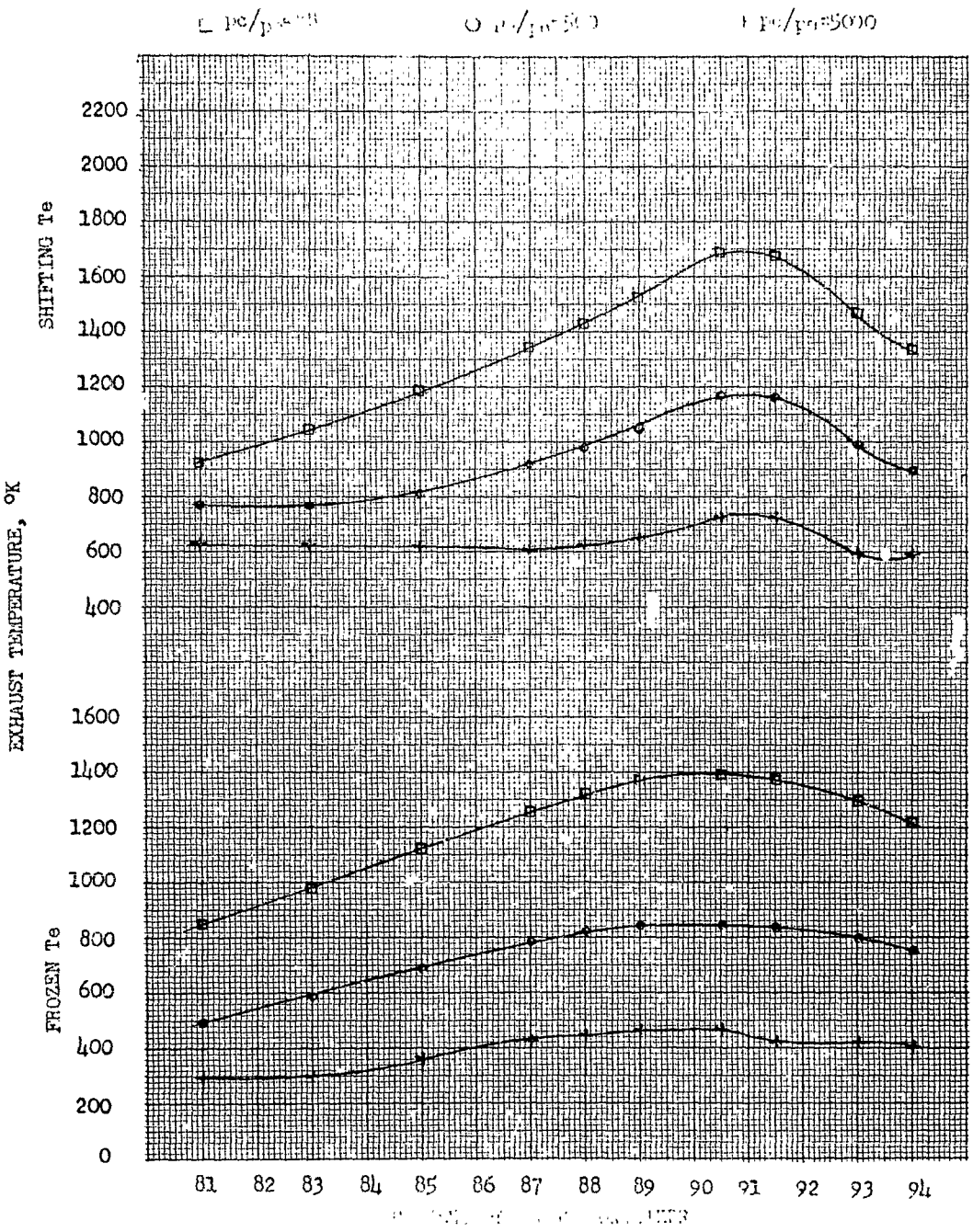
POLYETHYLENE – AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 11.8

p_c = 1000 psi

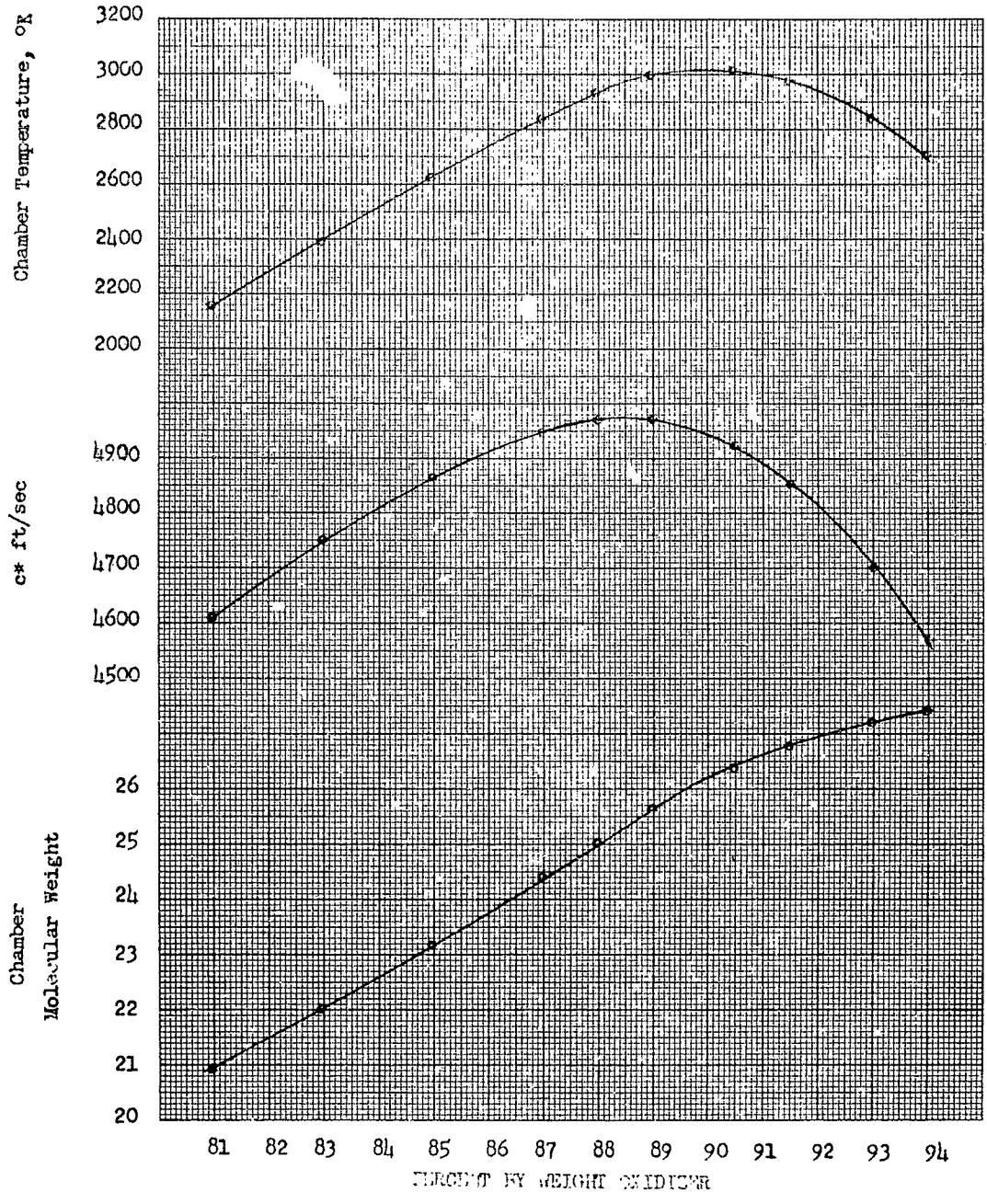
□ p_c/p_e=08 ○ p_c/p_e=500 + p_c/p_e=5000



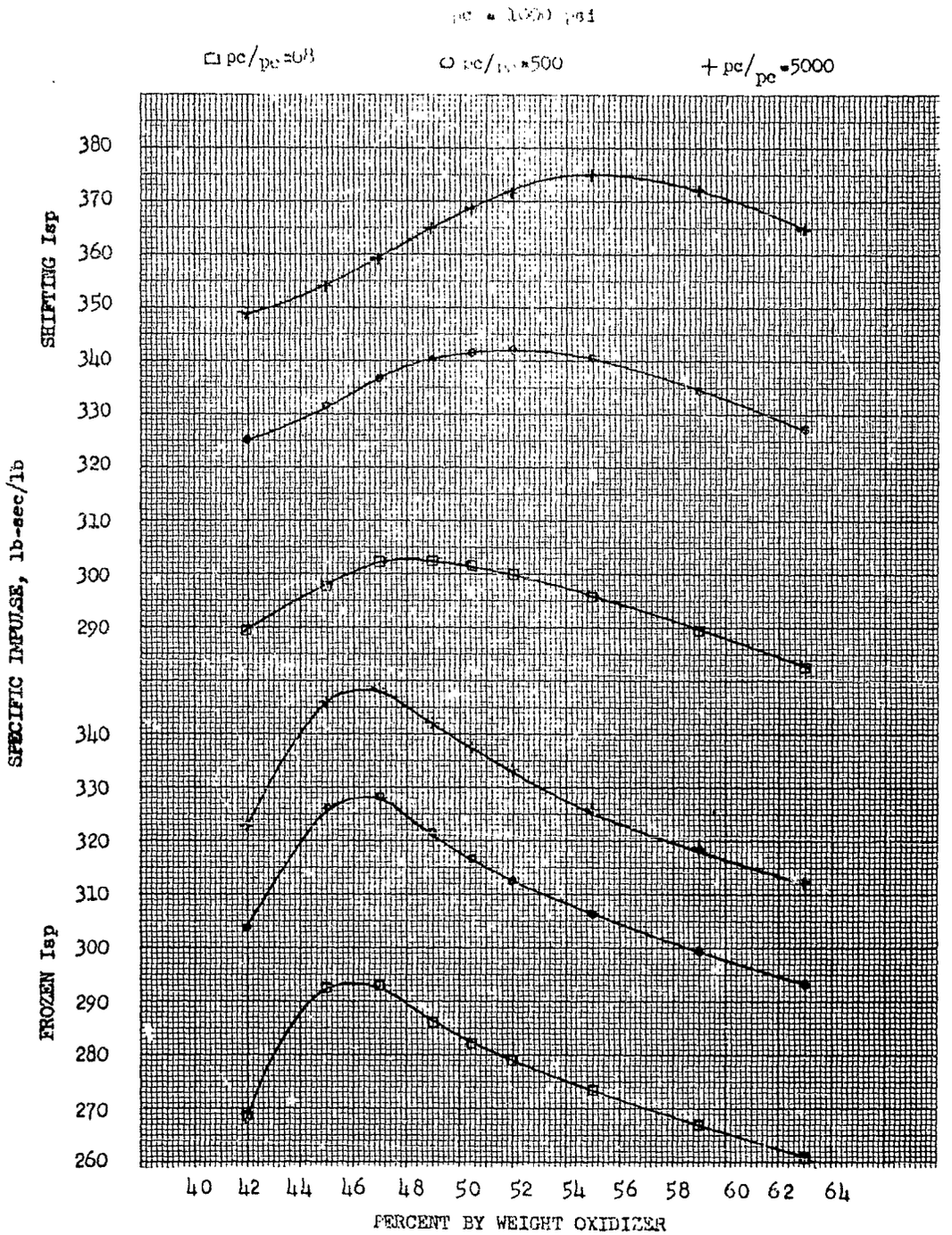
POLYETHYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 119



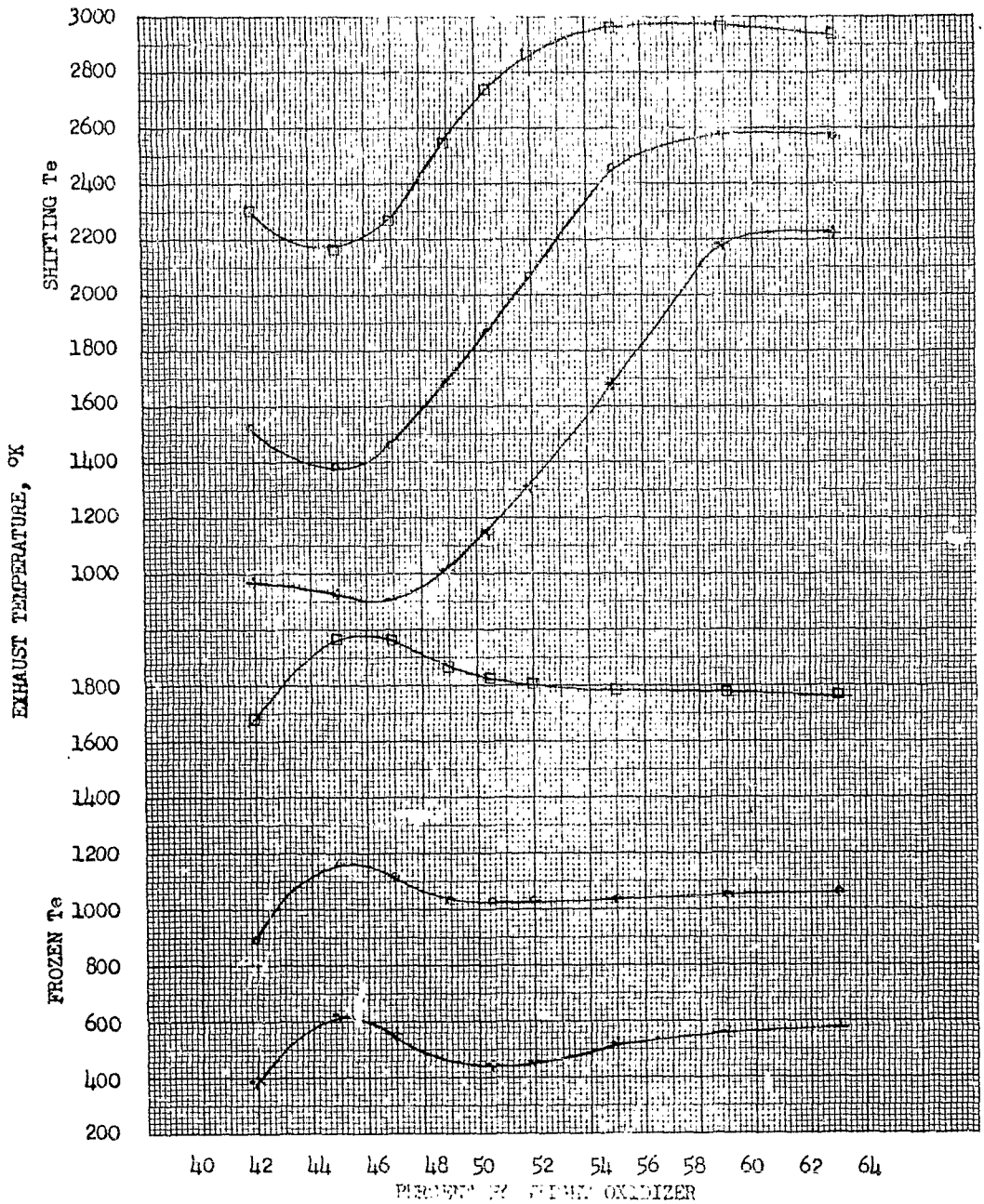
POLYETHYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 120



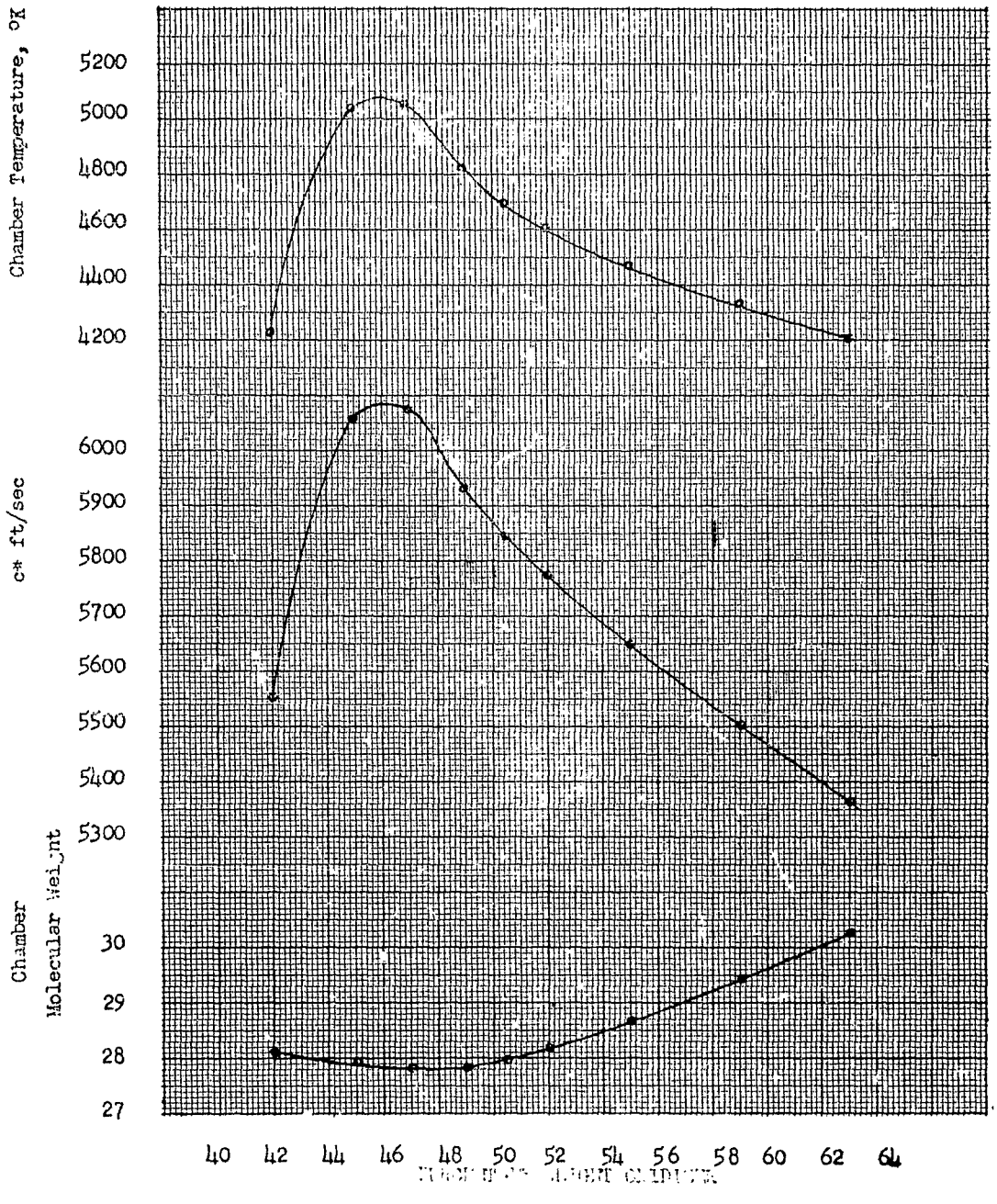
DICYANOACETYLENE – LIQUID OXYGEN PERFORMANCE CURVES FIGURE 121



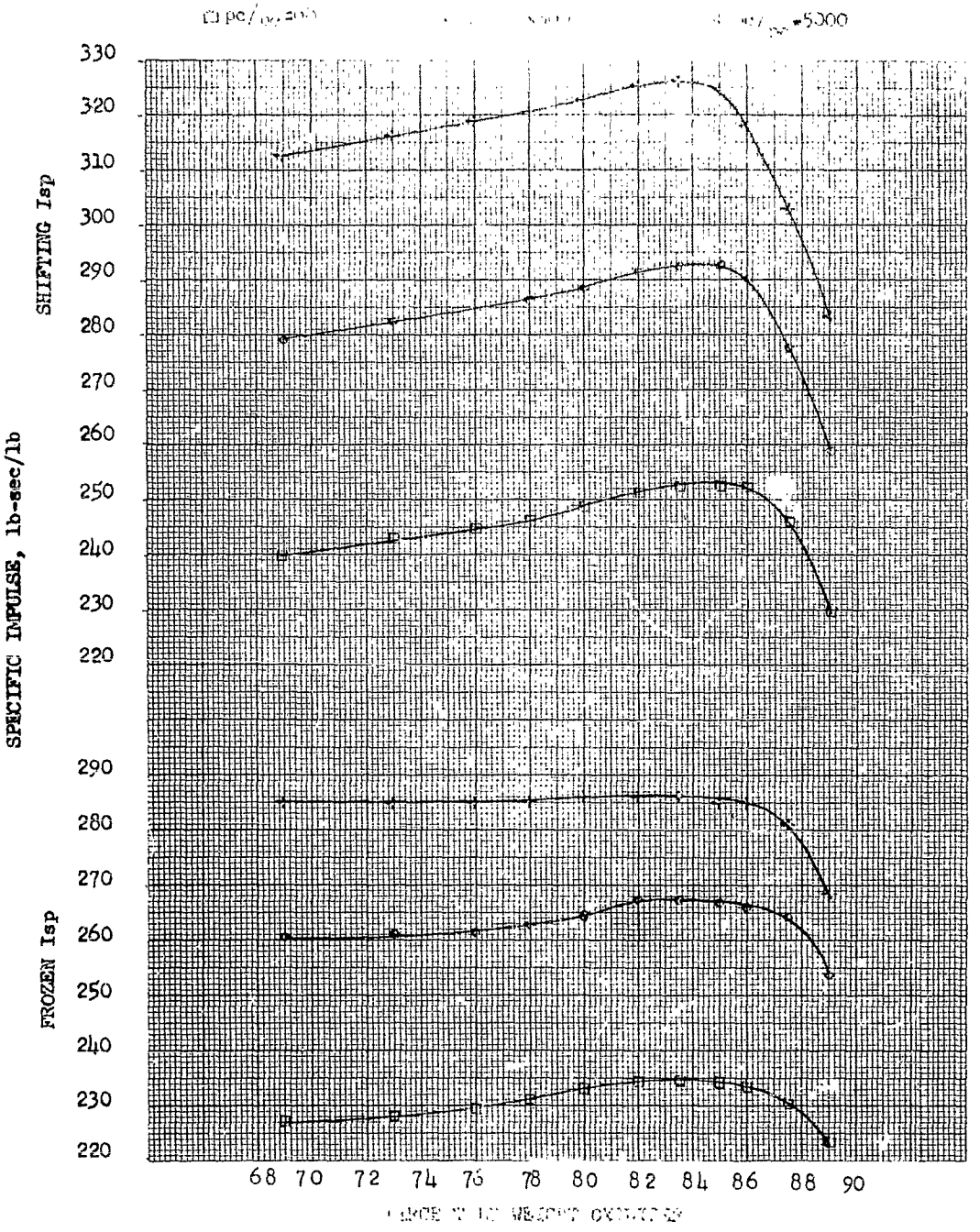
DICYANOACETYLENE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 122



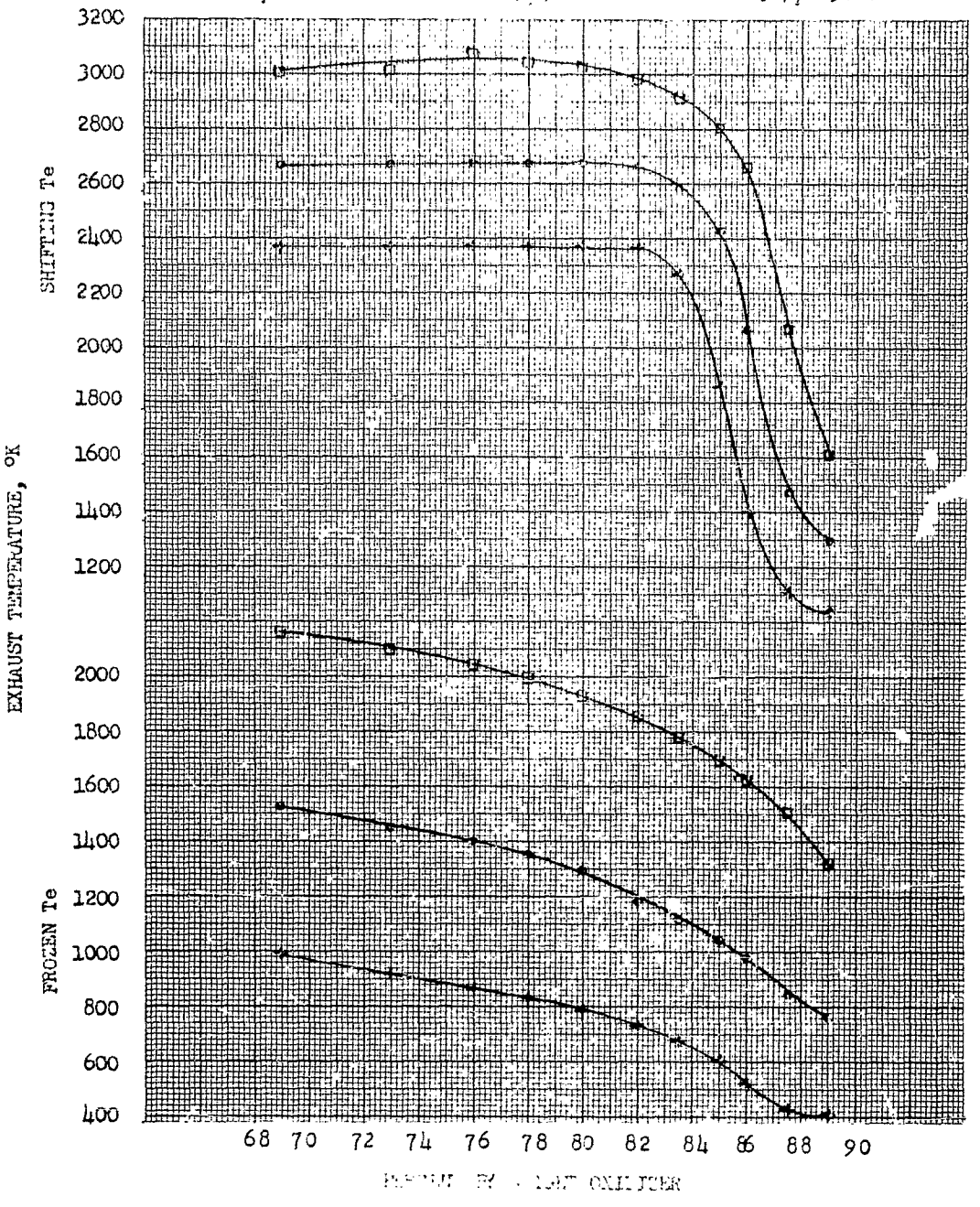
DICYANOACETYLENE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 123



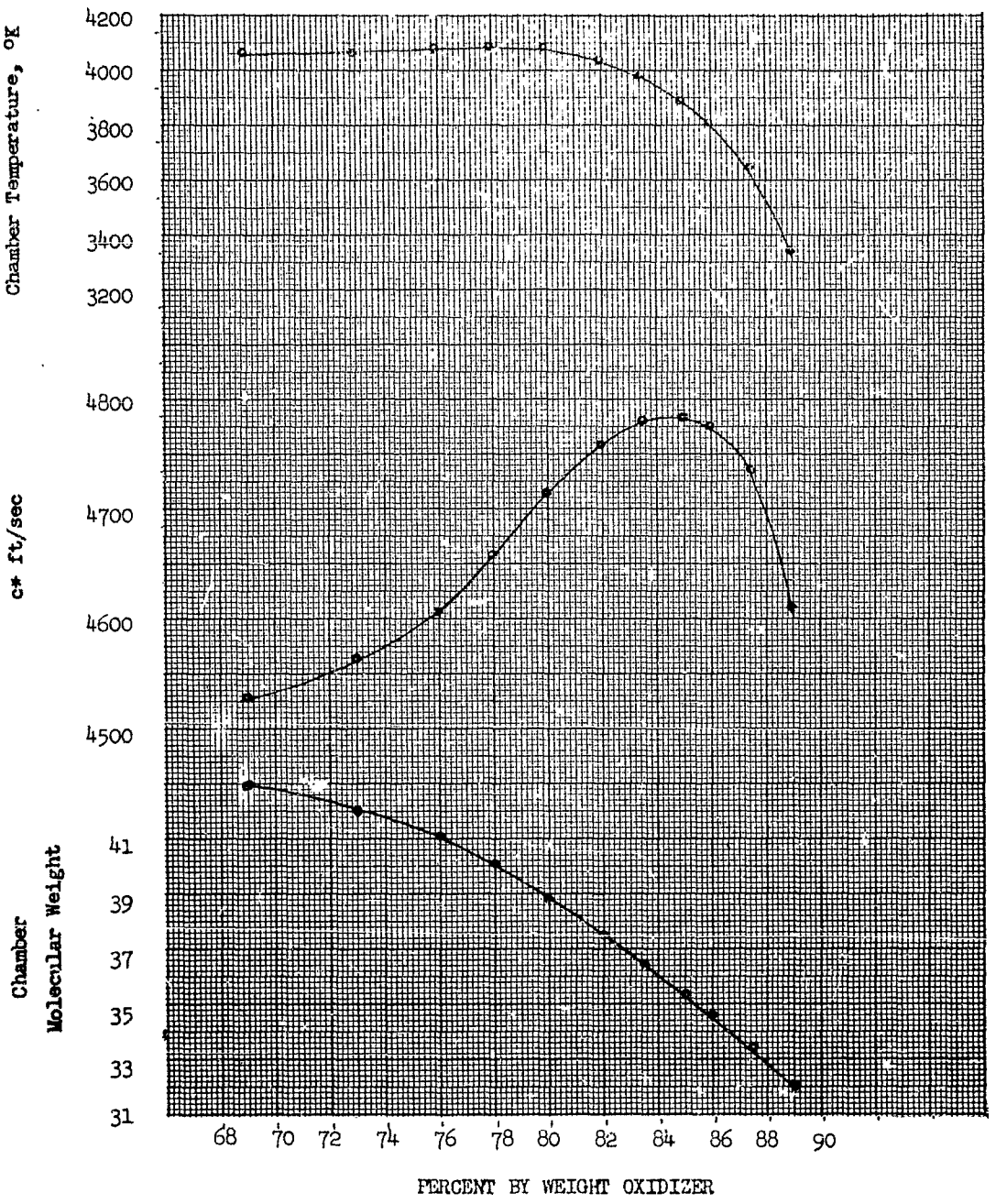
DICYANOACETYLENE - [illegible] FIGURE 124



DICYANOACETYLENE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 125



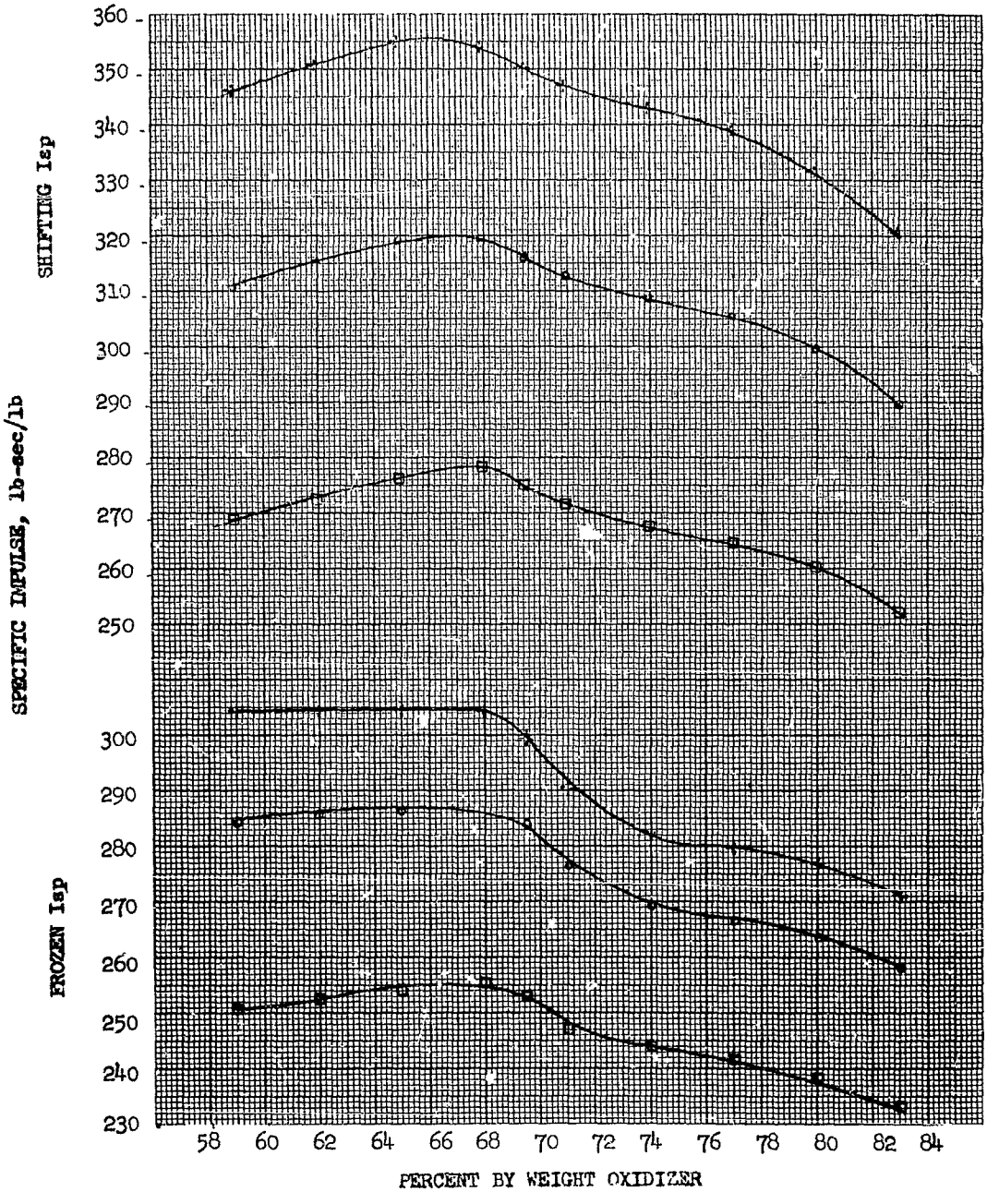
DICYANOACETYLENE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 126



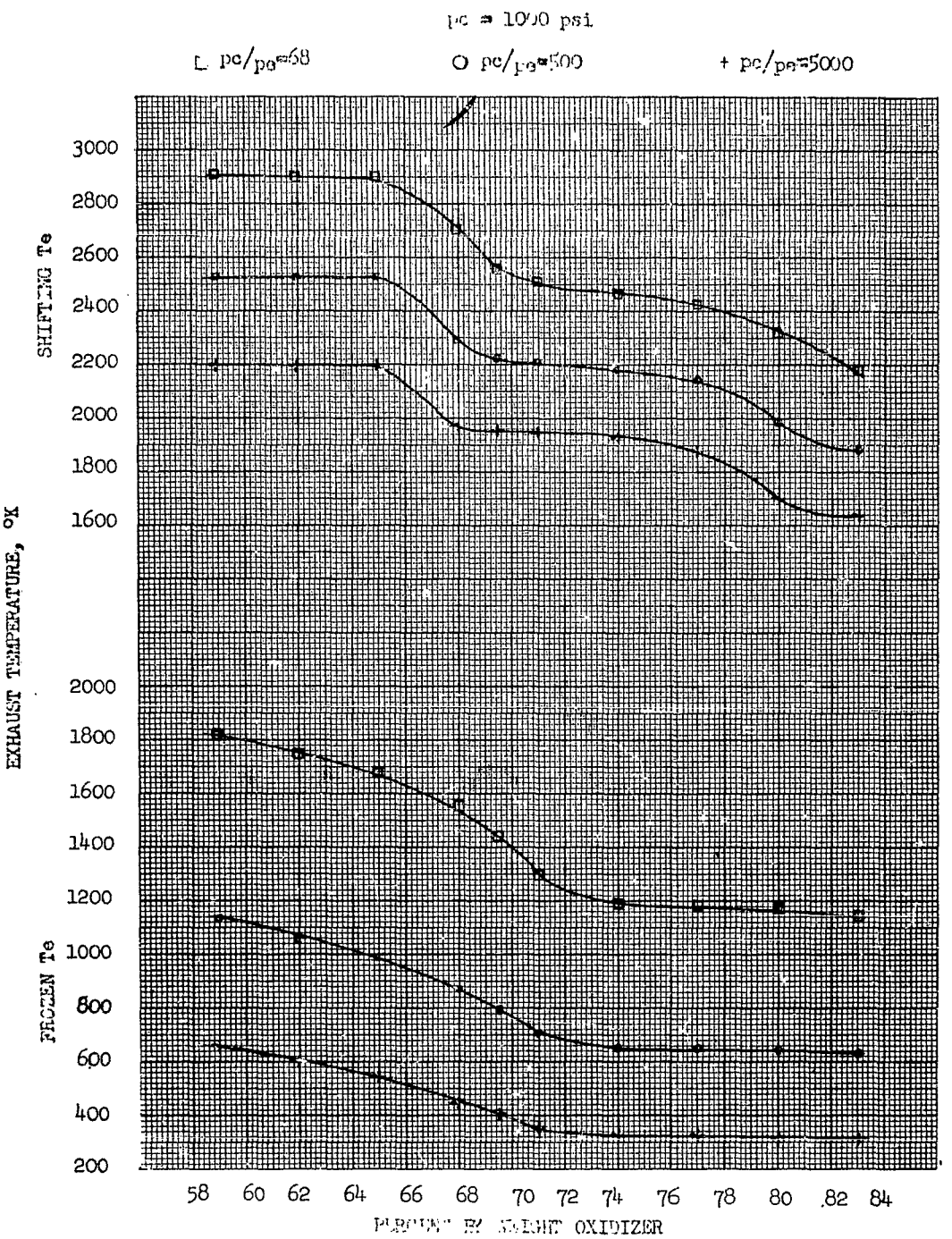
DICYANOACETYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 127

p_c = 1000 psi

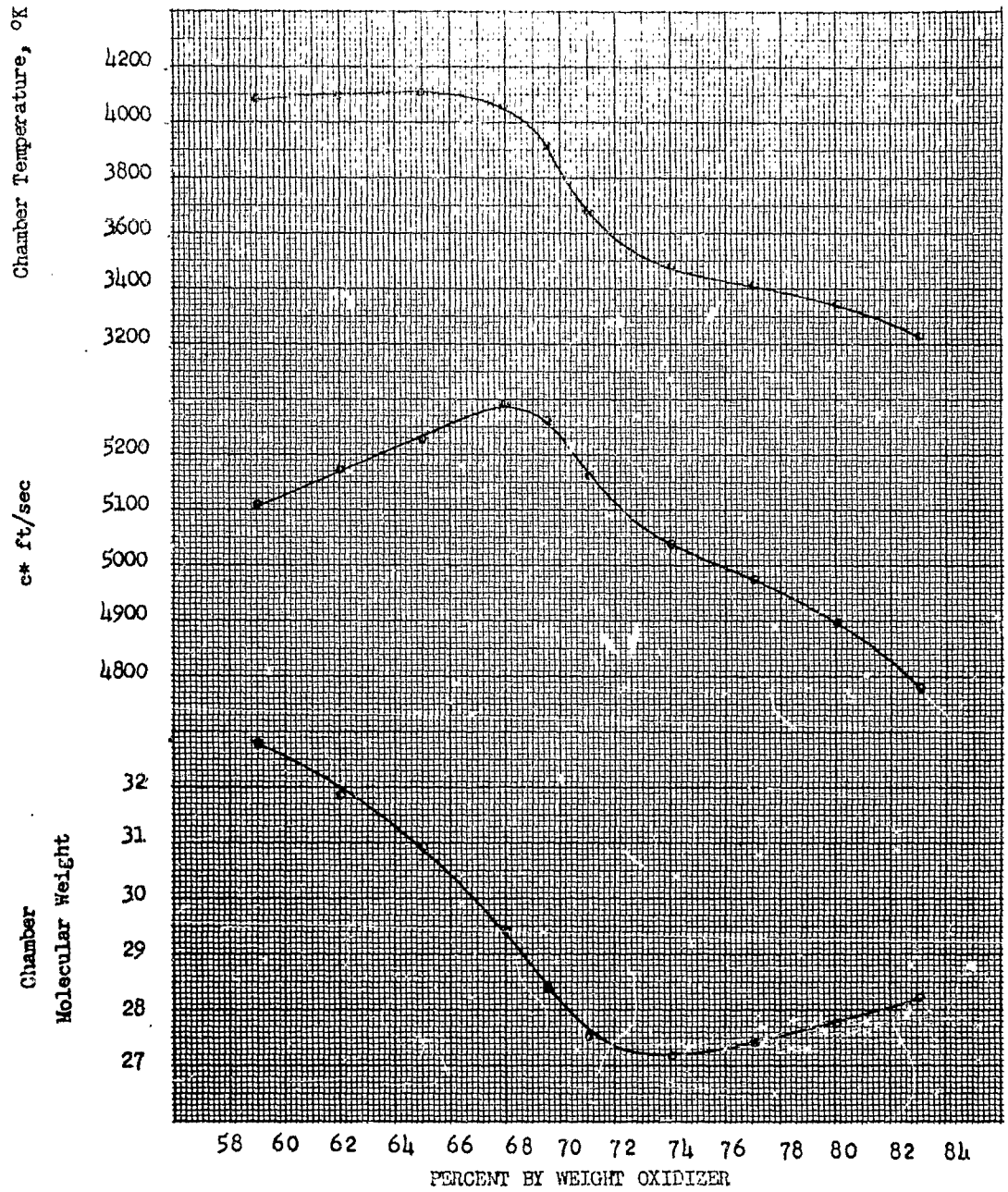
□ p_c/p_e=08 ○ p_c/p_e=500 + p_c/p_e=5000



DICYANOACETYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 128



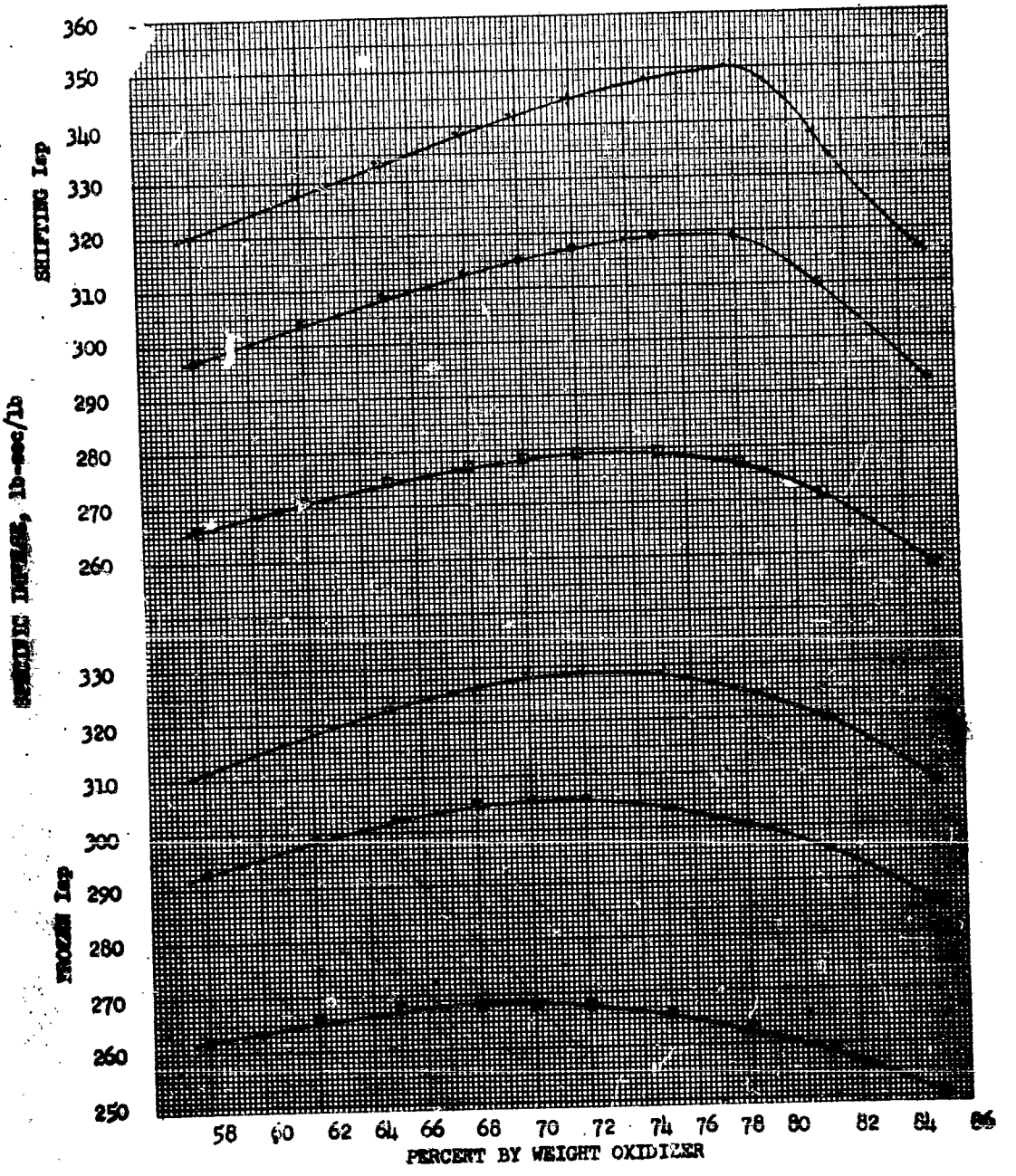
DICYANOACETYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 129



DICYANOACETYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 130

pc = 1000 psi

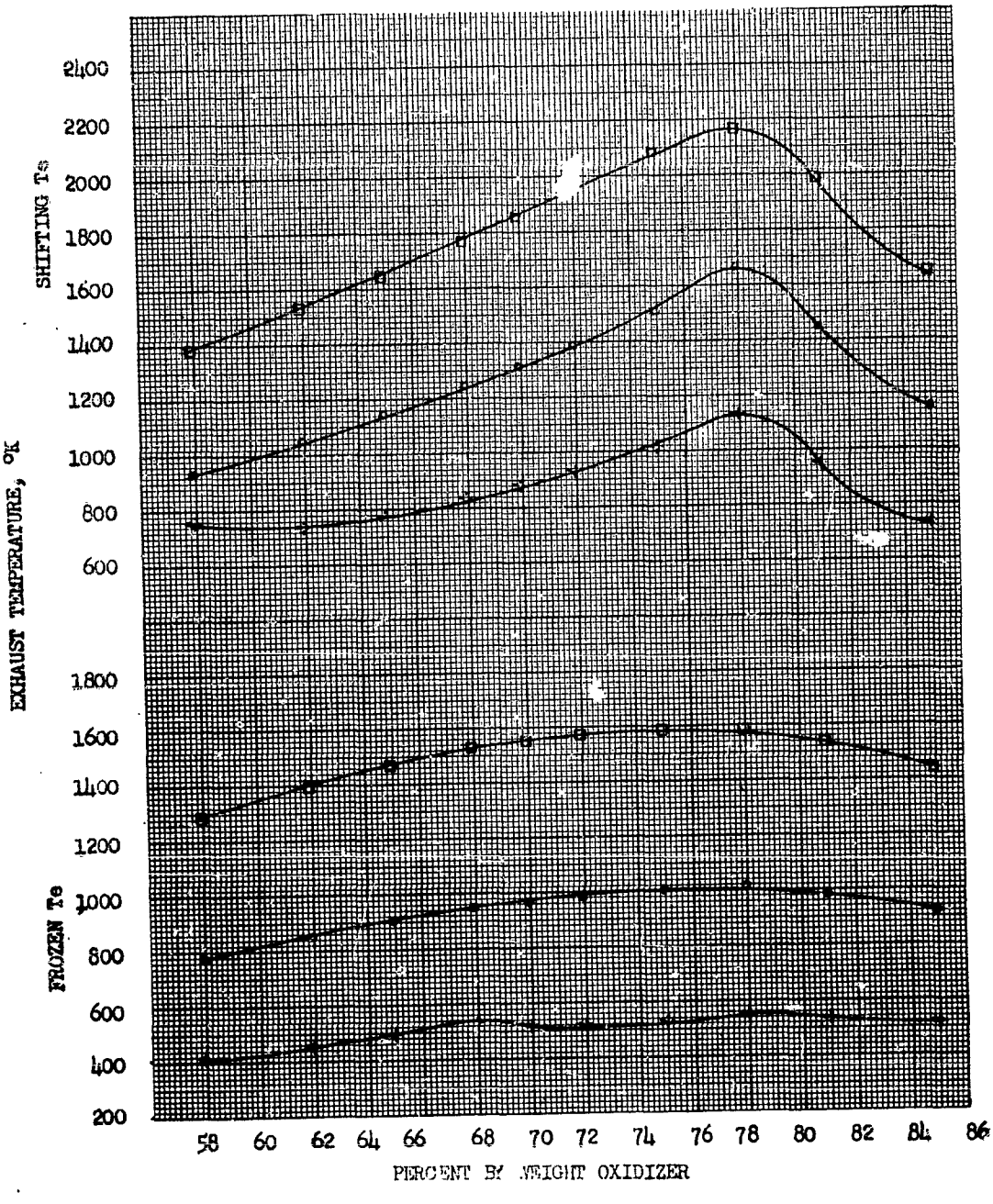
□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



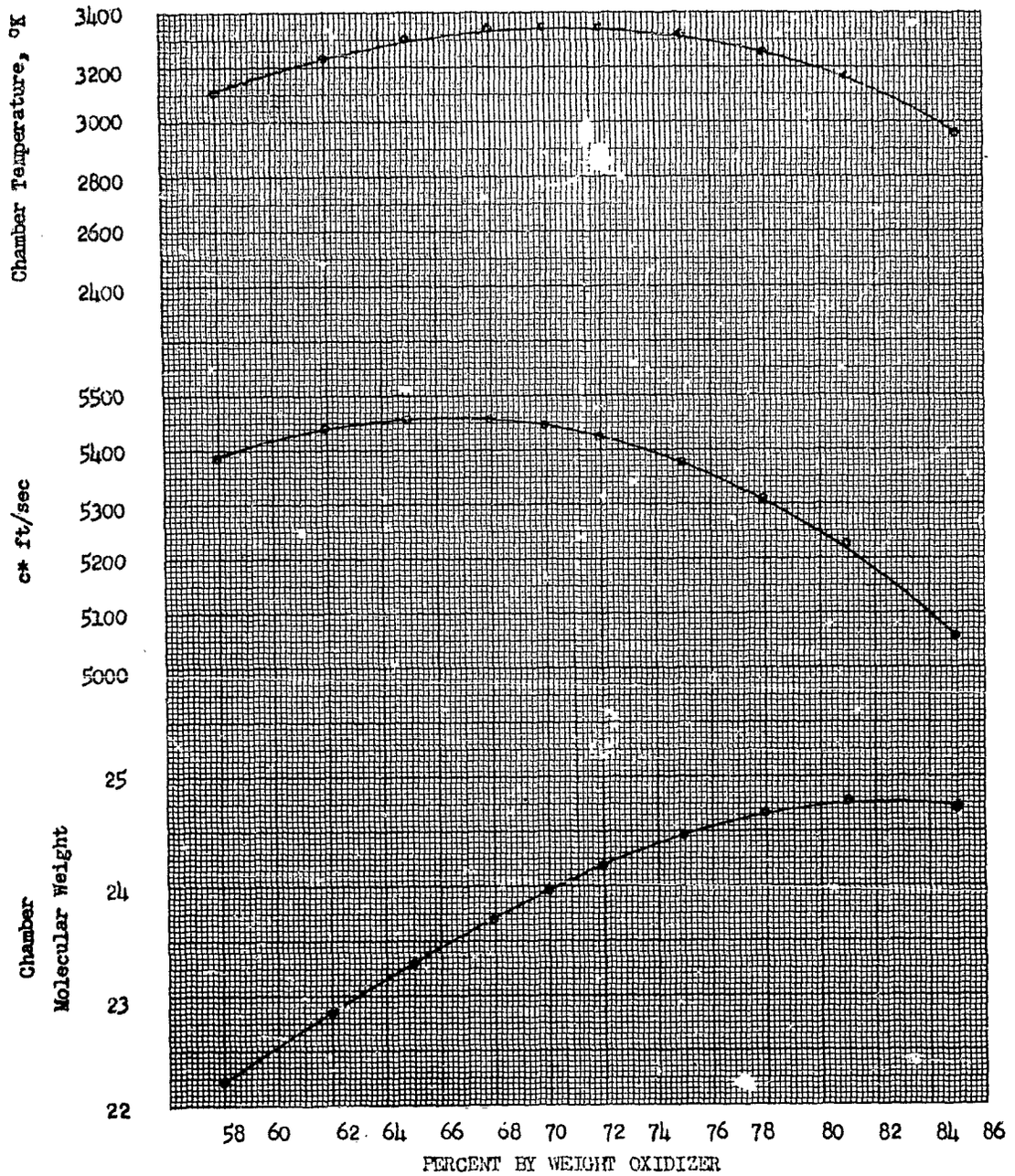
DICYANOACETYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 131

p_c = 1000 psi

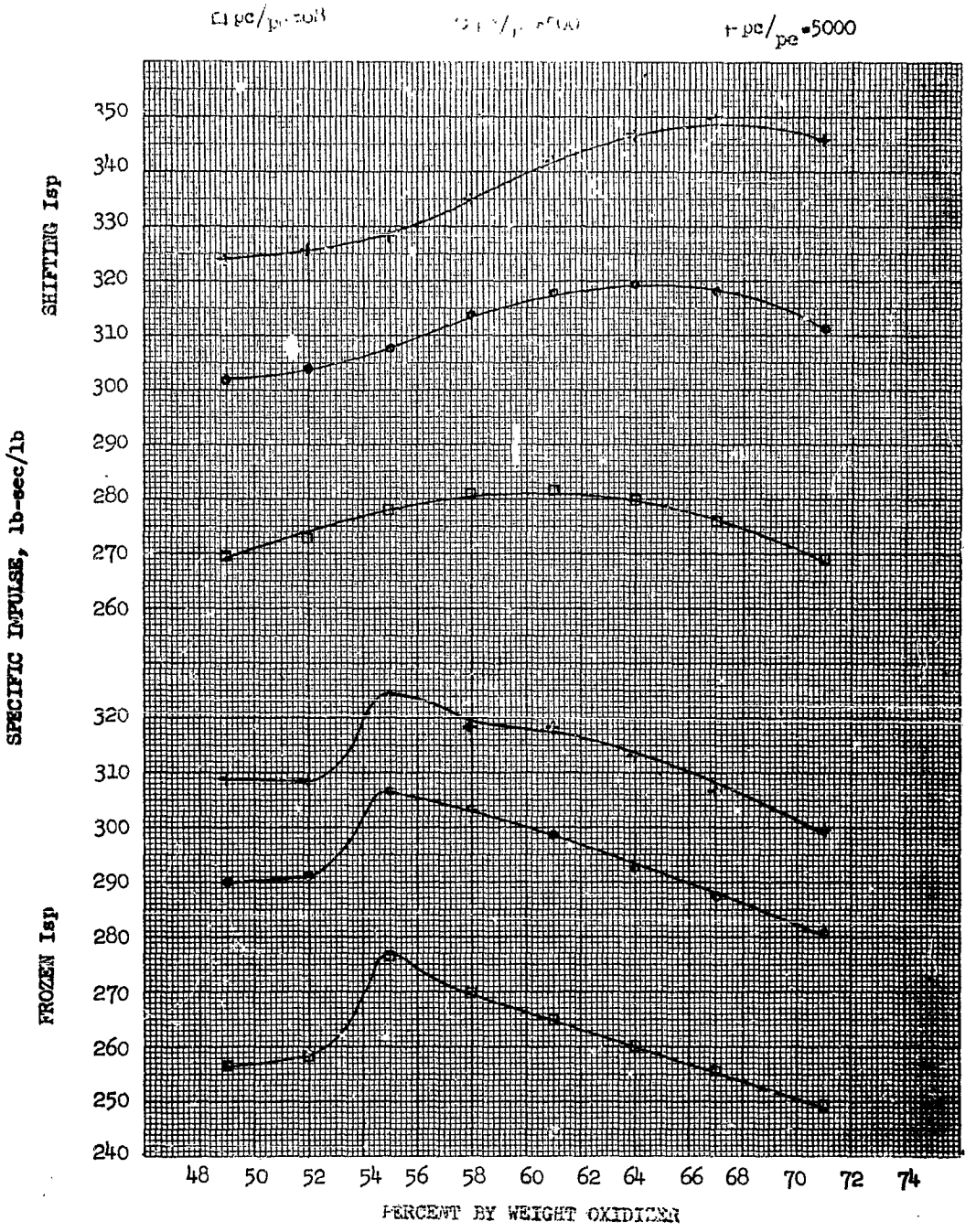
□ p_c/p_e=68 O p_c/p_e=500 + p_c/p_e=5000



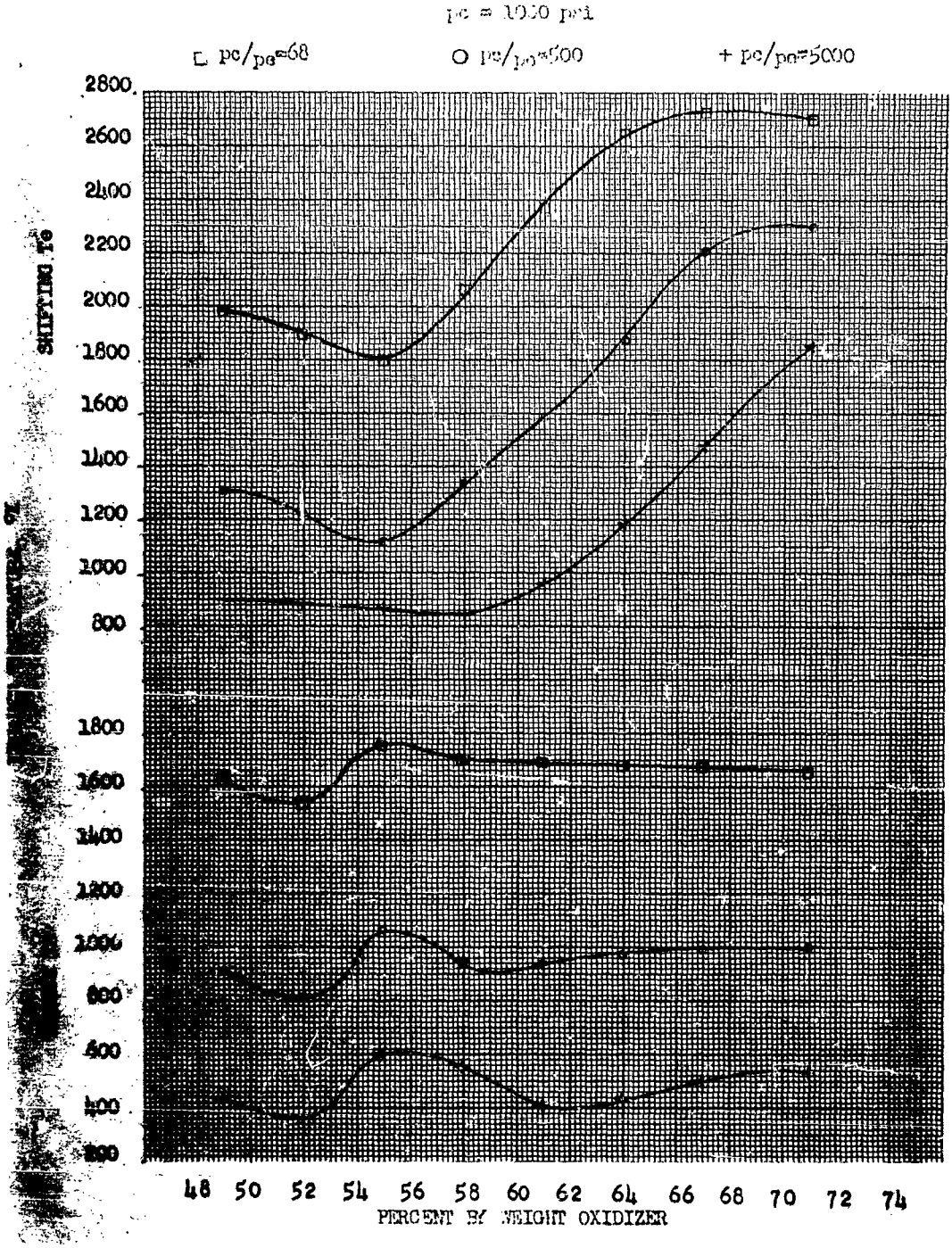
DICYANOACETYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 132



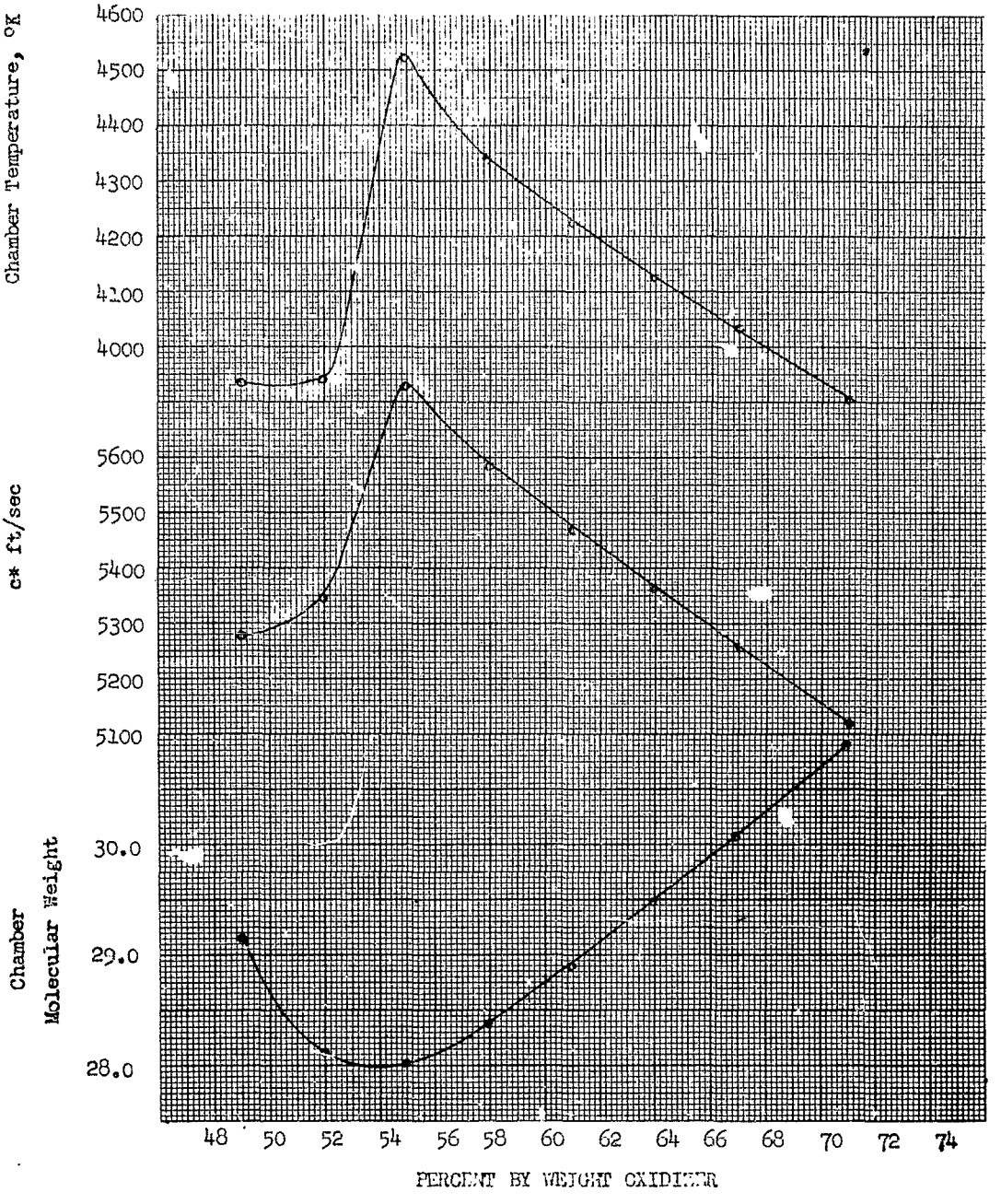
DICYANOACETYLENE-NITROGEN TETROXIDE [illegible] CURVES FIGURE 1.33



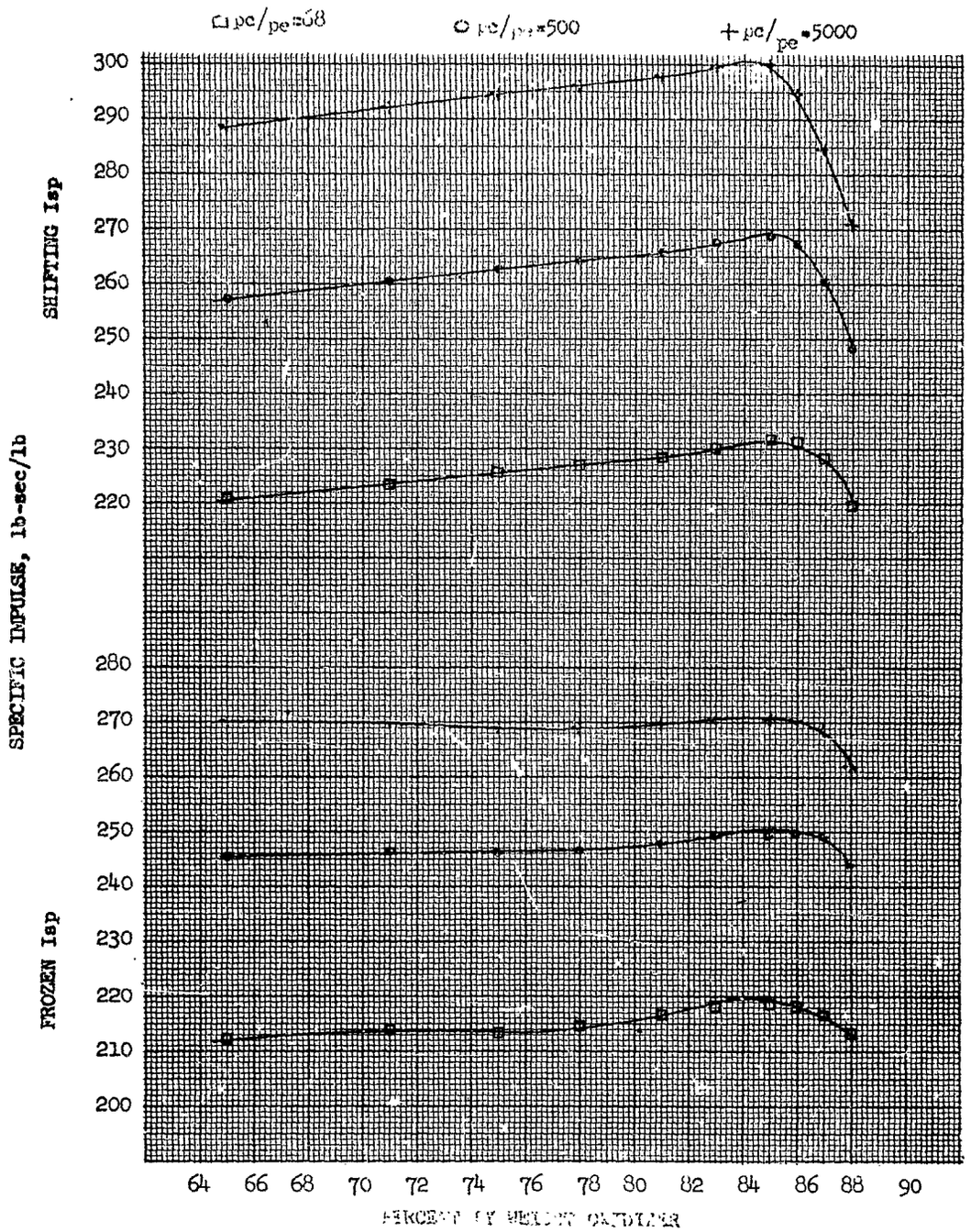
DICYANOACETYLENE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 134



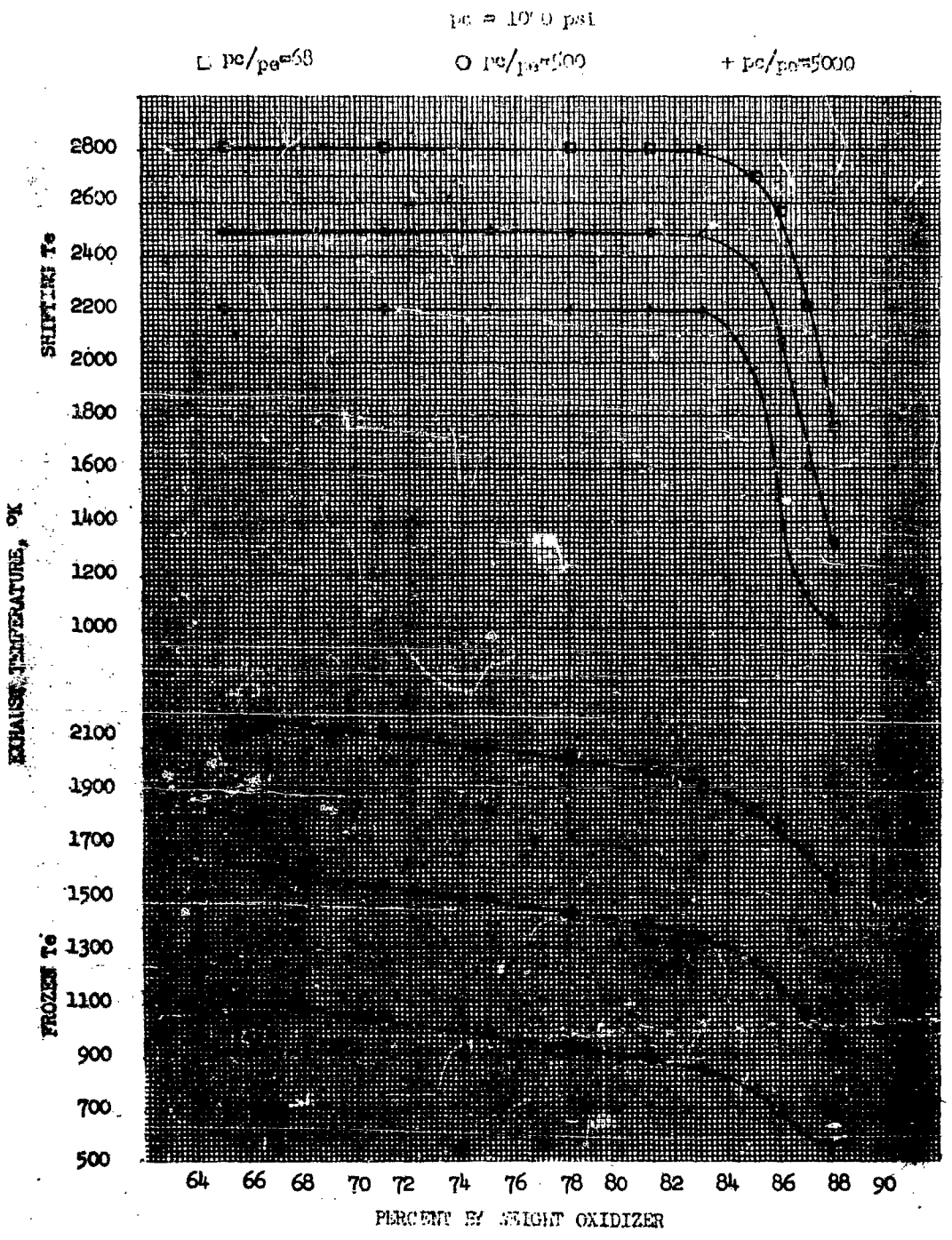
DICYANOACETYLENE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 135



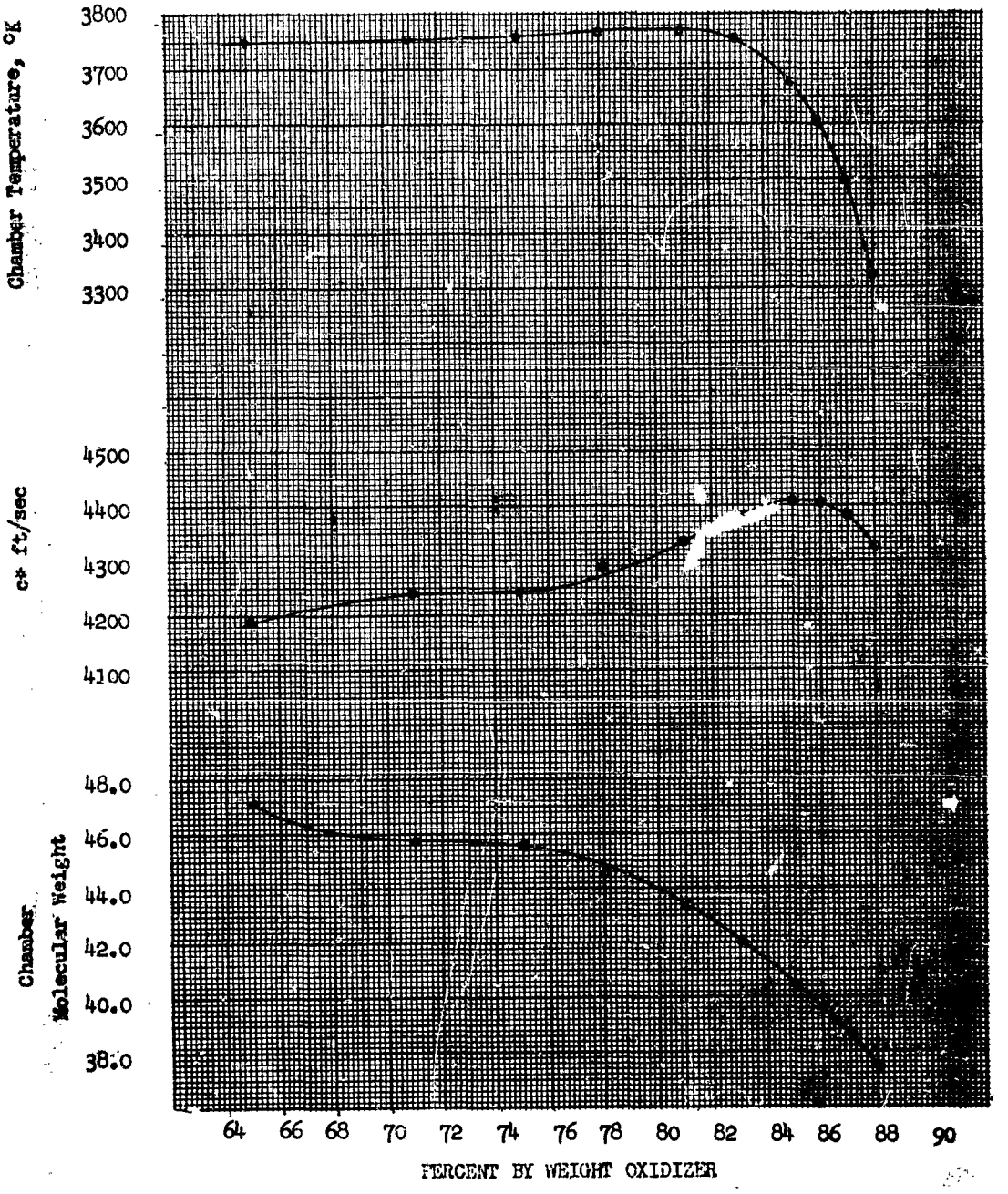
DICYANOACETYLENE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 136



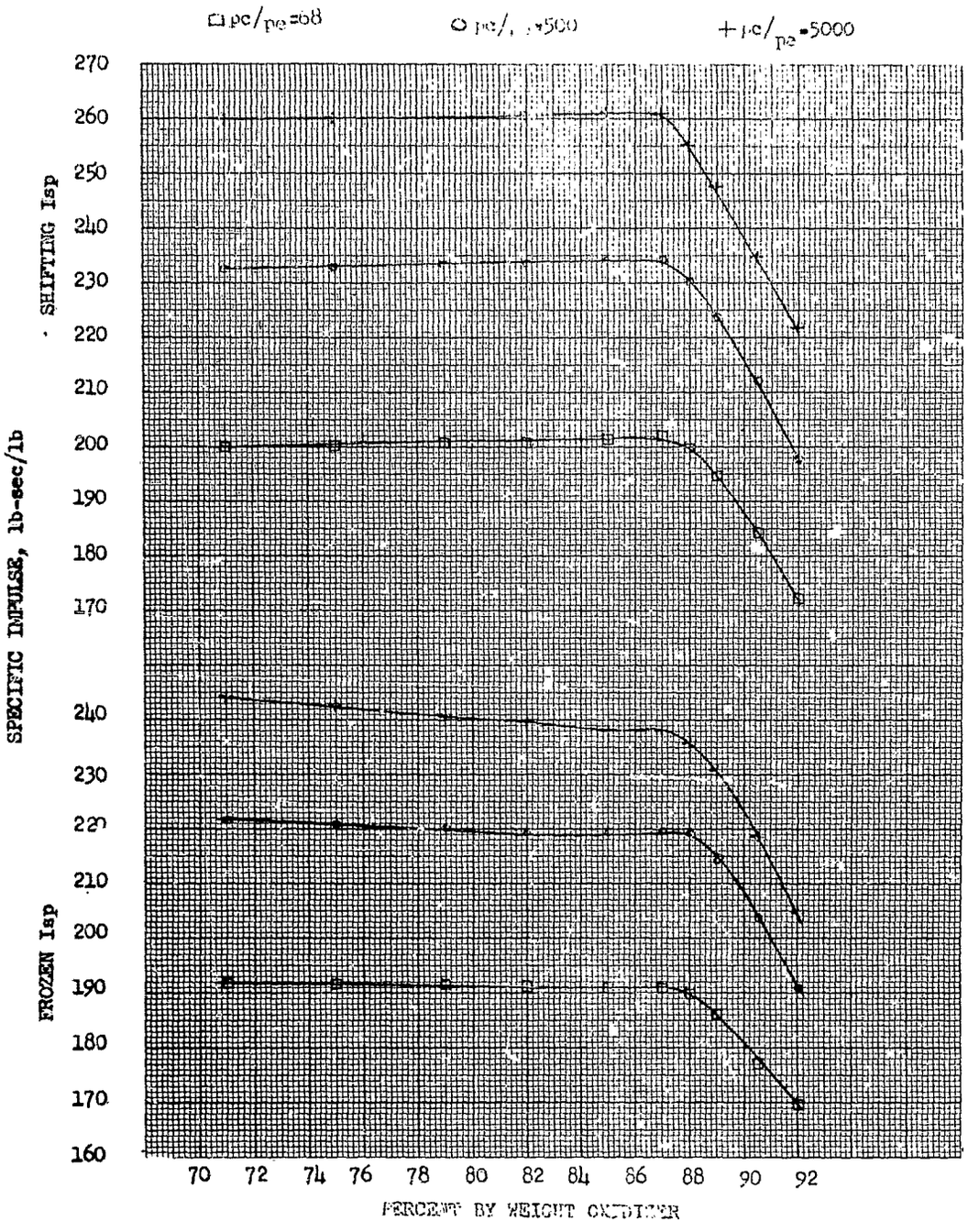
DICYANOACETYLENE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 137

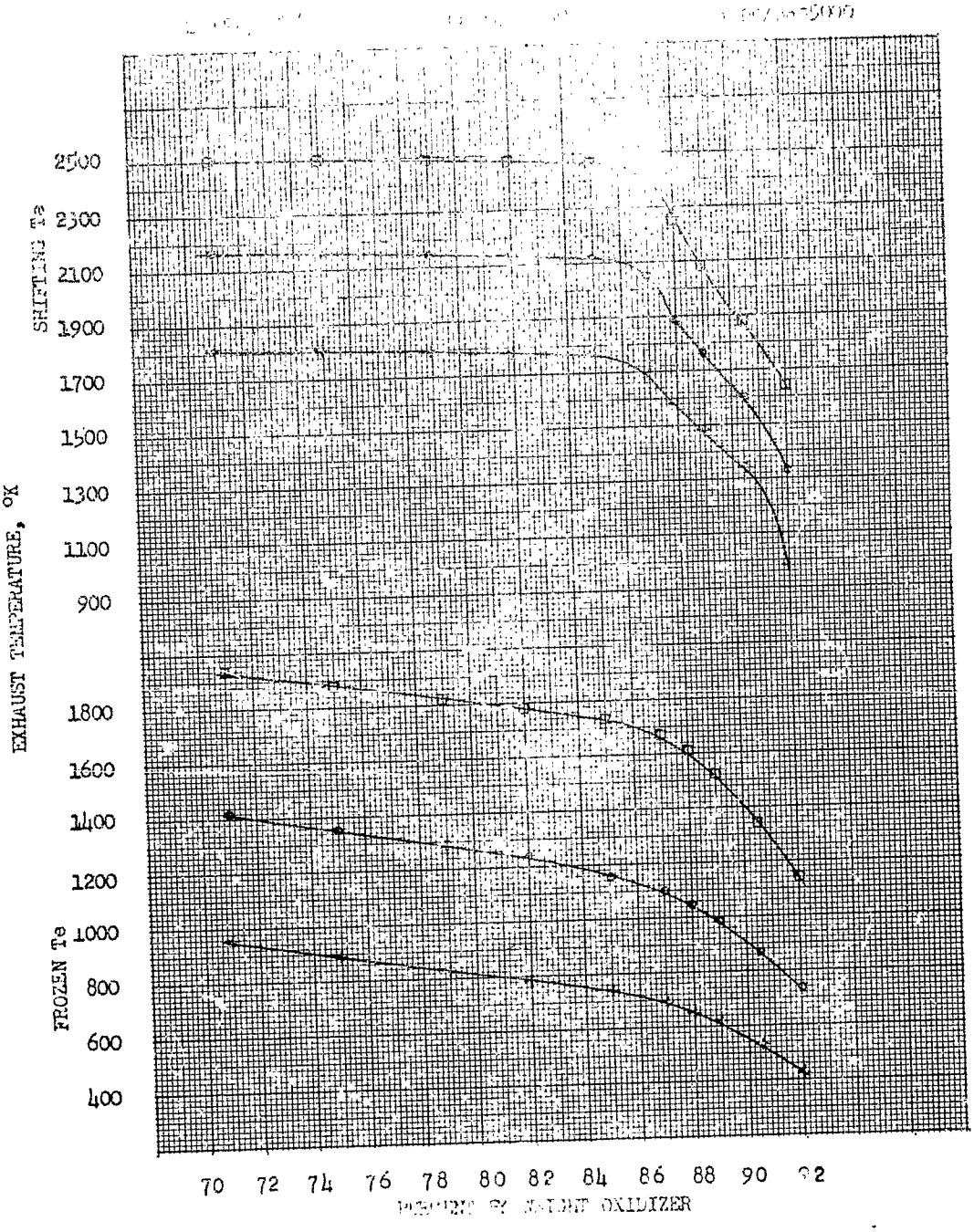


DICYANOACETYLENE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 138

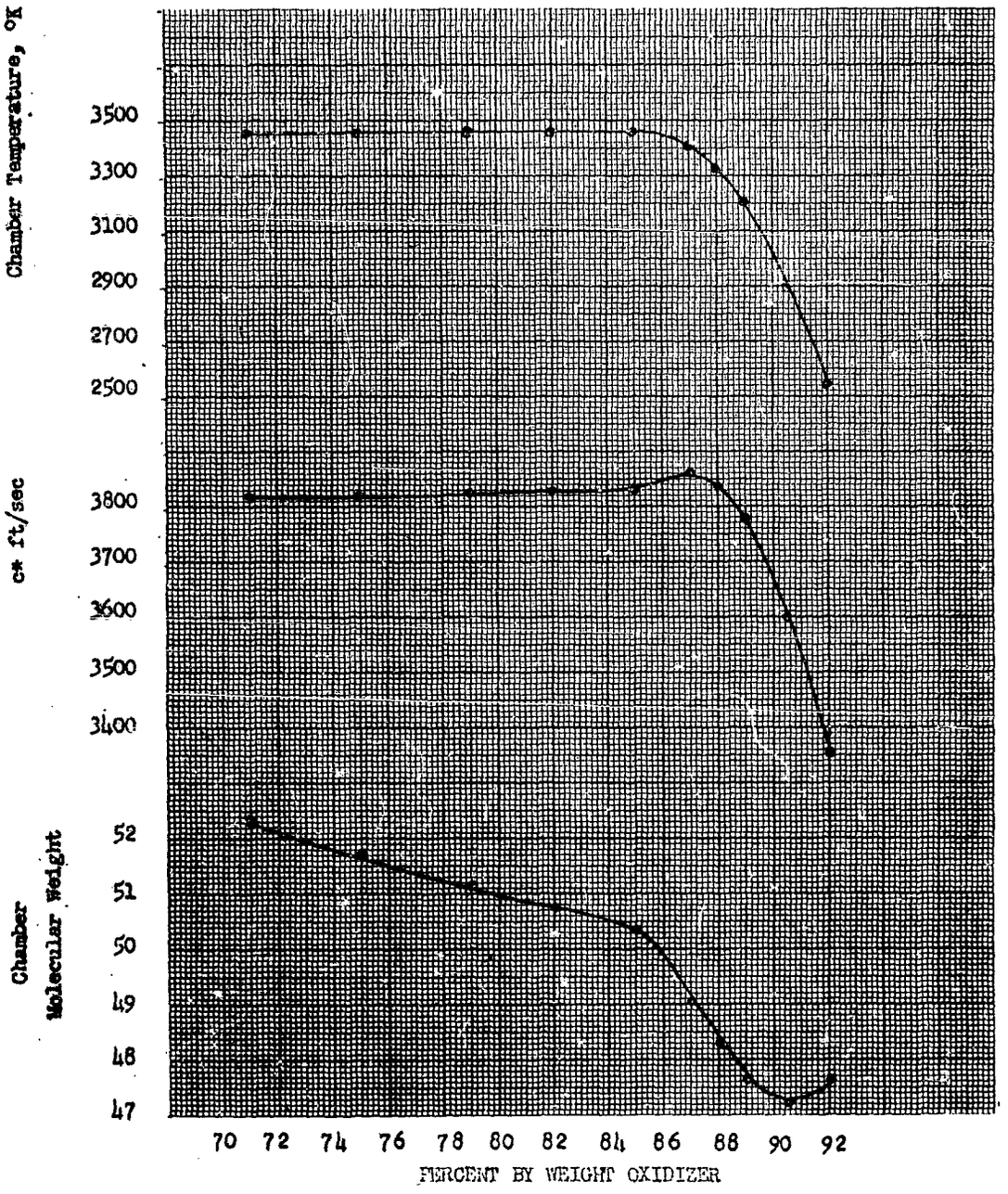


DICYANOACETYLLINE – CHLORINE TRIFLUORIDE [illegible] FIGURE 139




EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
2500
2300
2100
1900
1700
1500
1300
1100
900
1800
1600
1400
1200
1000
800
600
400
70 72 74 76 78 80 82 84 86 88 90 92

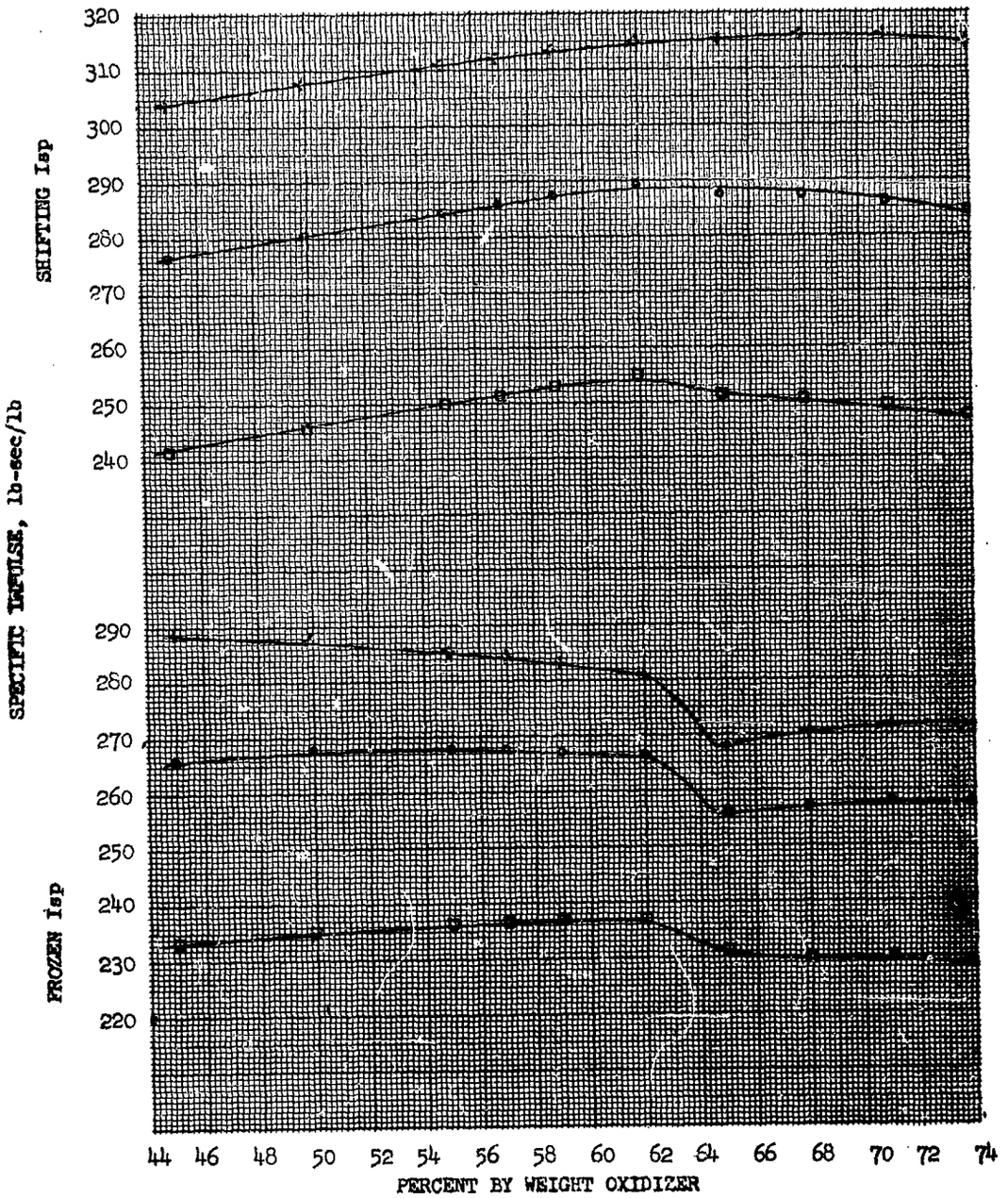
DICYANOACETYLENE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 141

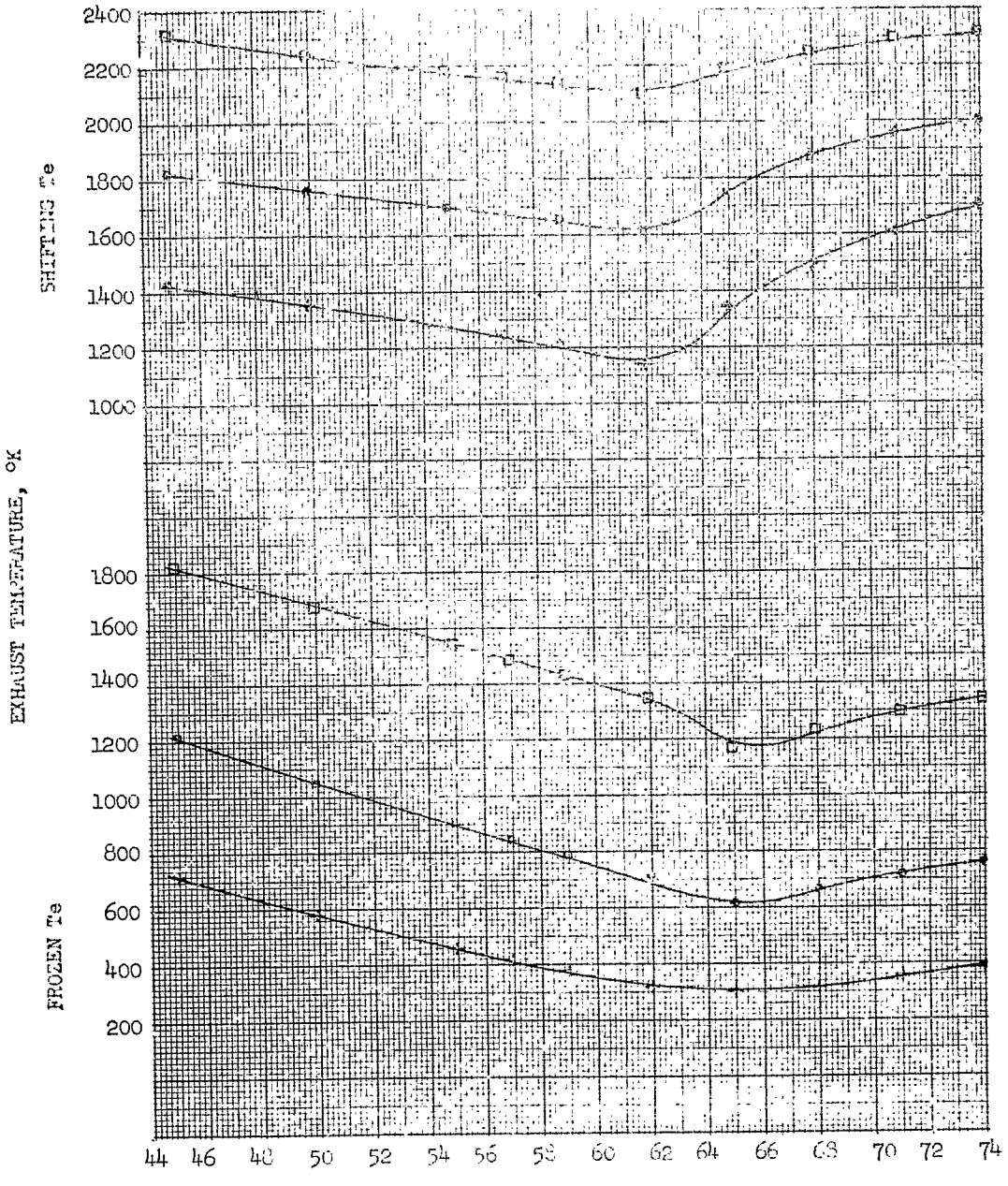


DICYANOACETYLENE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 142

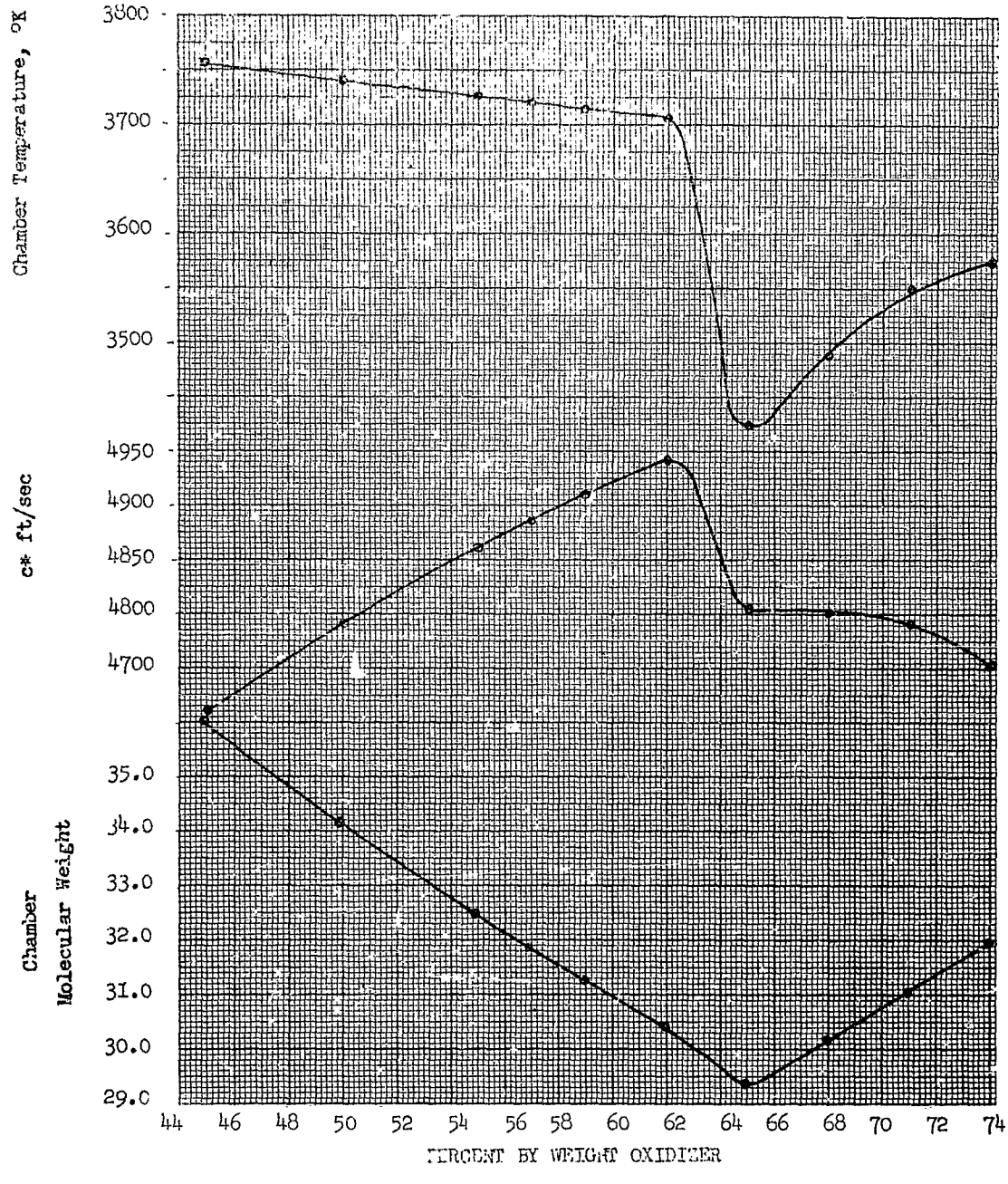
p_c = 1000 psi

□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000

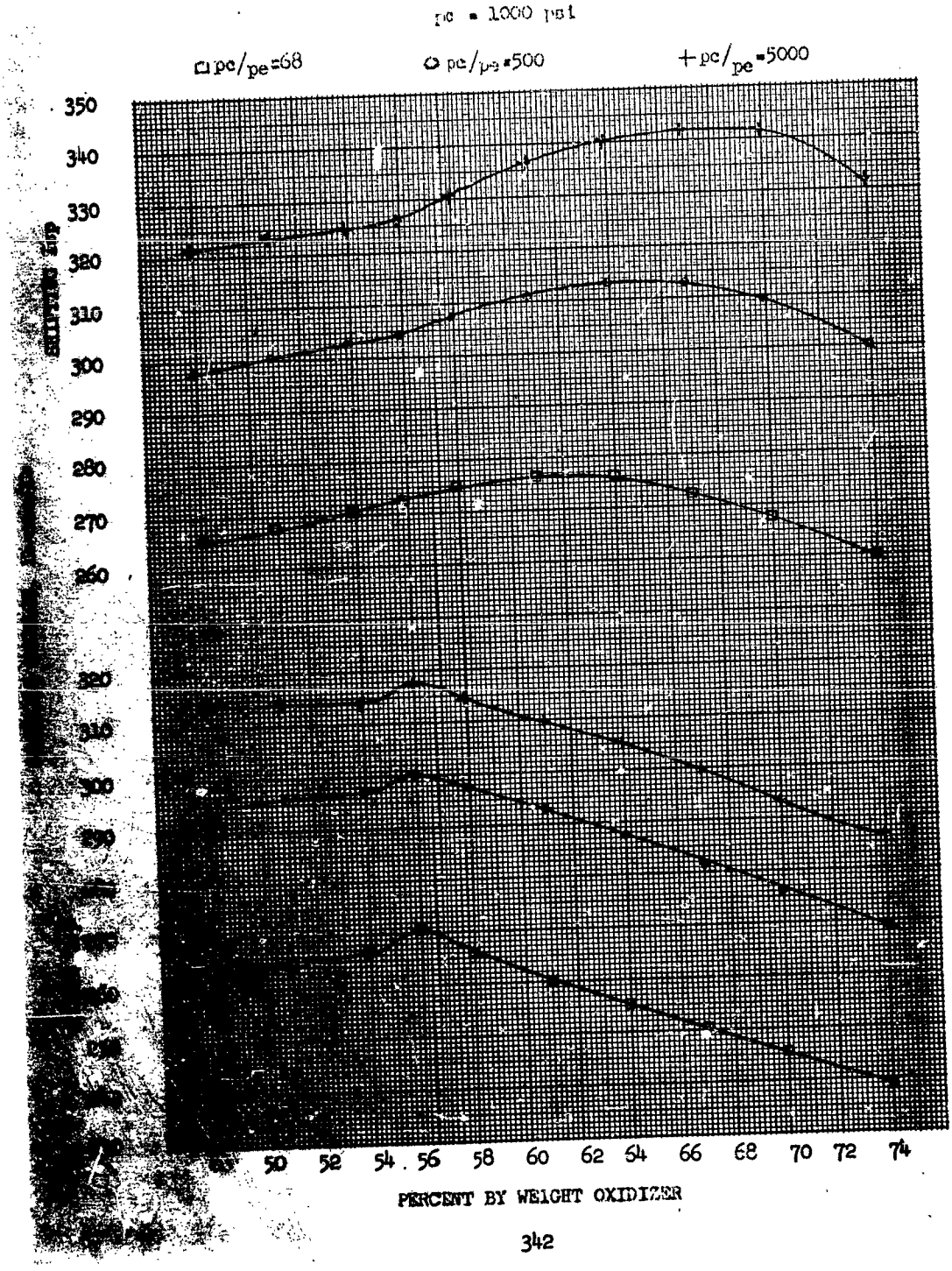



EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
2400
2200
2000
1800
1600
1400
1200
1000
1800
1600
1400
1200
1000
800
600
400
200
44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74

DICYANOACETYLENE - OXYGEN BINARY PROPELLANT PERFORMANCE CURVES FIGURE 144



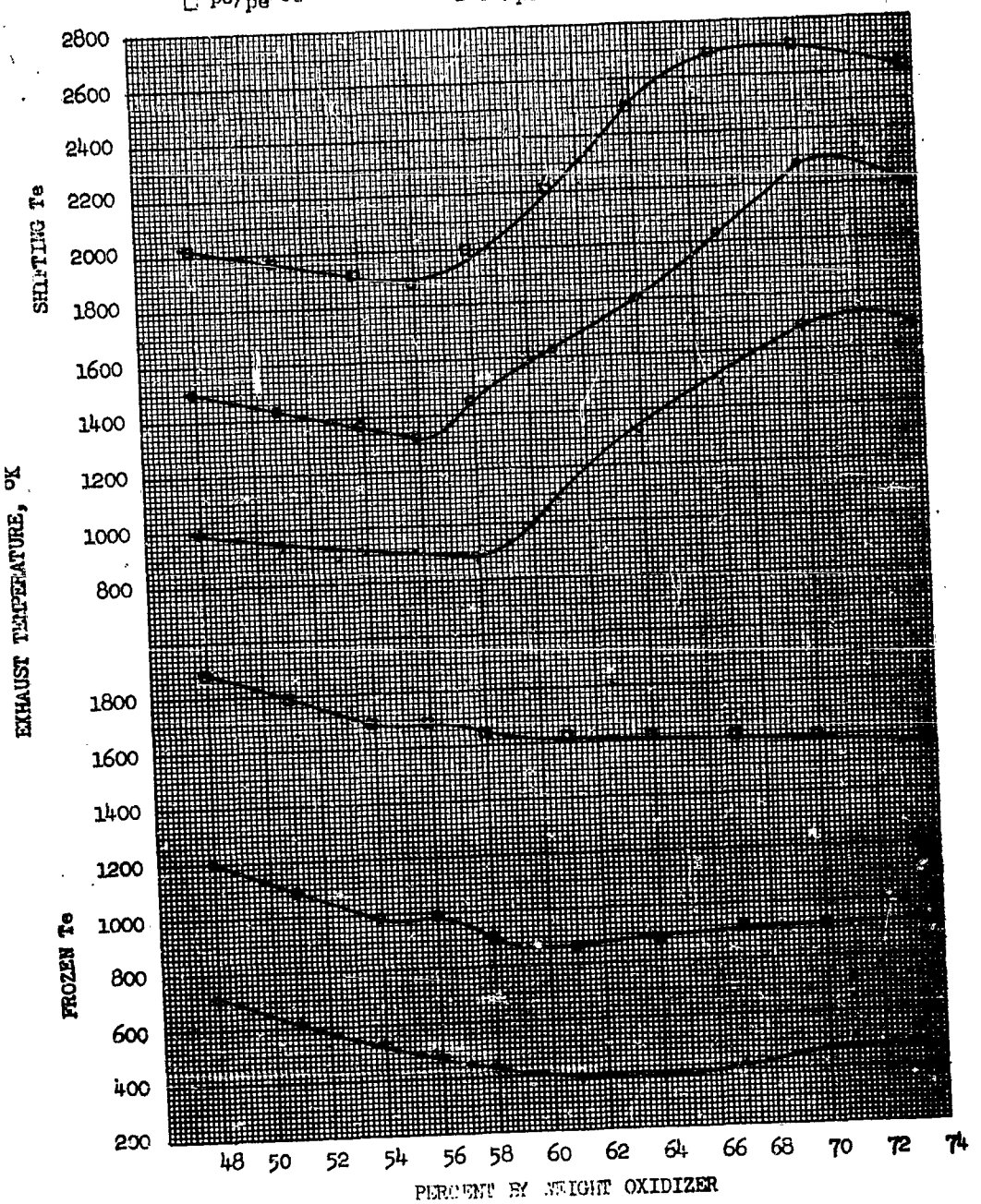
DICYANOACETYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 145



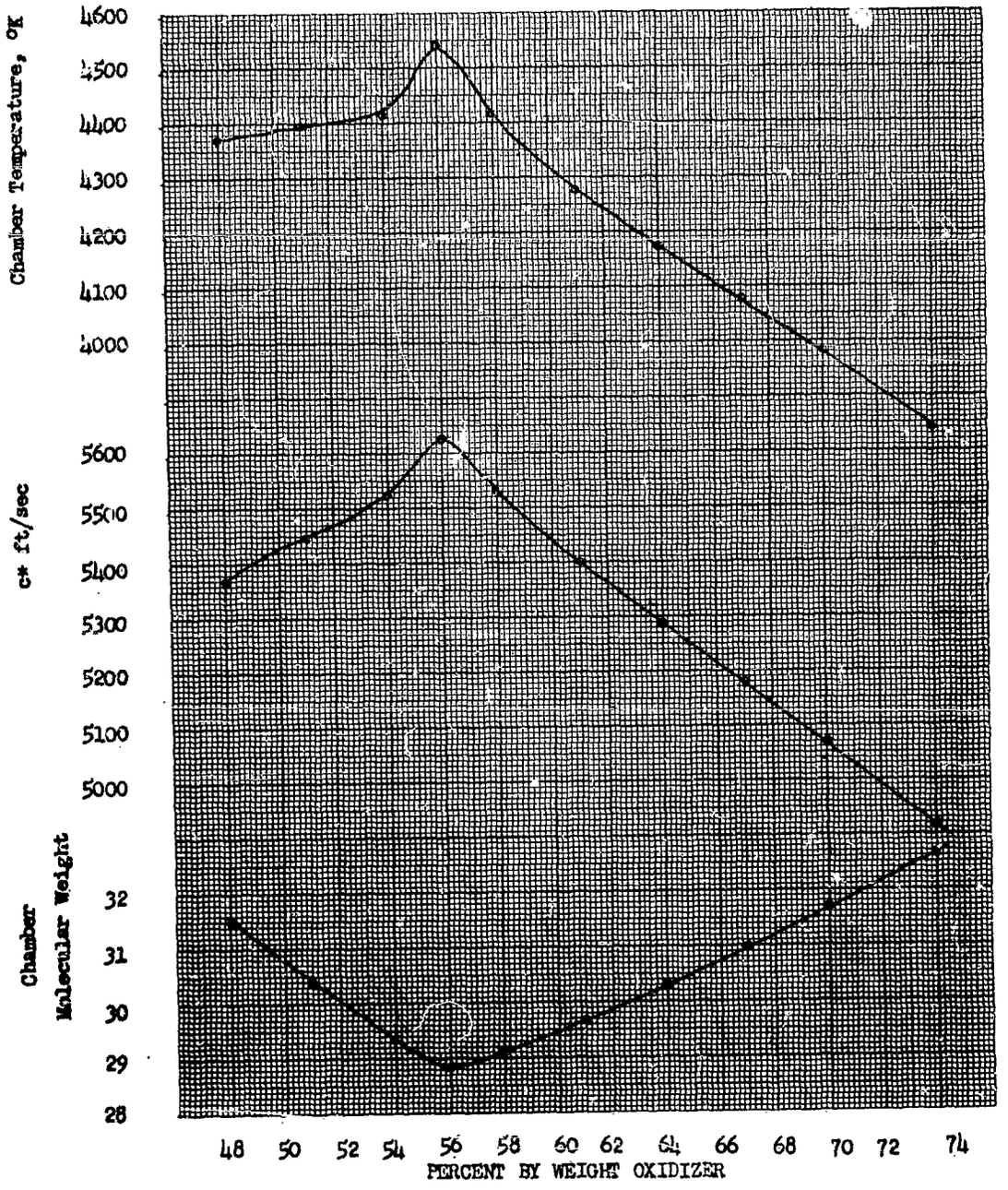
DICYANOACETYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 146

p_c = 1000 psi

□ p_c/p_e=68 O p_c/p_e=500 + p_c/p_e=5000



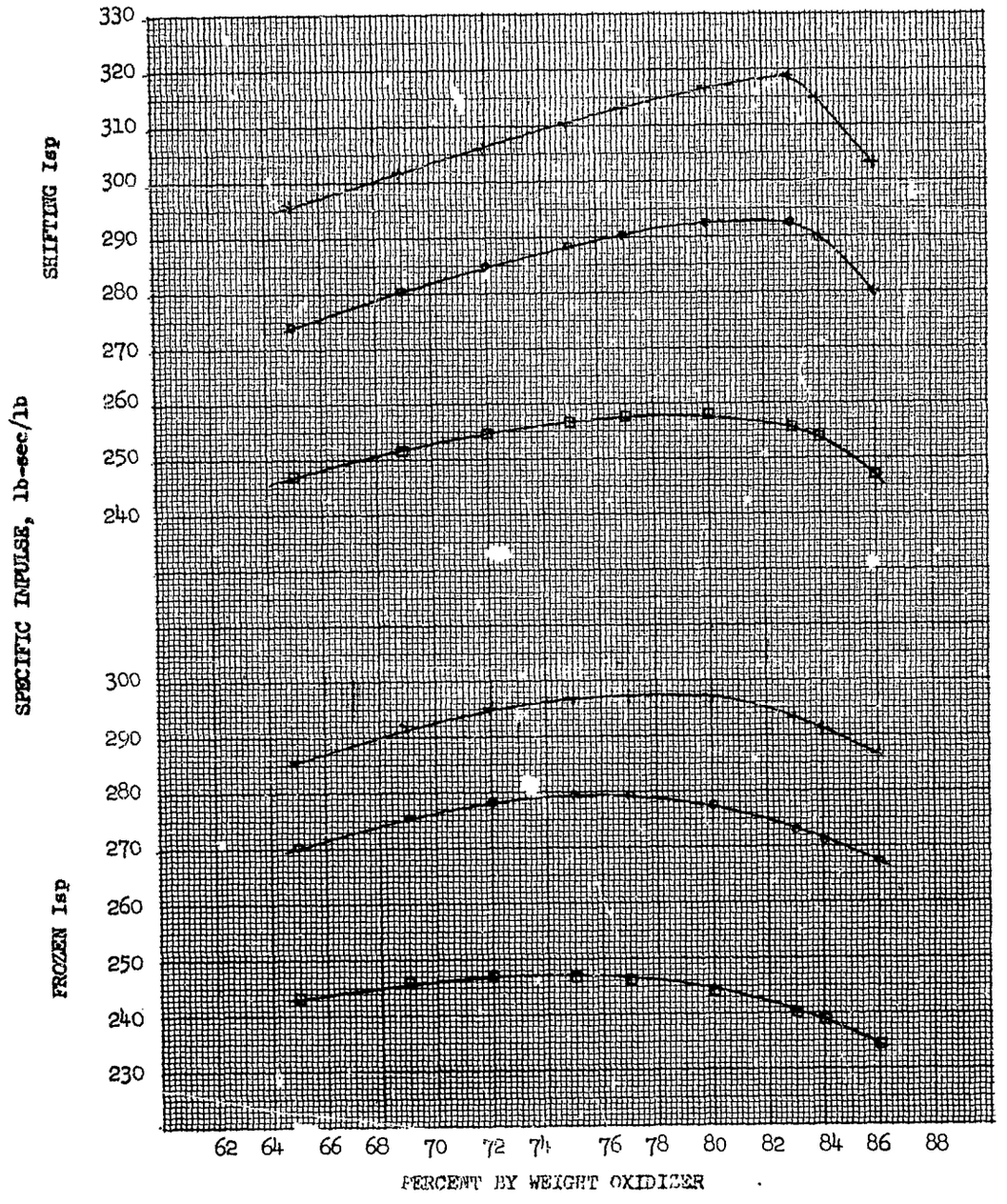
DICYANOACETYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 147



DICYANOACETYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 145

p_c = 1,000 psi

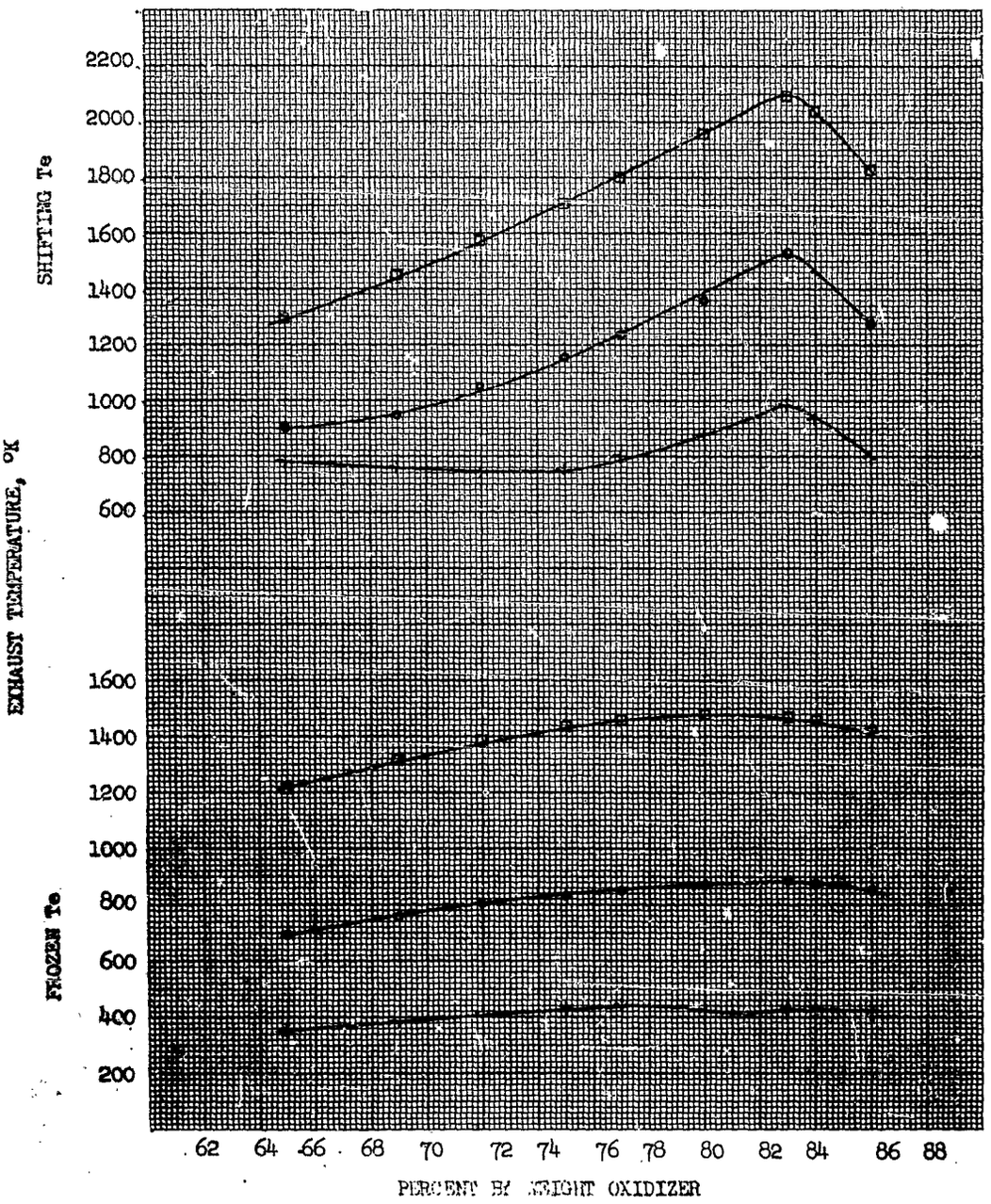
□ p_c/p_e=200 ○ p_c/p_e=500 + p_c/p_e=5000



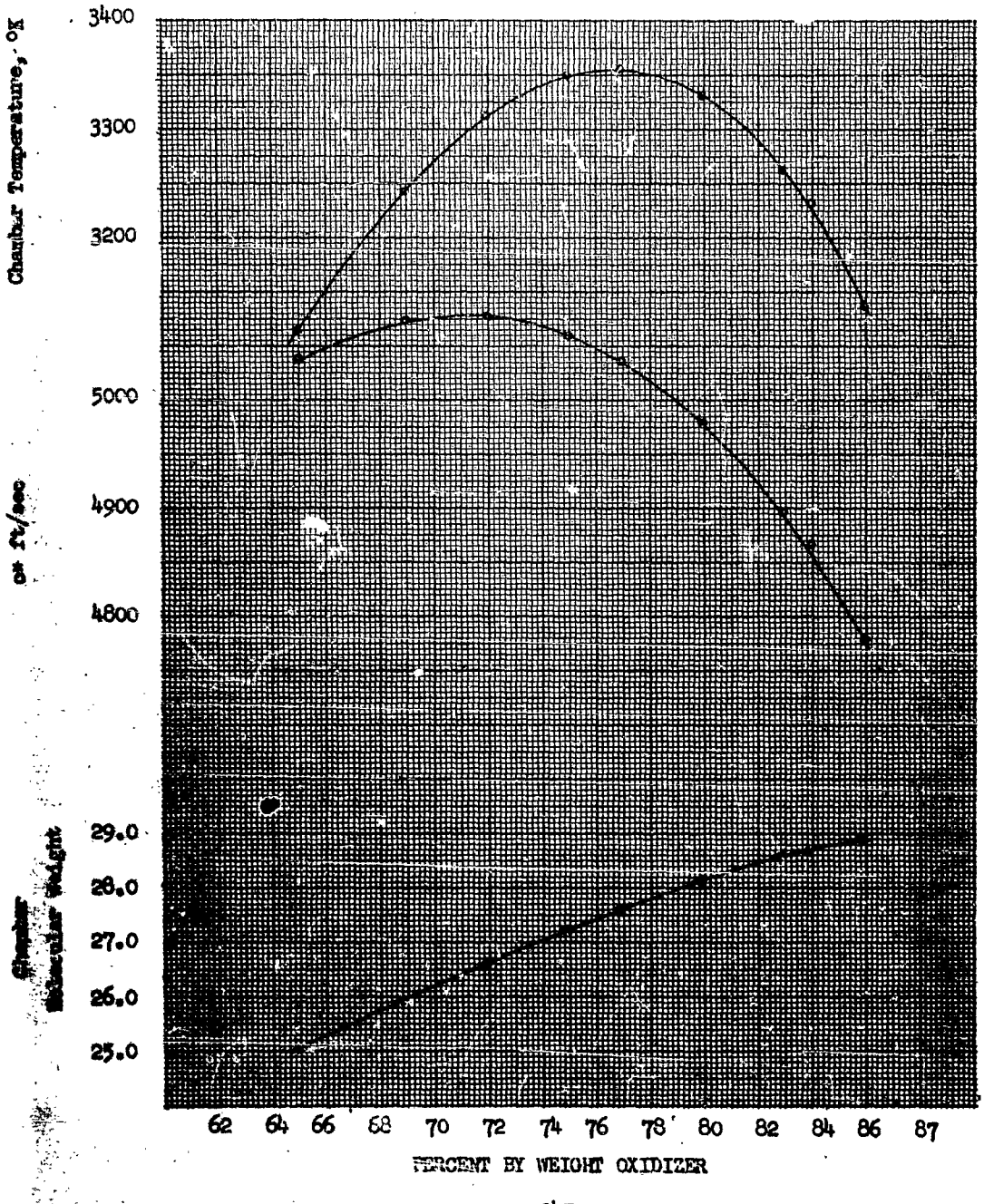
DICYANOACETYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 159

p_c = 1000 psi

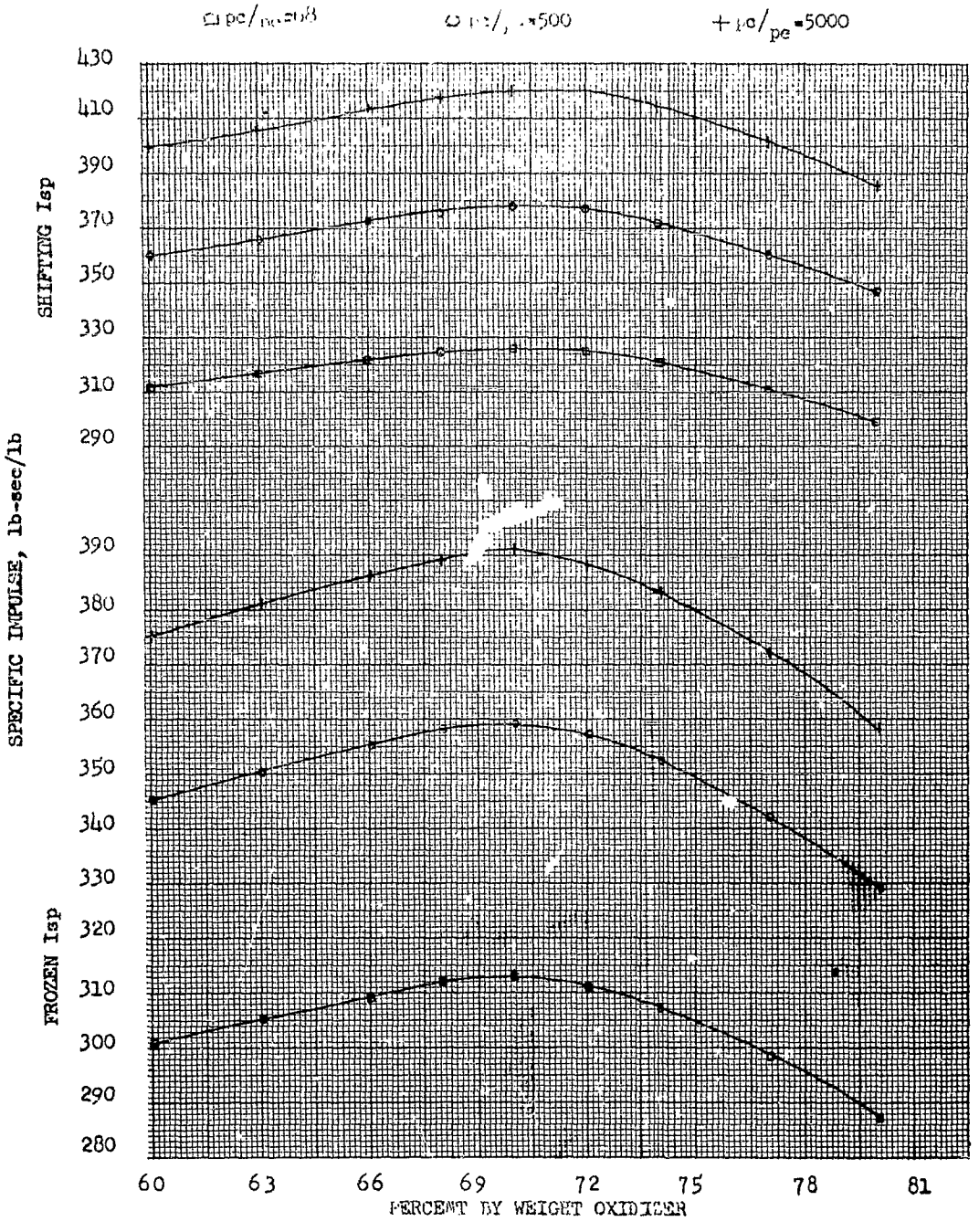
□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



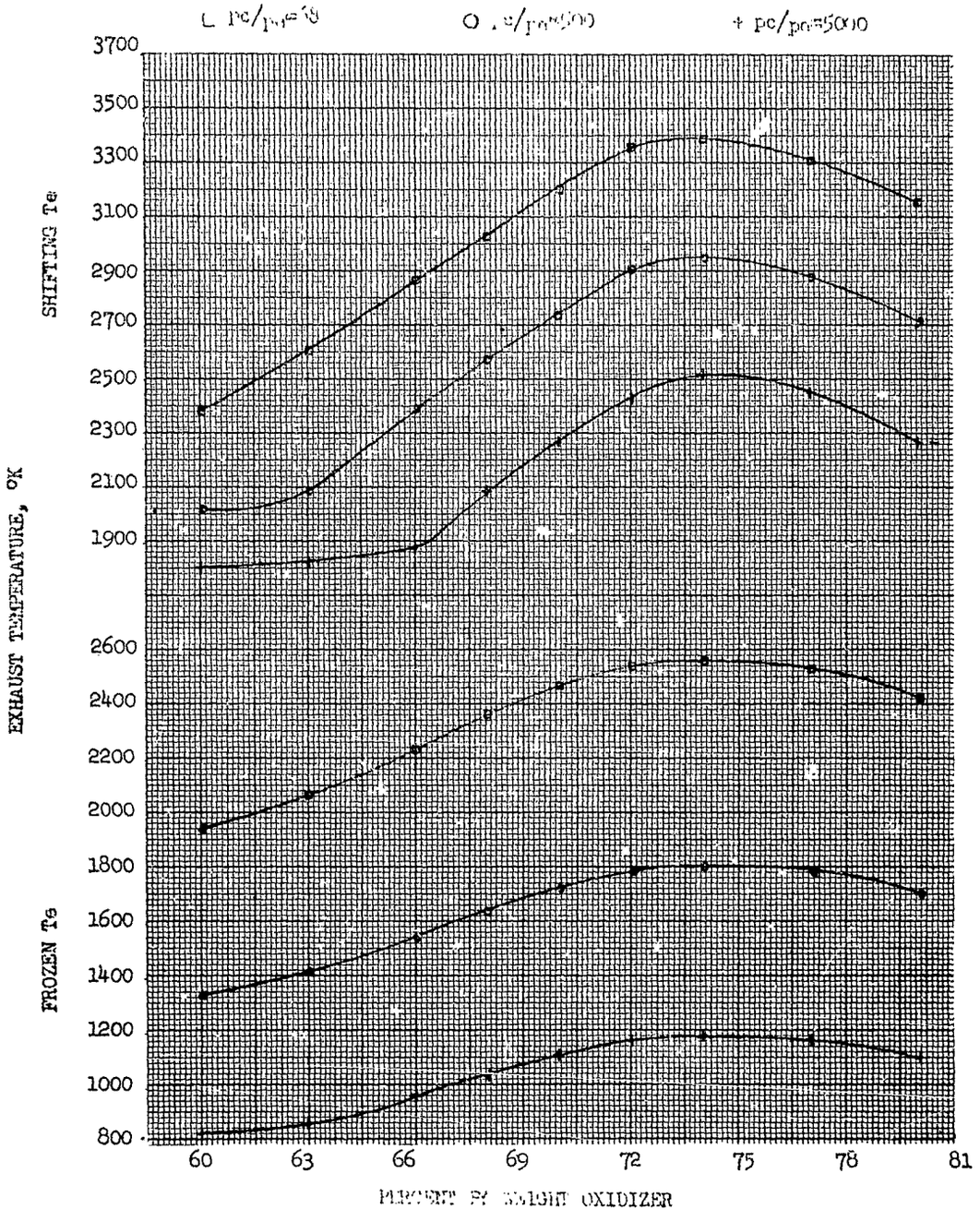
DICYANOACETYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 1.0



PENTAPOHANE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 151

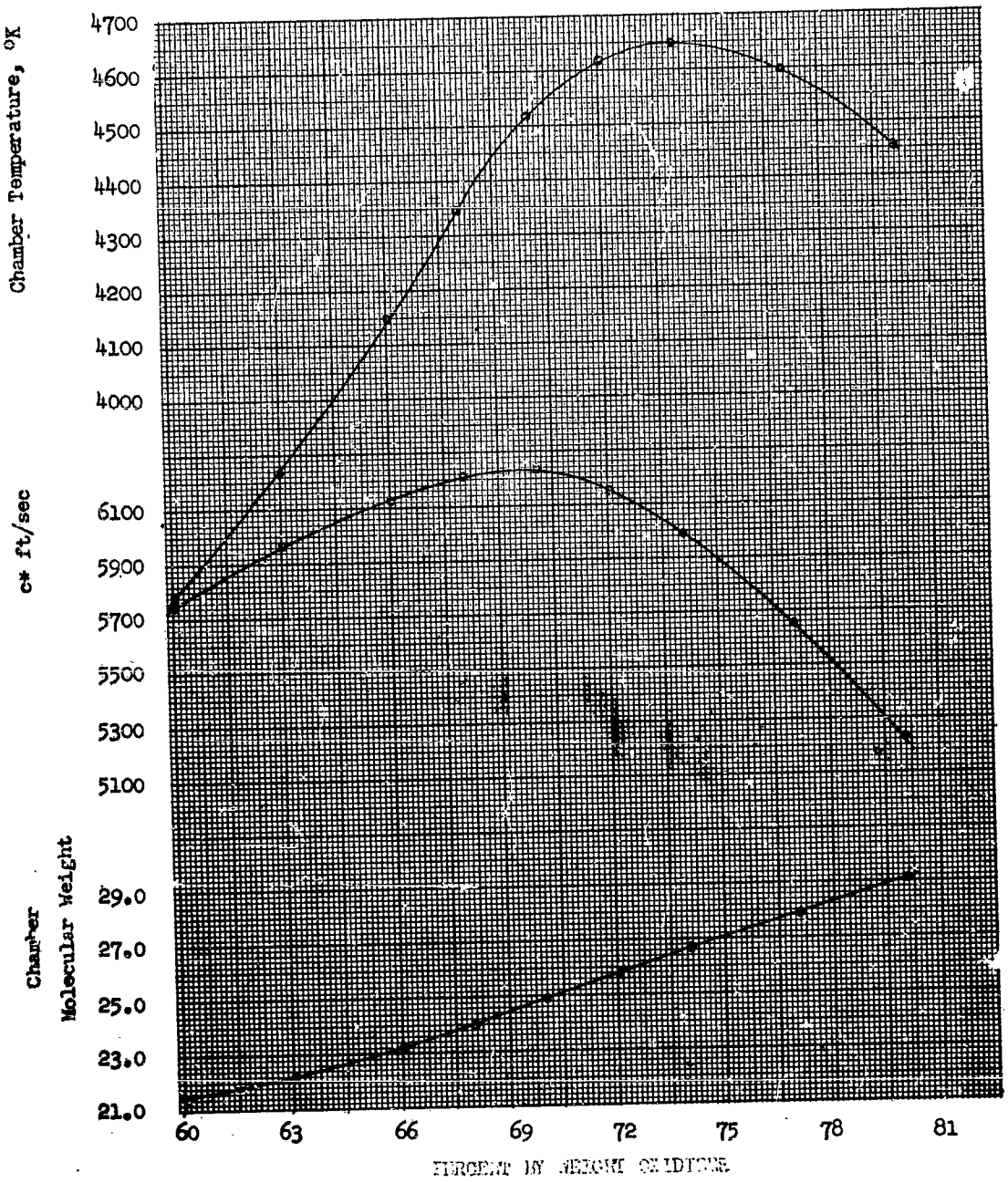


PENTABORANE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 152

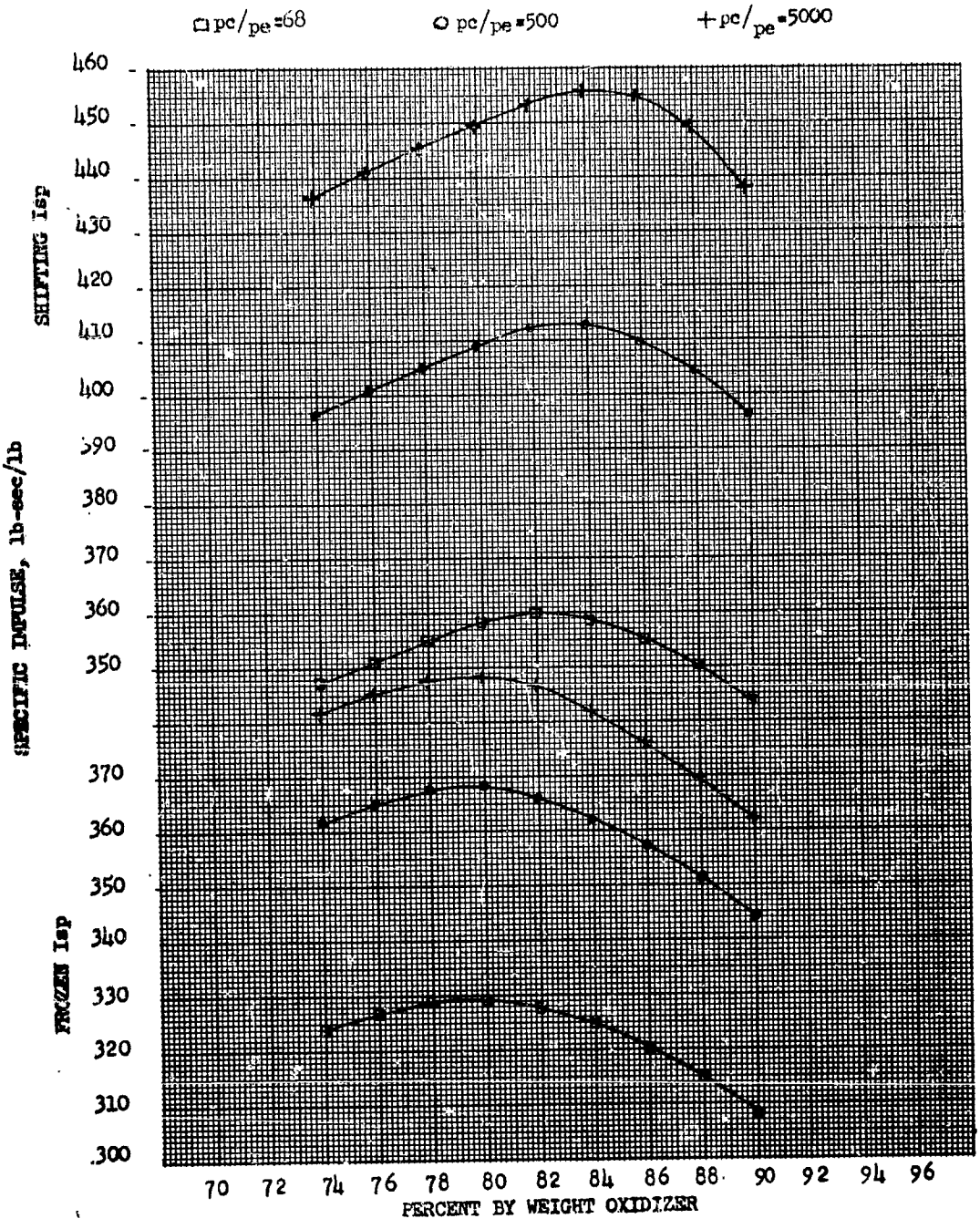


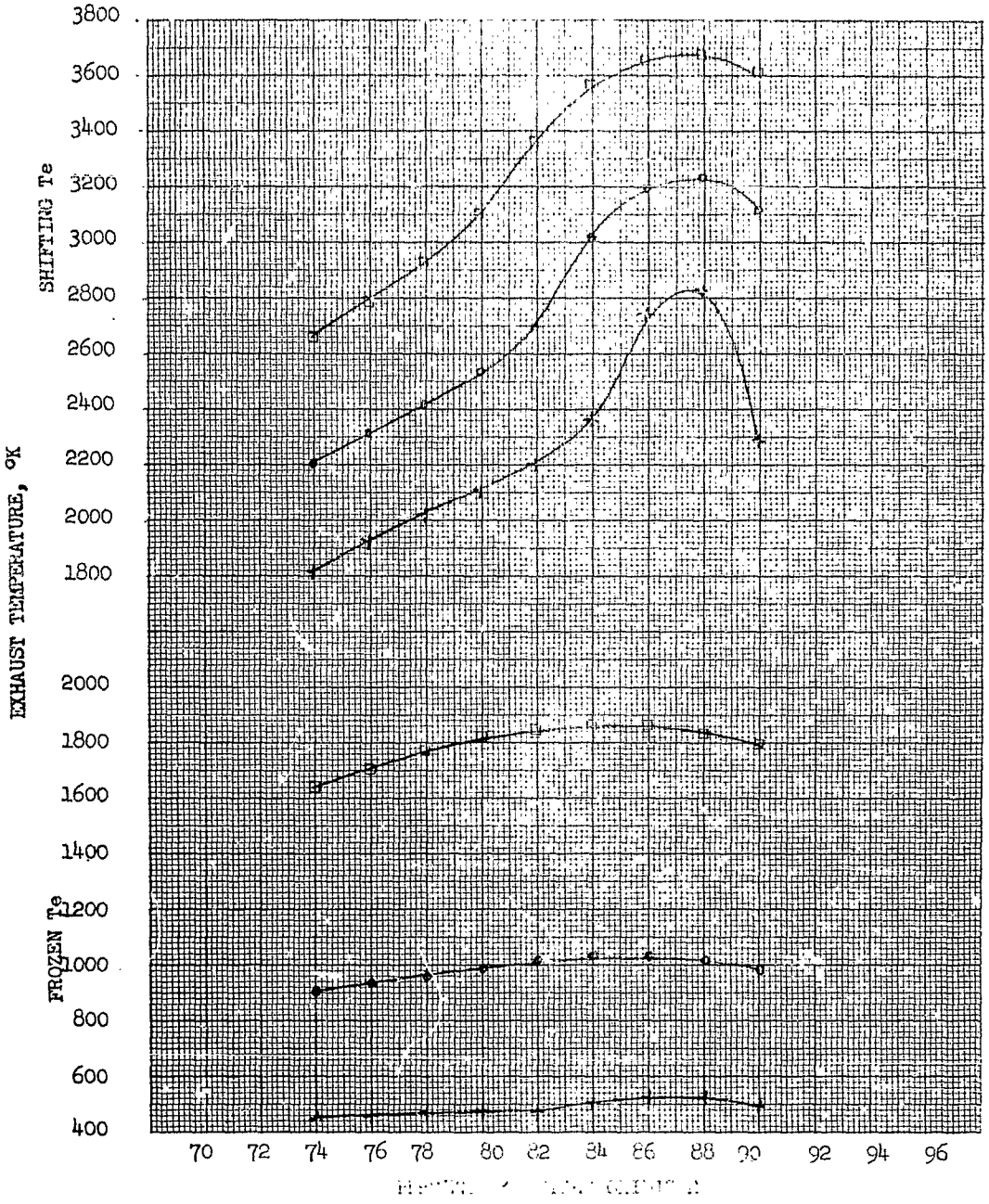
PERCENT BY WEIGHT OXIDIZER

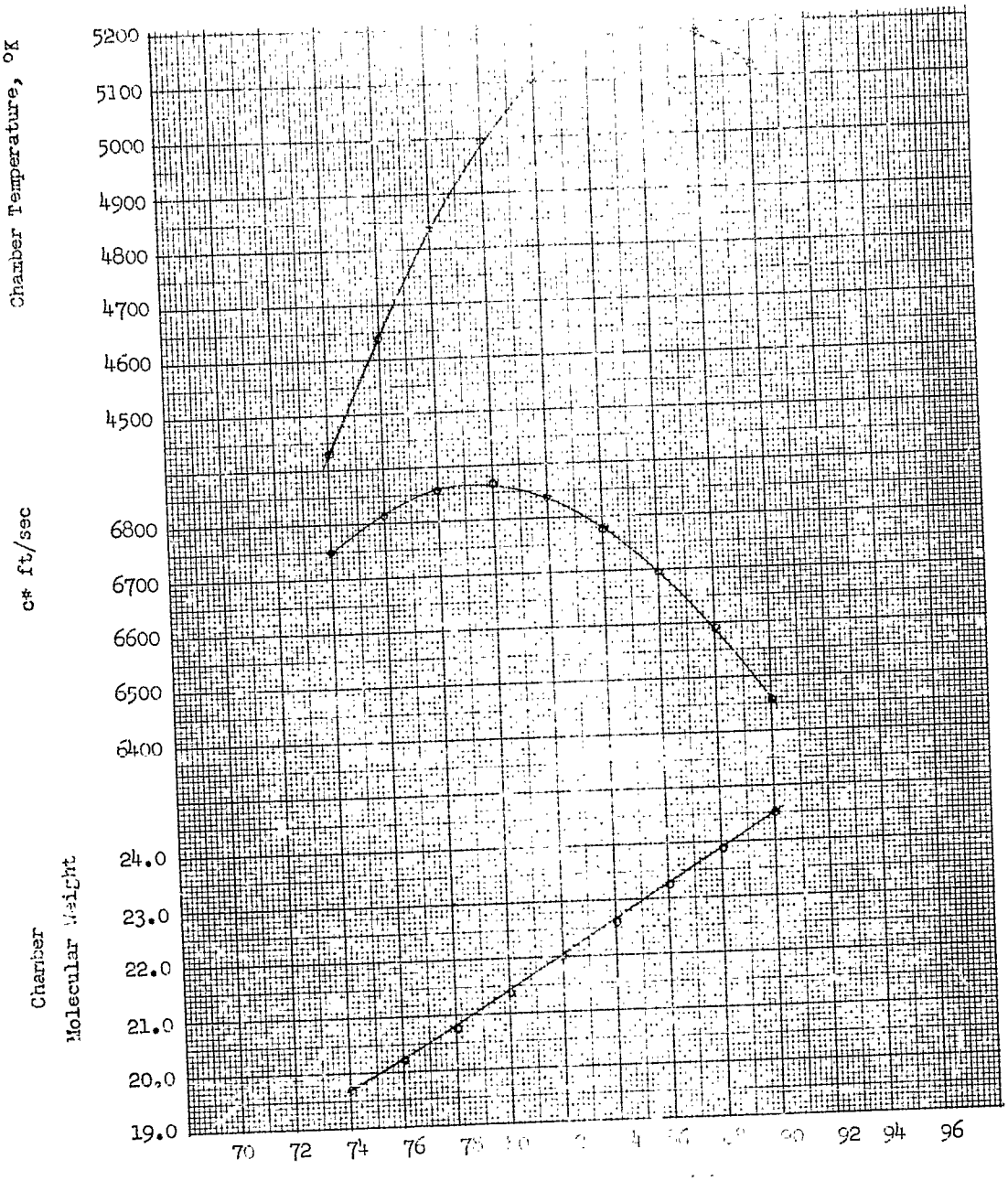
PENTABORANE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 153



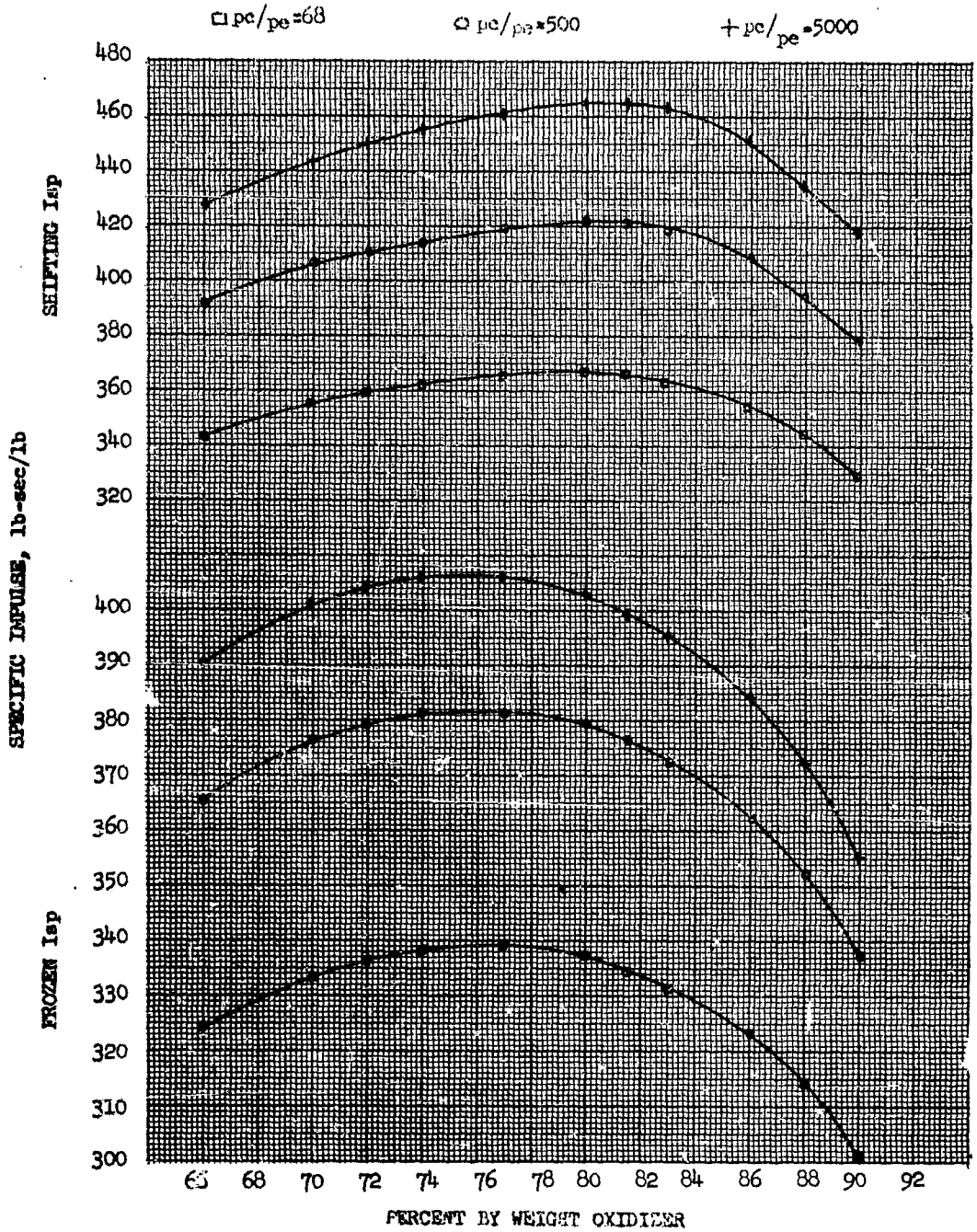
PENTABORANE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 154




EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
2000
1800
1600
1400
1200
1000
800
600
400
70
72
74
76
78
80
82
84
86
88
90
92
94
96


Chamber Temperature, °K
5200
5100
5000
4900
4800
4700
4600
4500
c* ft/sec
6800
6700
6600
6500
6400
Chamber
Molecular Weight
24.0
23.0
22.0
21.0
20.0
19.0
70
72
74
76
92
94
96

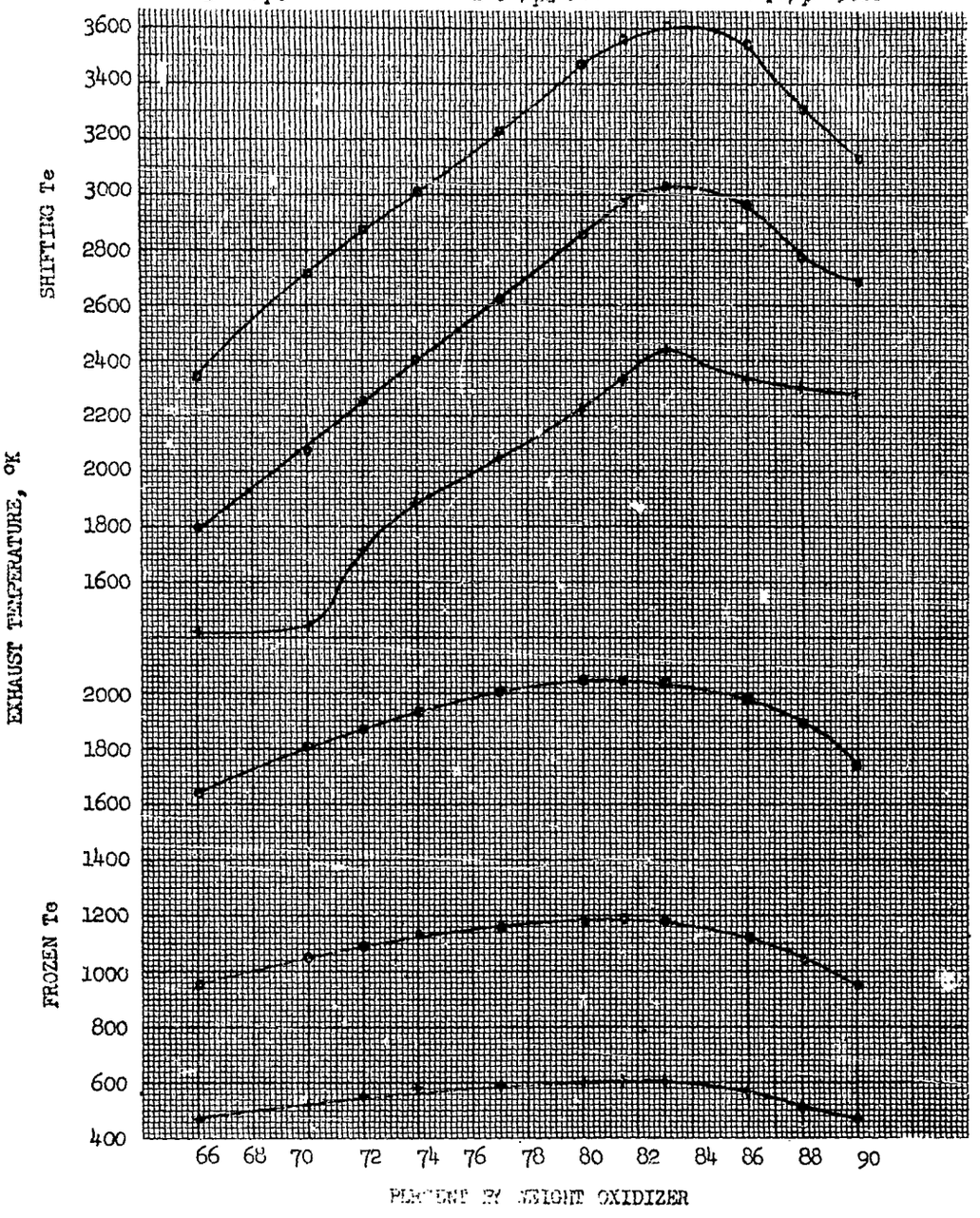
PENTABORANE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 157

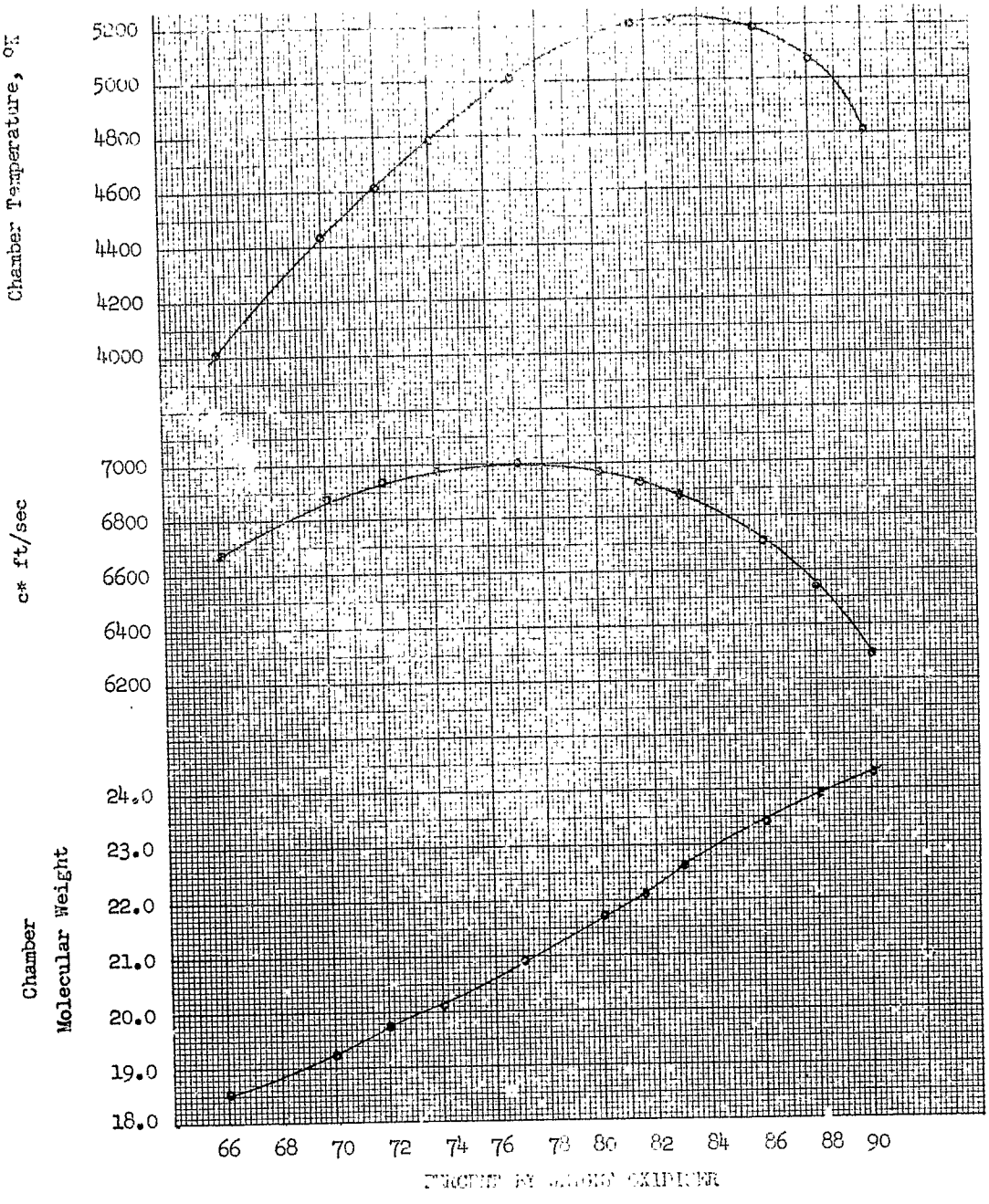


PENTABORANE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 158

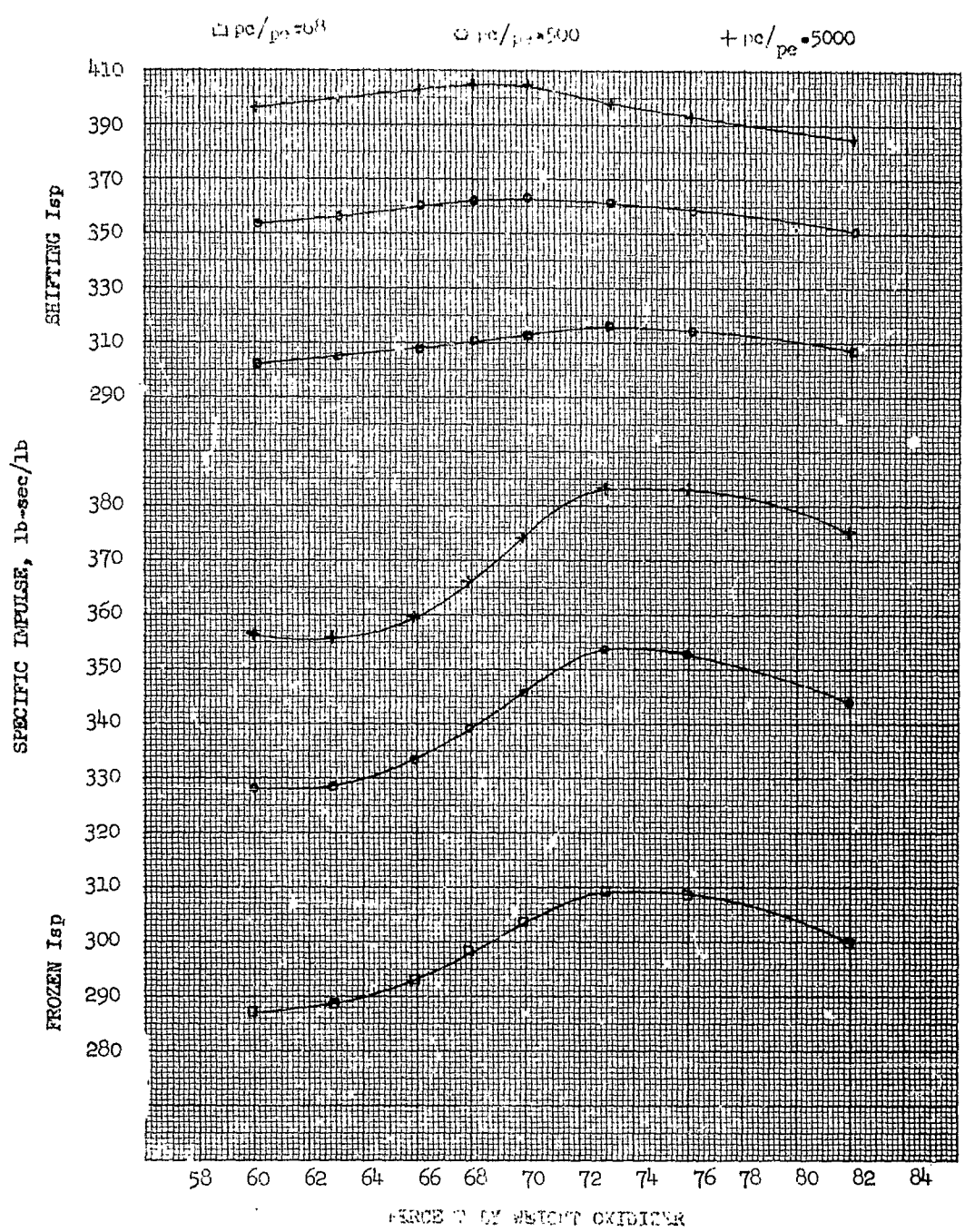
p_c = 1000 psi

L p_c/p_e=68 O p_c/p_e=500 + p_c/p_e=5000



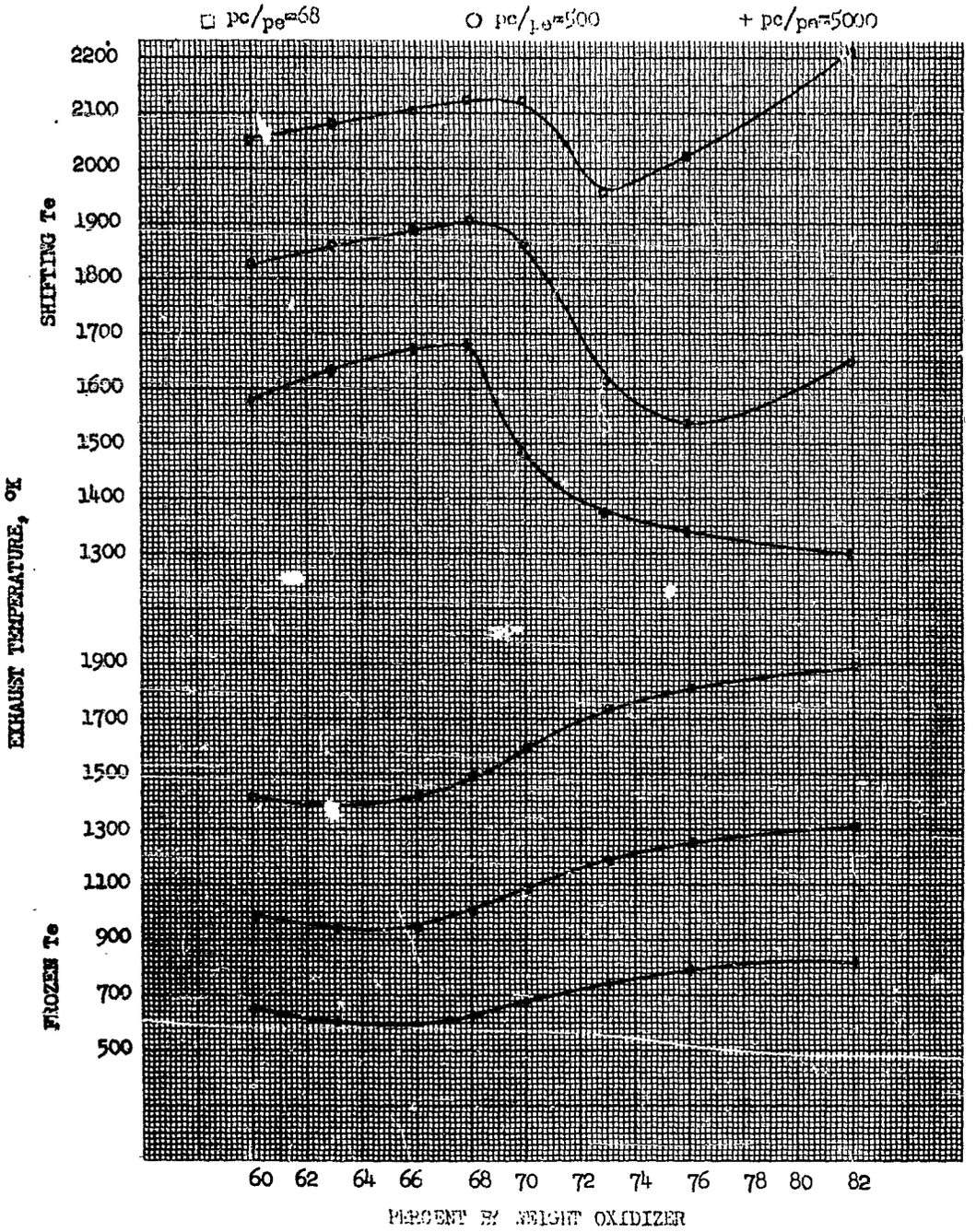

Chamber Temperature, °R
5200
5000
4800
4600
4400
4200
4000
c* ft/sec
7000
6800
6600
6400
6200
Chamber Molecular Weight
24.0
23.0
22.0
21.0
20.0
19.0
18.0
66
68
70
72
74
76
78
80
82
84
86
88
90

PENTABORANE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 160

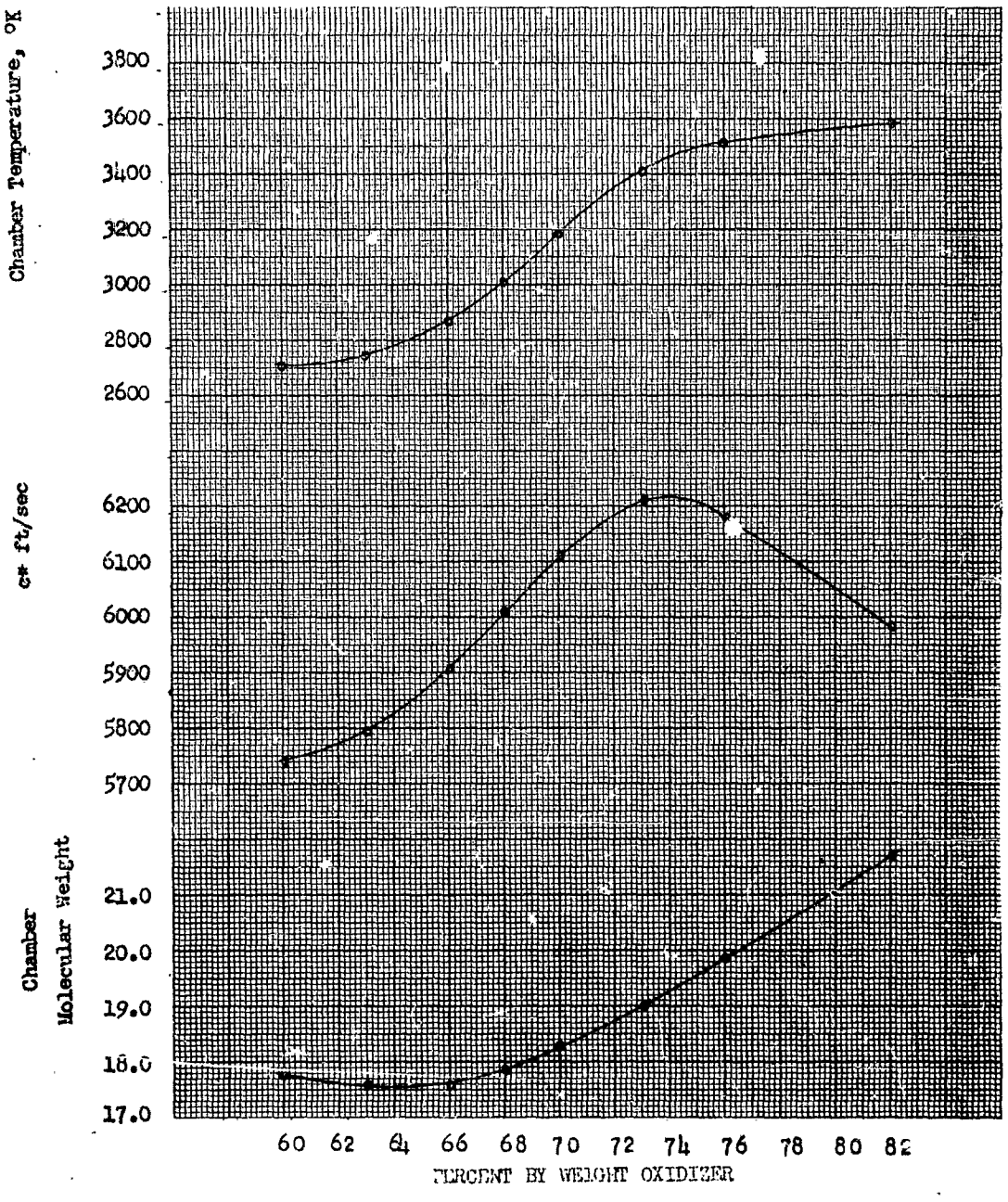


PENTABORANE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 161

p_c = 1000 psi



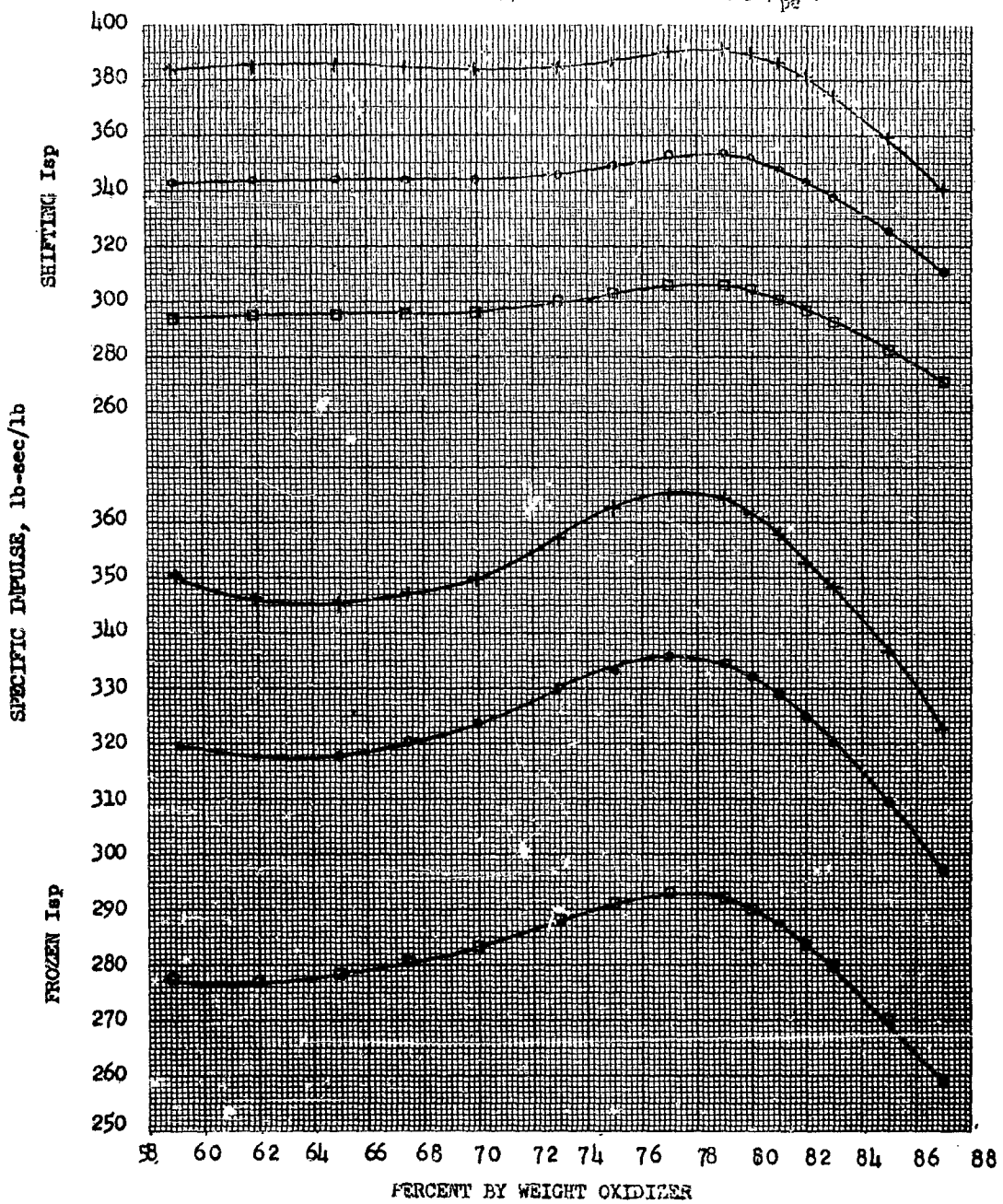
PENTABORANE -- HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 1-2



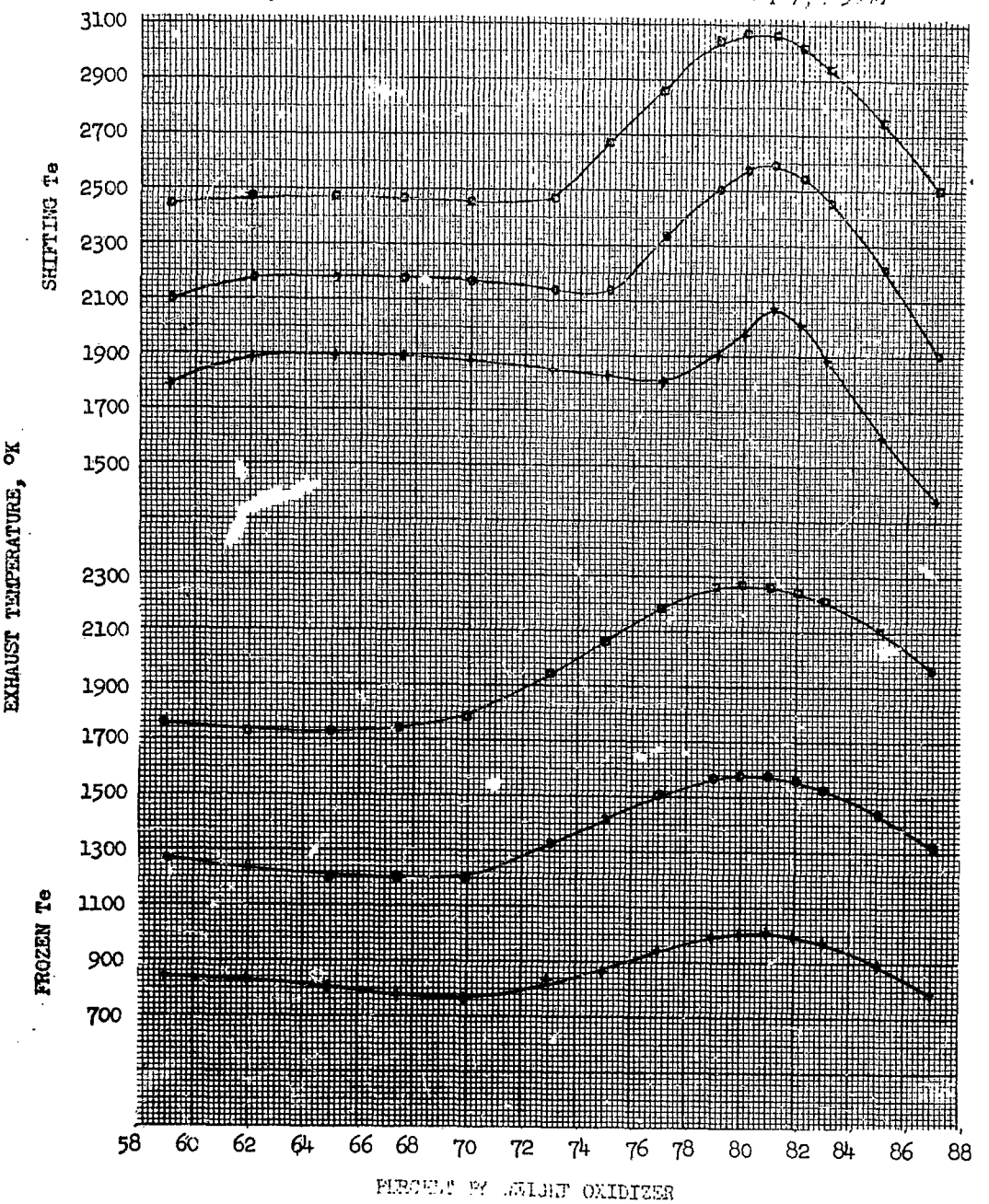
PENTABORANE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 163

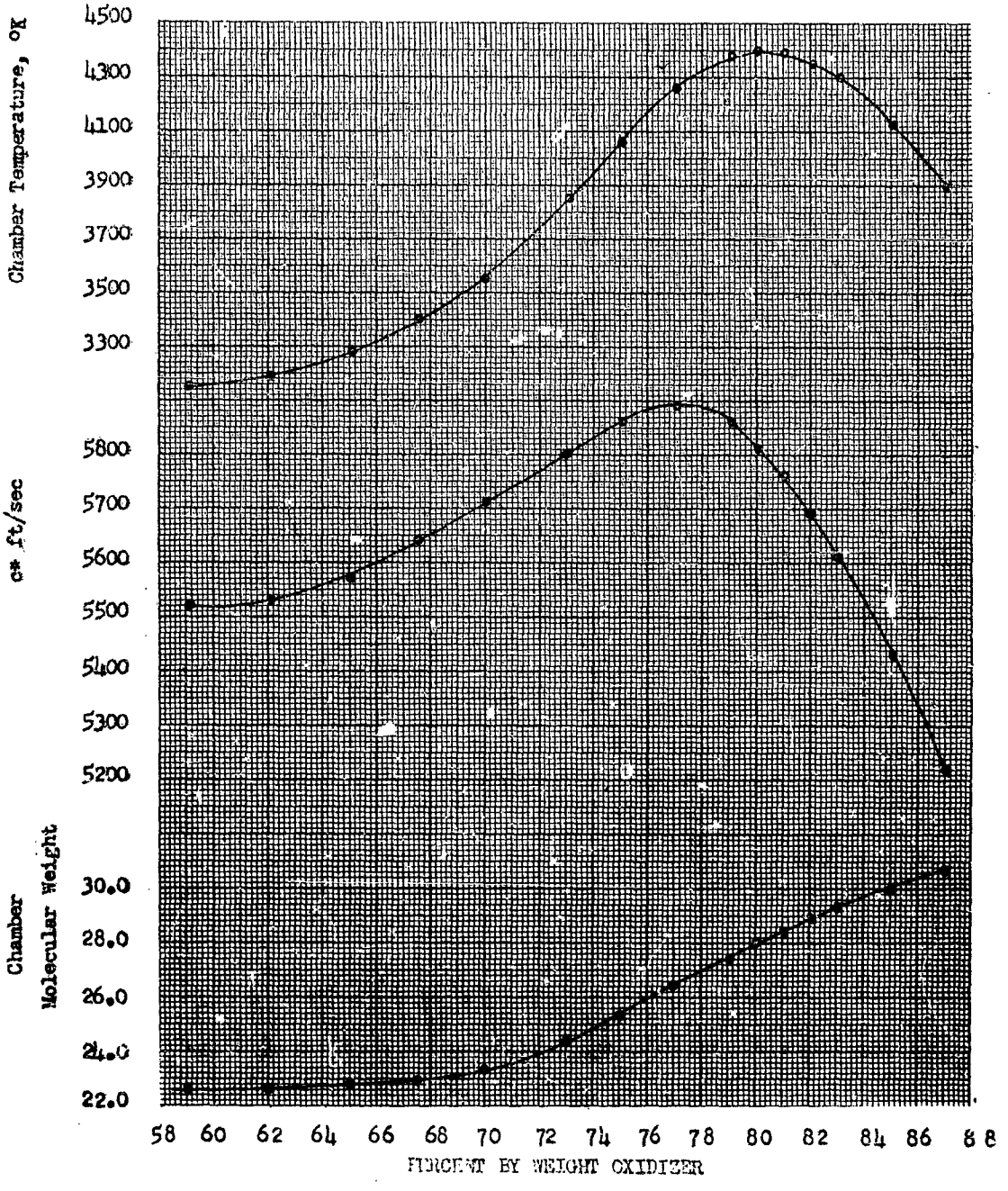
p_c = 1000 psi

□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



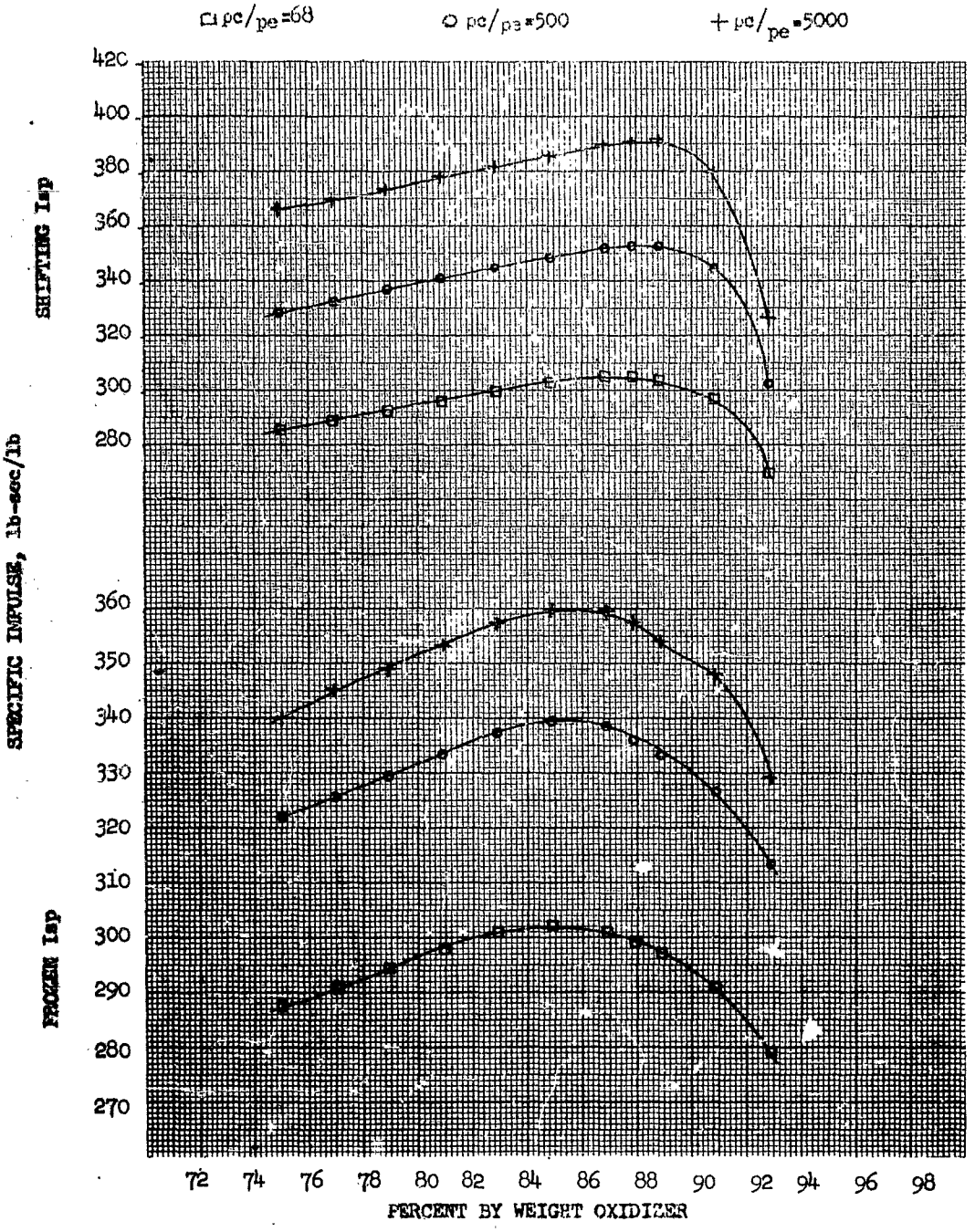
PENTABORANE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 104



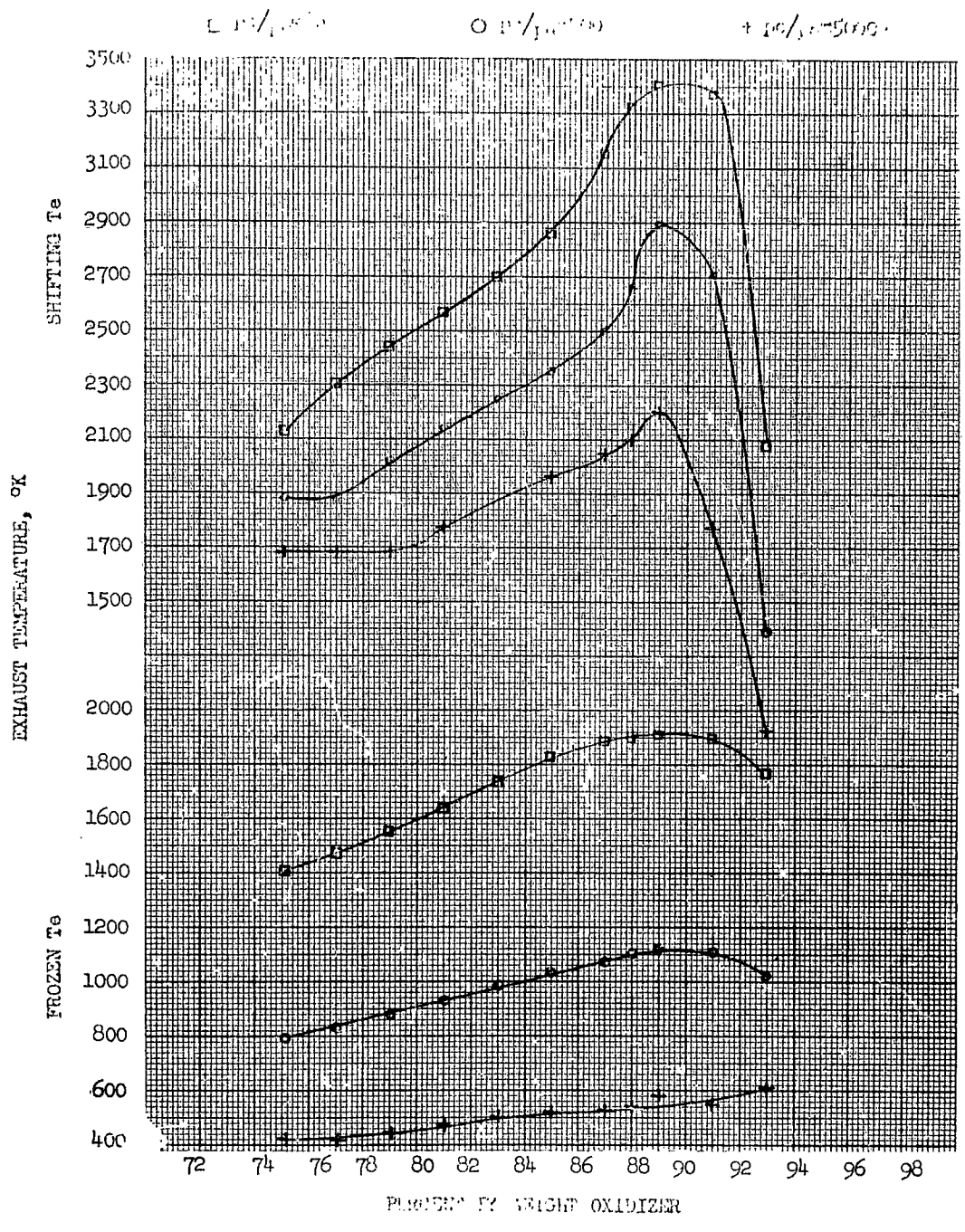

Chamber Temperature, °K
4500
4300
4100
3900
3700
3500
3300
c* ft/sec
5800
5700
5600
5500
5400
5300
5200
Chamber Molecular Weight
30.0
28.0
26.0
24.0
22.0
58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88
PERCENT BY WEIGHT OXIDIZER

PENTABORANE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 166

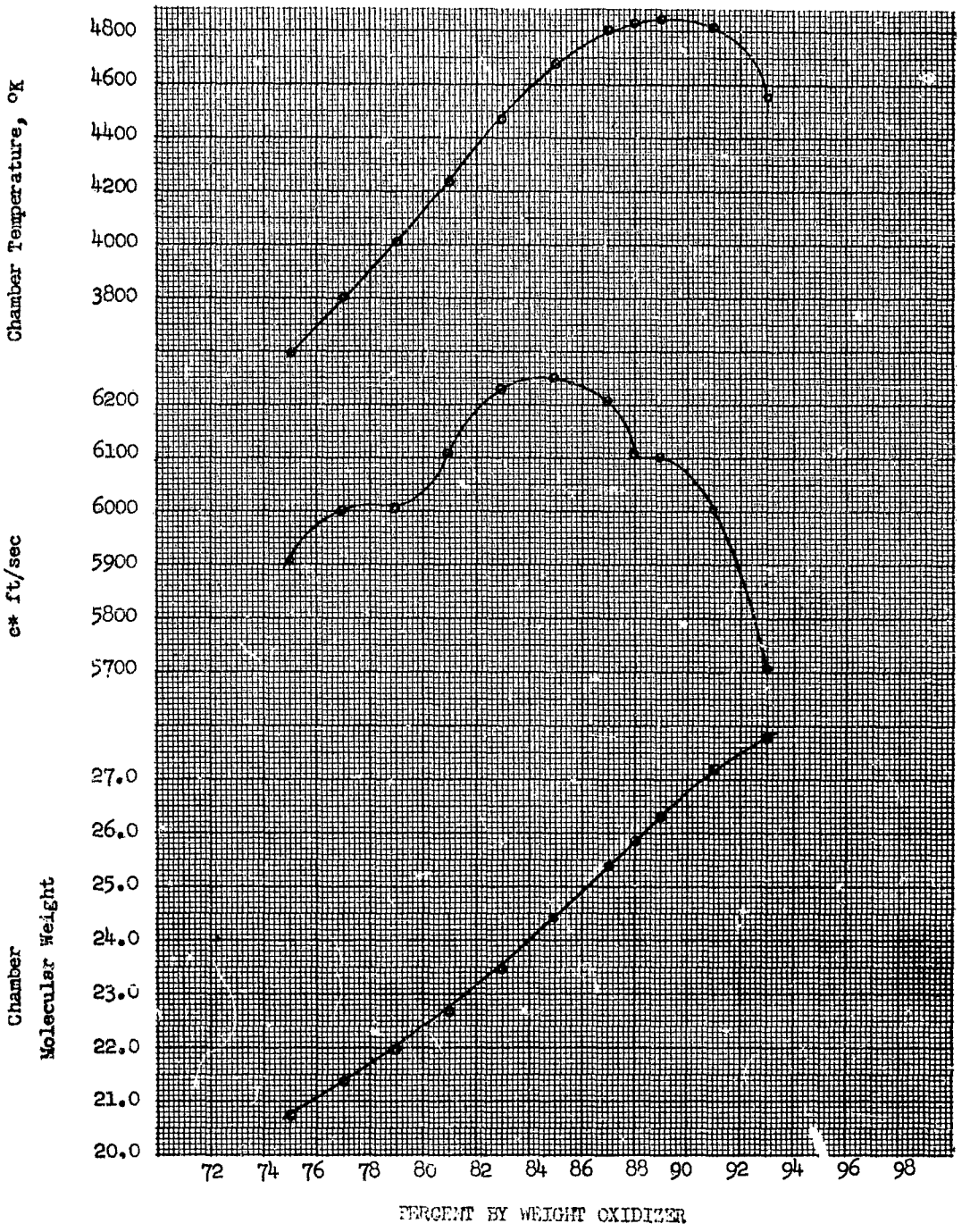
p_c = 1000 psi



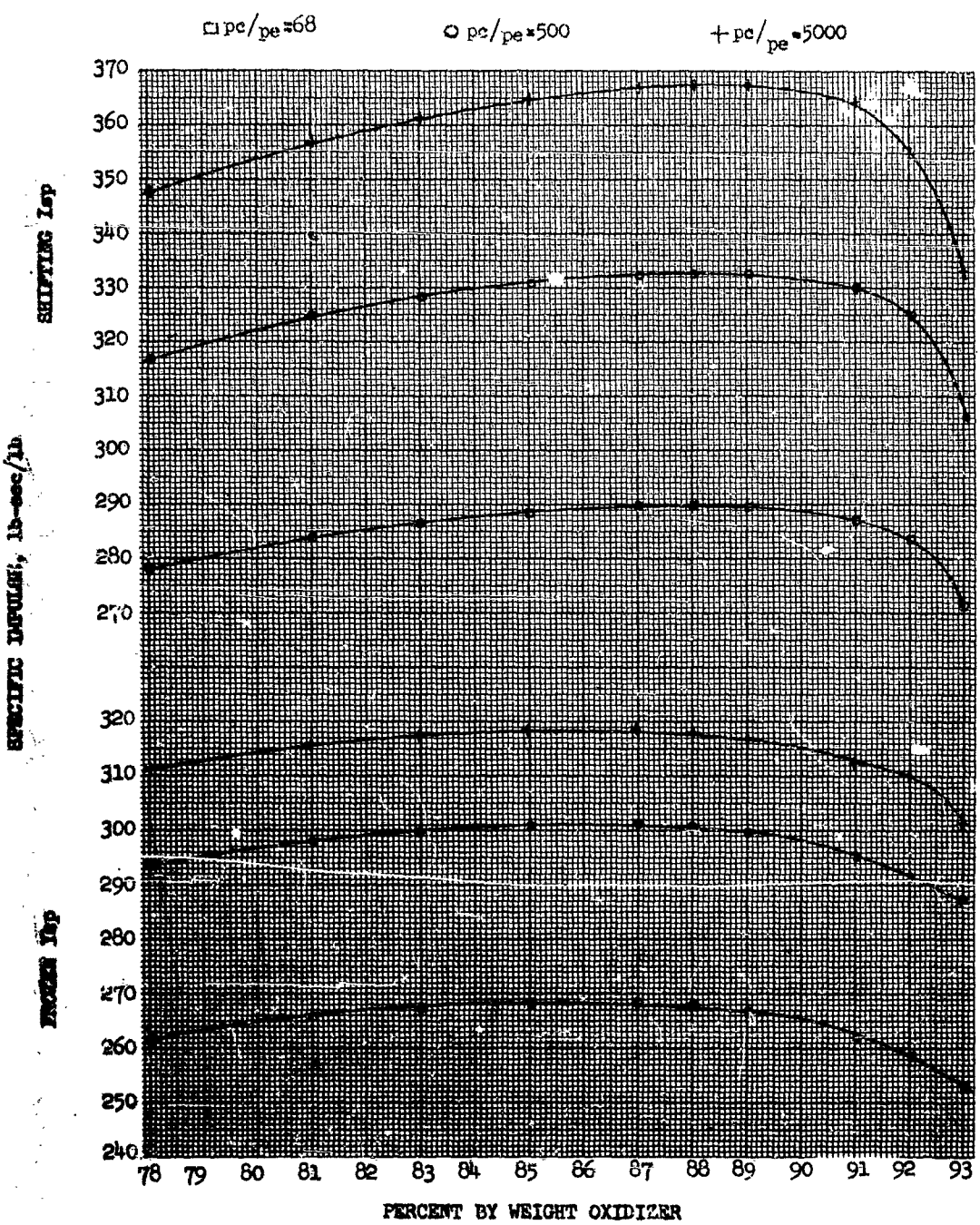
PENTABORANE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 167



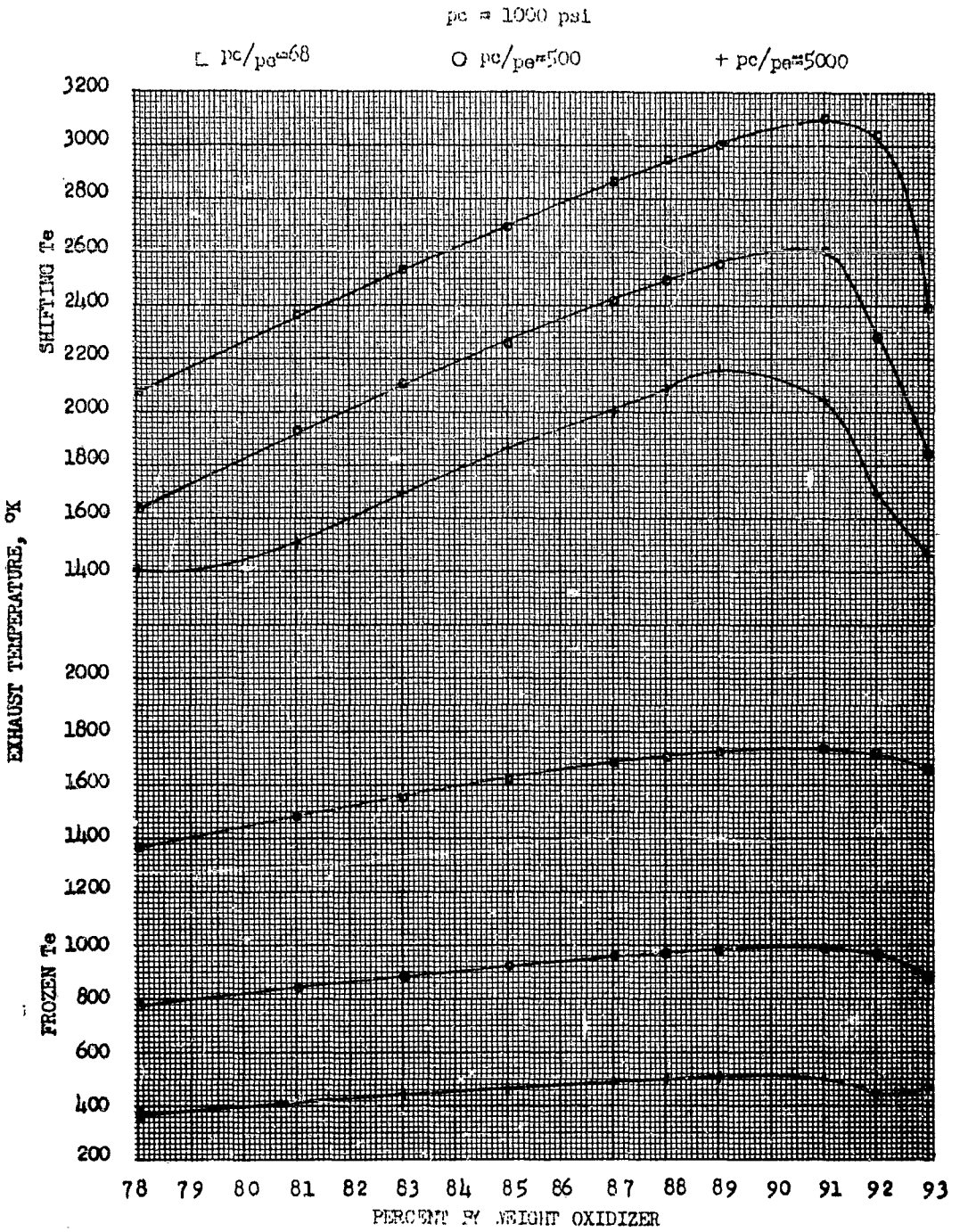
PENTABORANE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 168



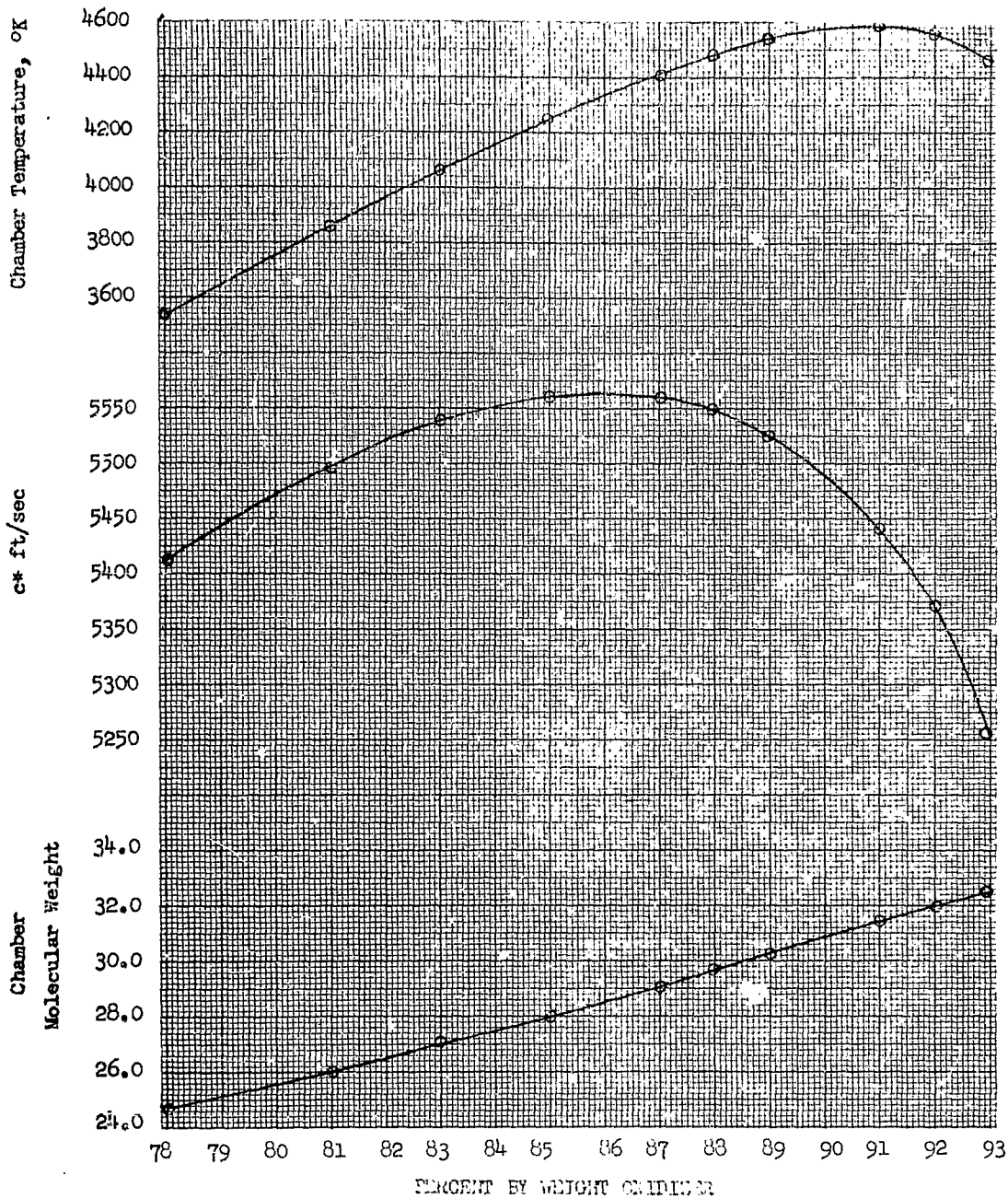
PENTABORANE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 169

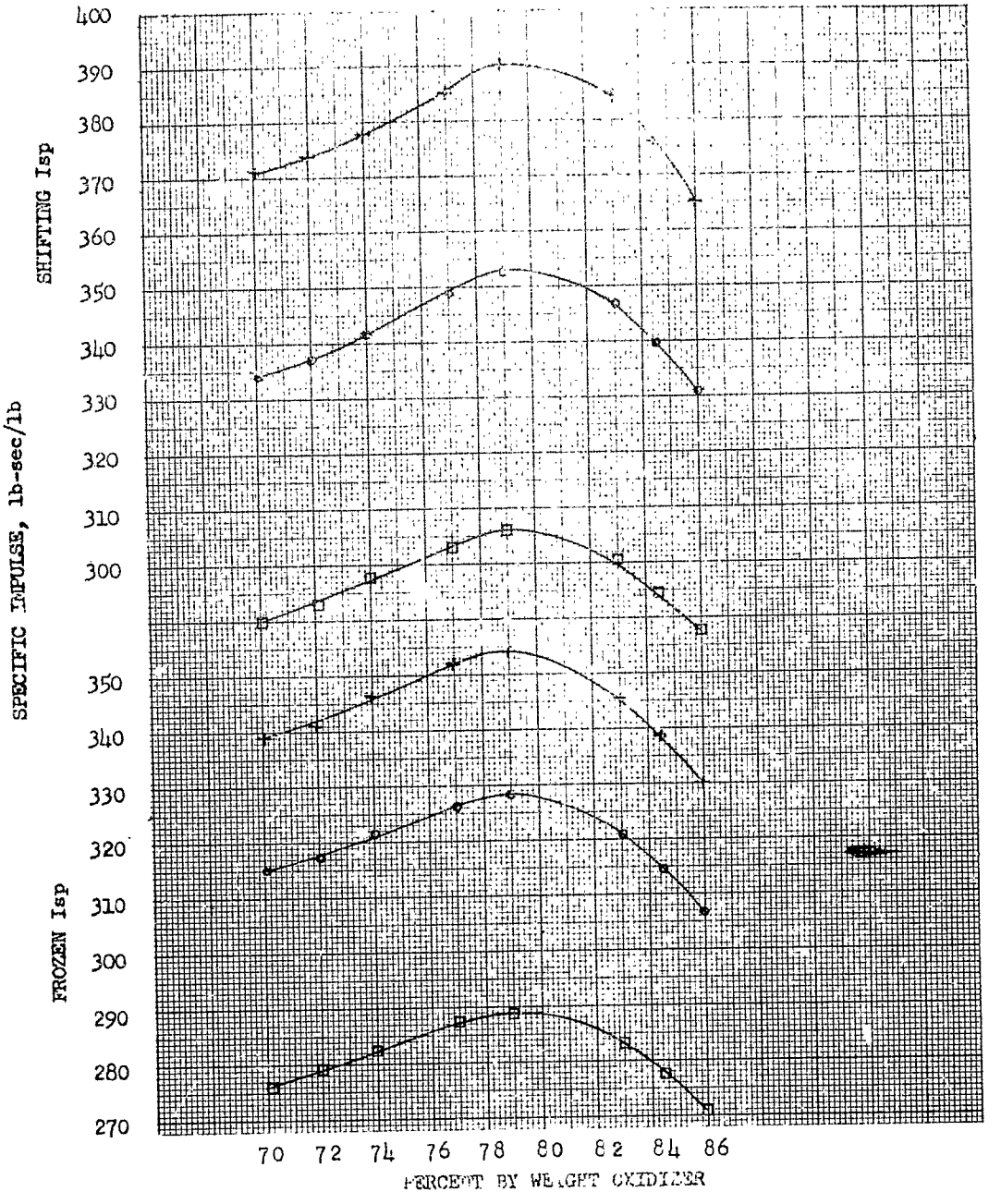


PENTABORANE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 170



PENTABORANE - CHLORINE TRIFLUORIDE [illegible] FIGURE 171

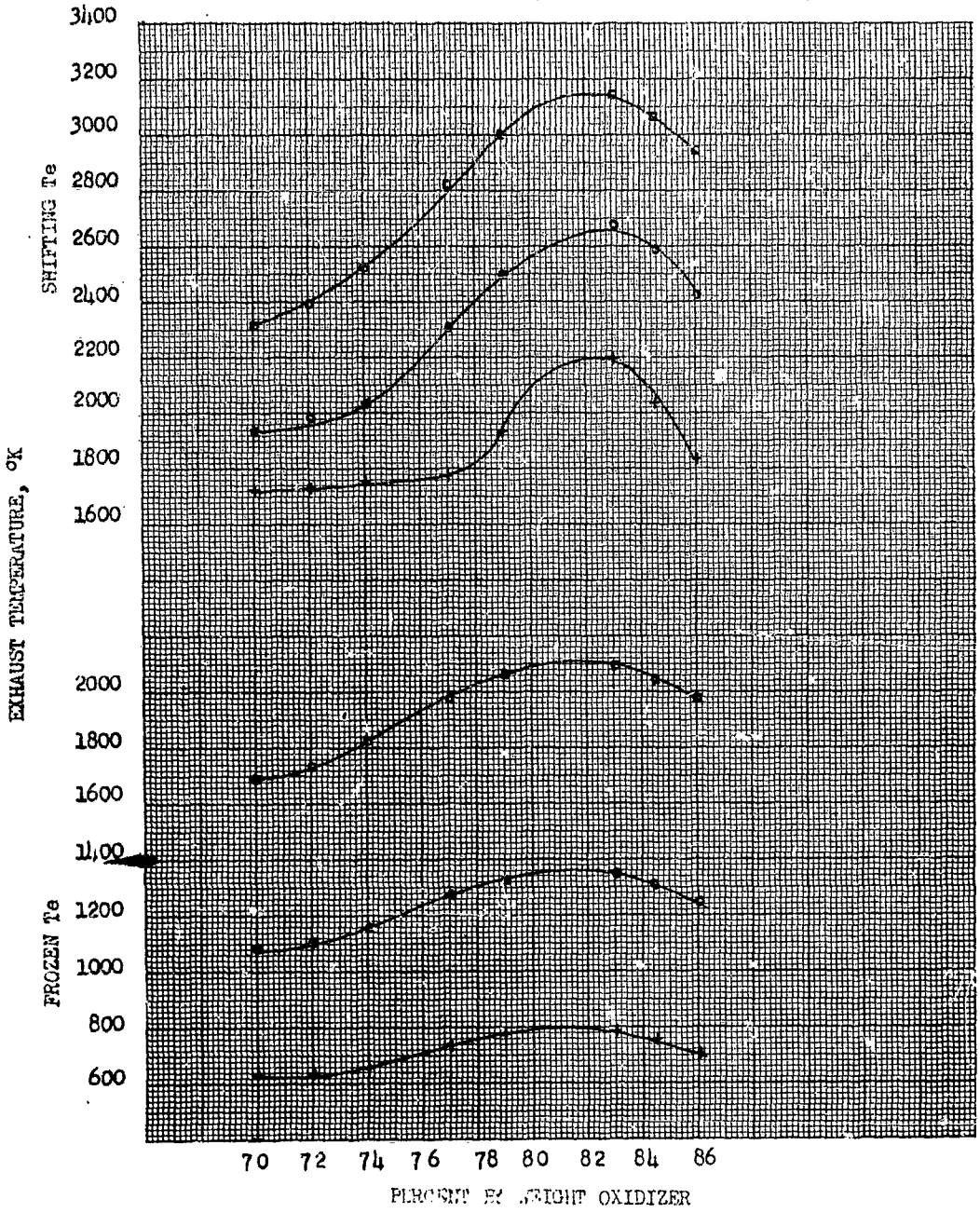


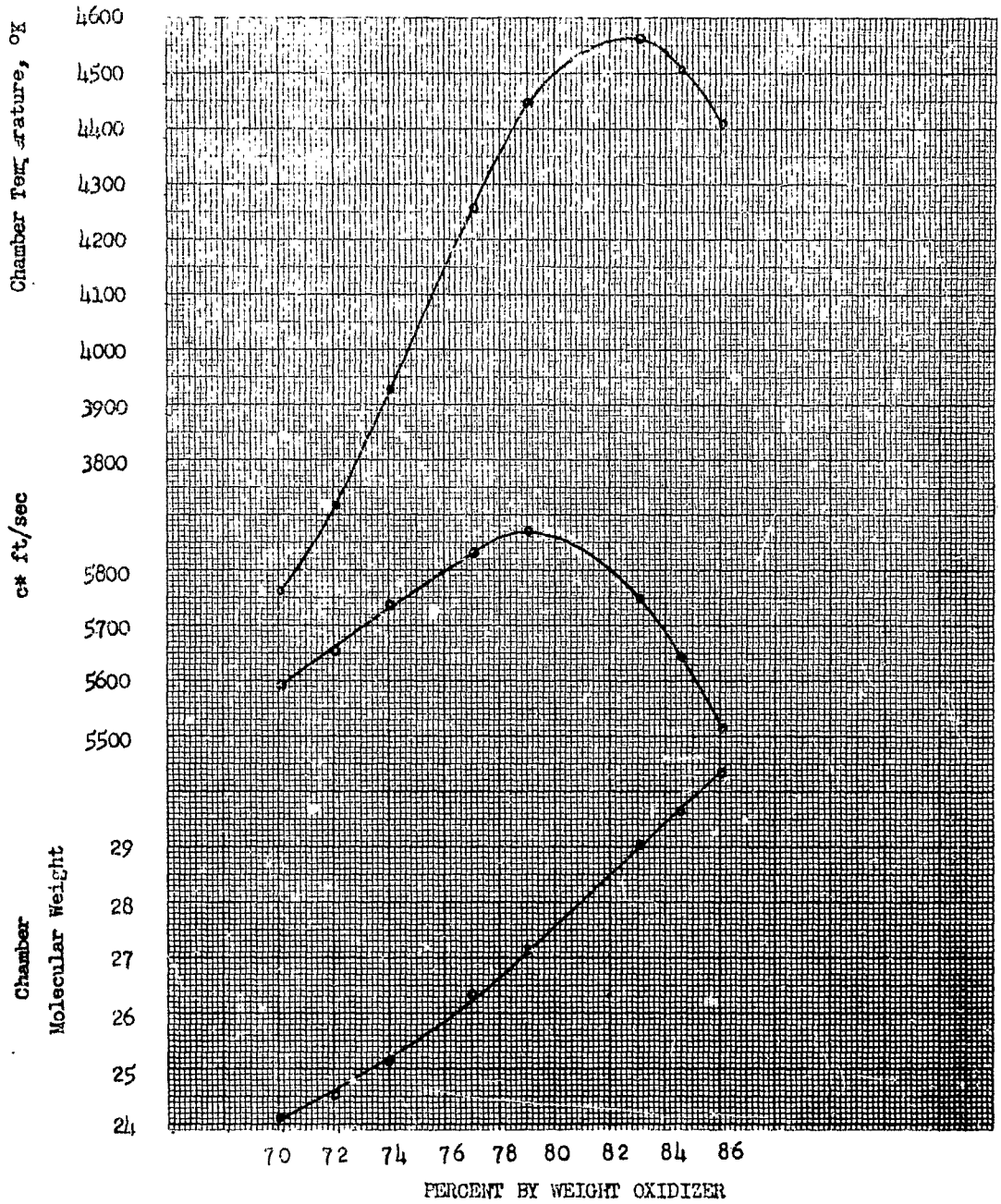

SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
400
390
380
370
360
350
340
330
320
310
300
350
340
330
320
310
300
290
280
270
70 72 74 76 78 80 82 84 86
PERCENT BY WEIGHT OXIDIZER

PENTABORANE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 173

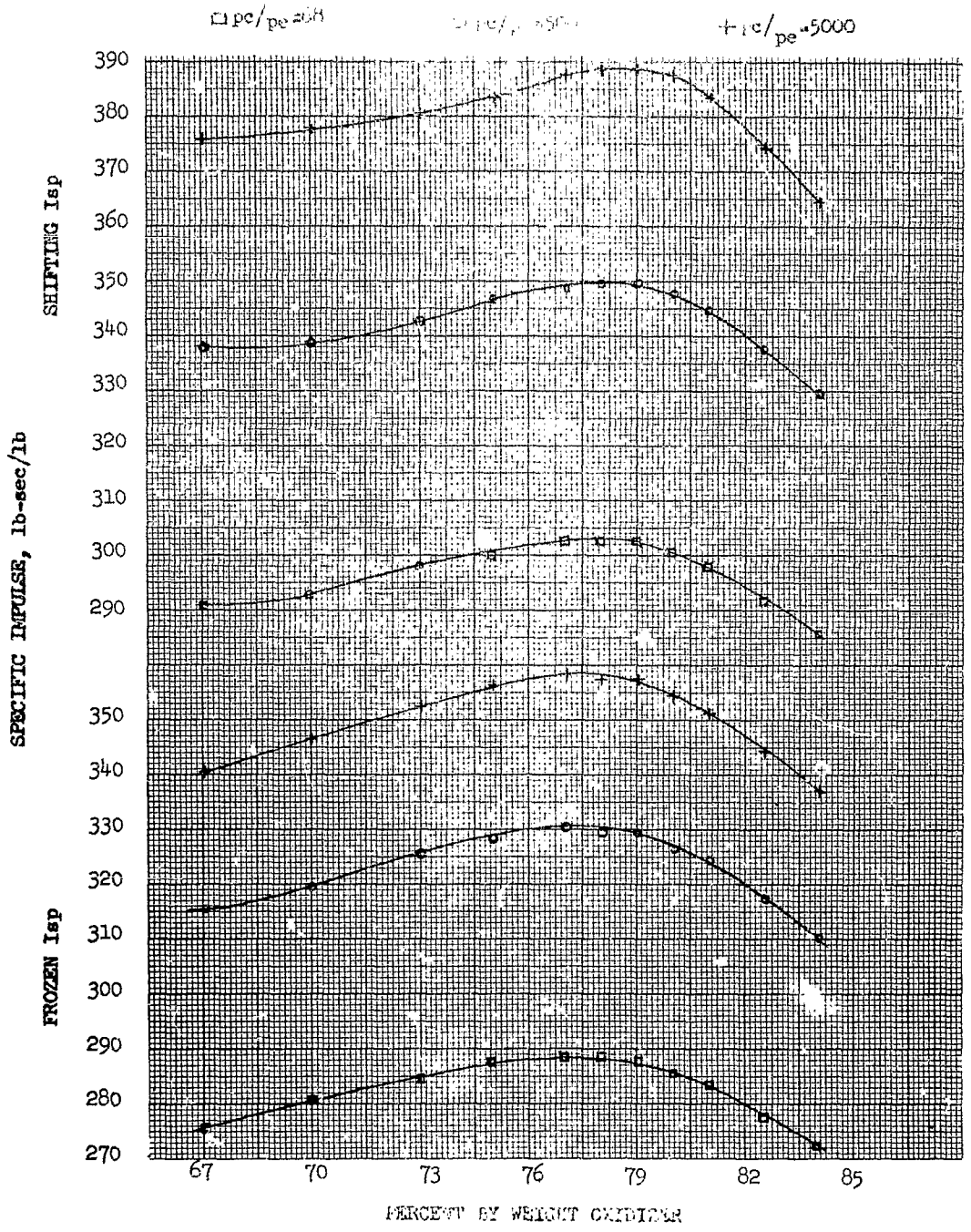
p_c = 1000 psi

Δ p_c/p_e=68 O p_c/p_e=500 + p_c/p_e=5000

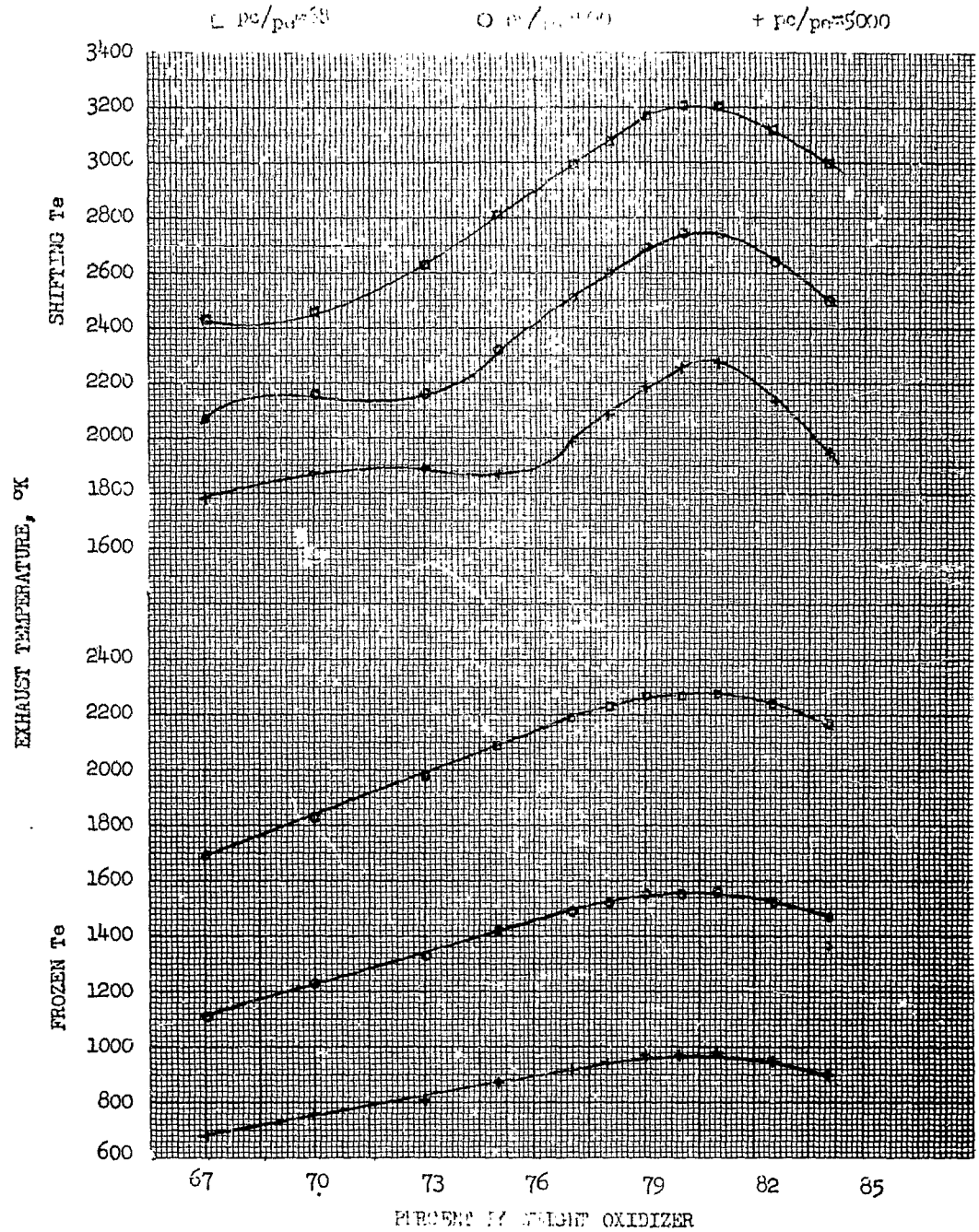



Chamber Temperature, °K
4600
4500
4400
4300
4200
4100
4000
3900
3800
c* ft/sec
5800
5700
5600
5500
Chamber Molecular Weight
29
28
27
26
25
24
70 72 74 76 78 80 82 84 86
PERCENT BY WEIGHT OXIDIZER

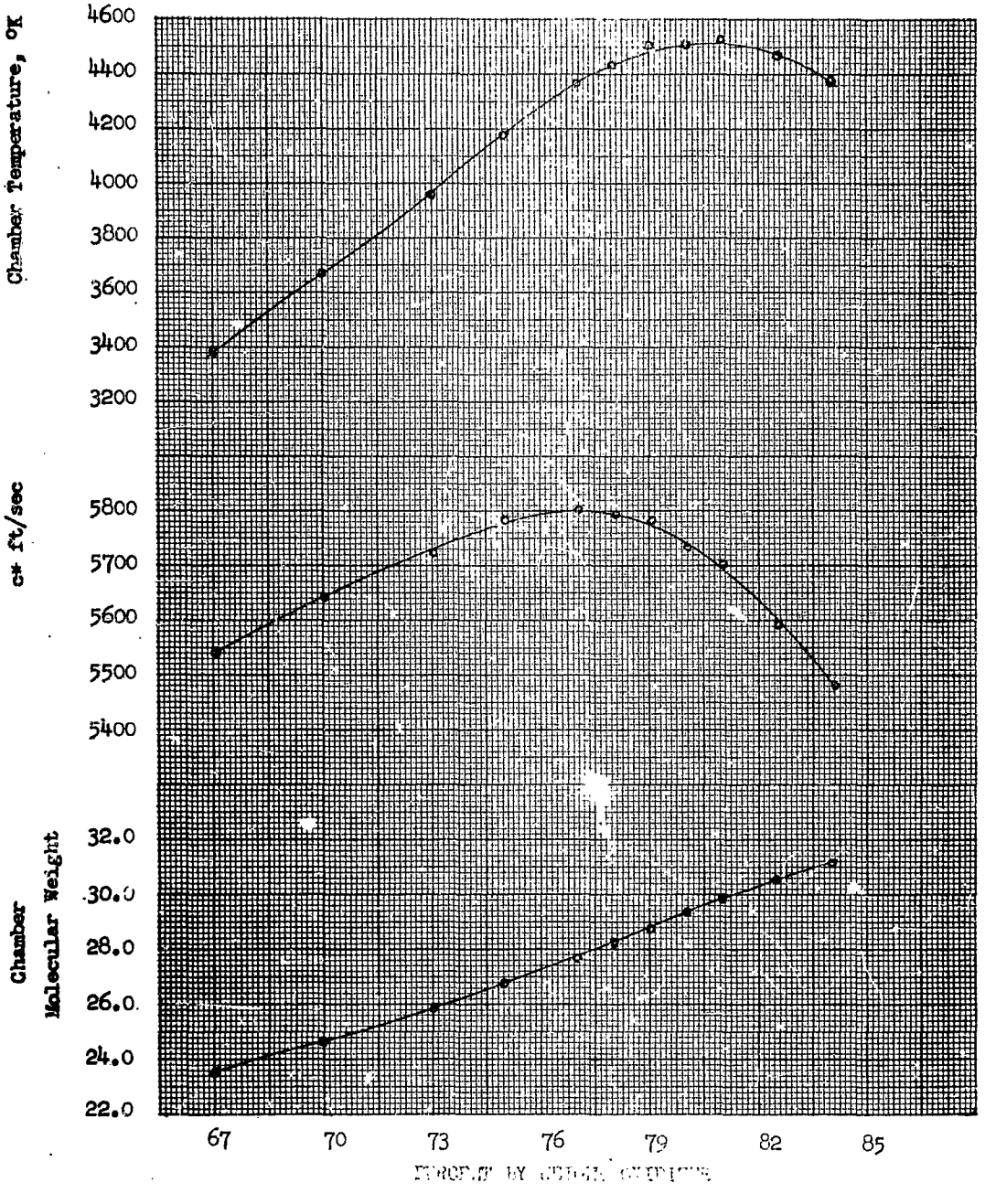
PENTABORANE - [illegible]



PENTABORANE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 176

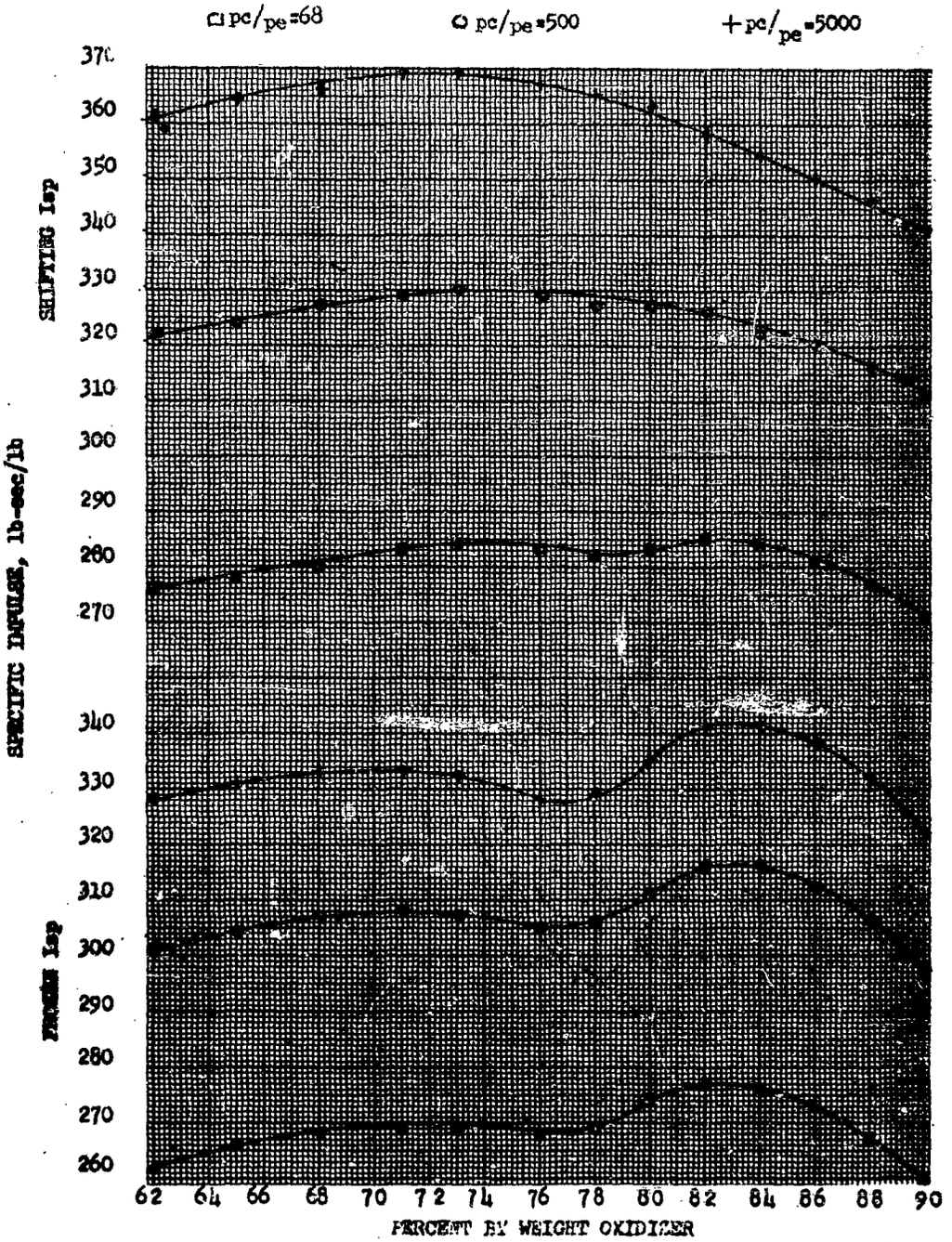


PENTABORANE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 177



PENTABORANE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 178

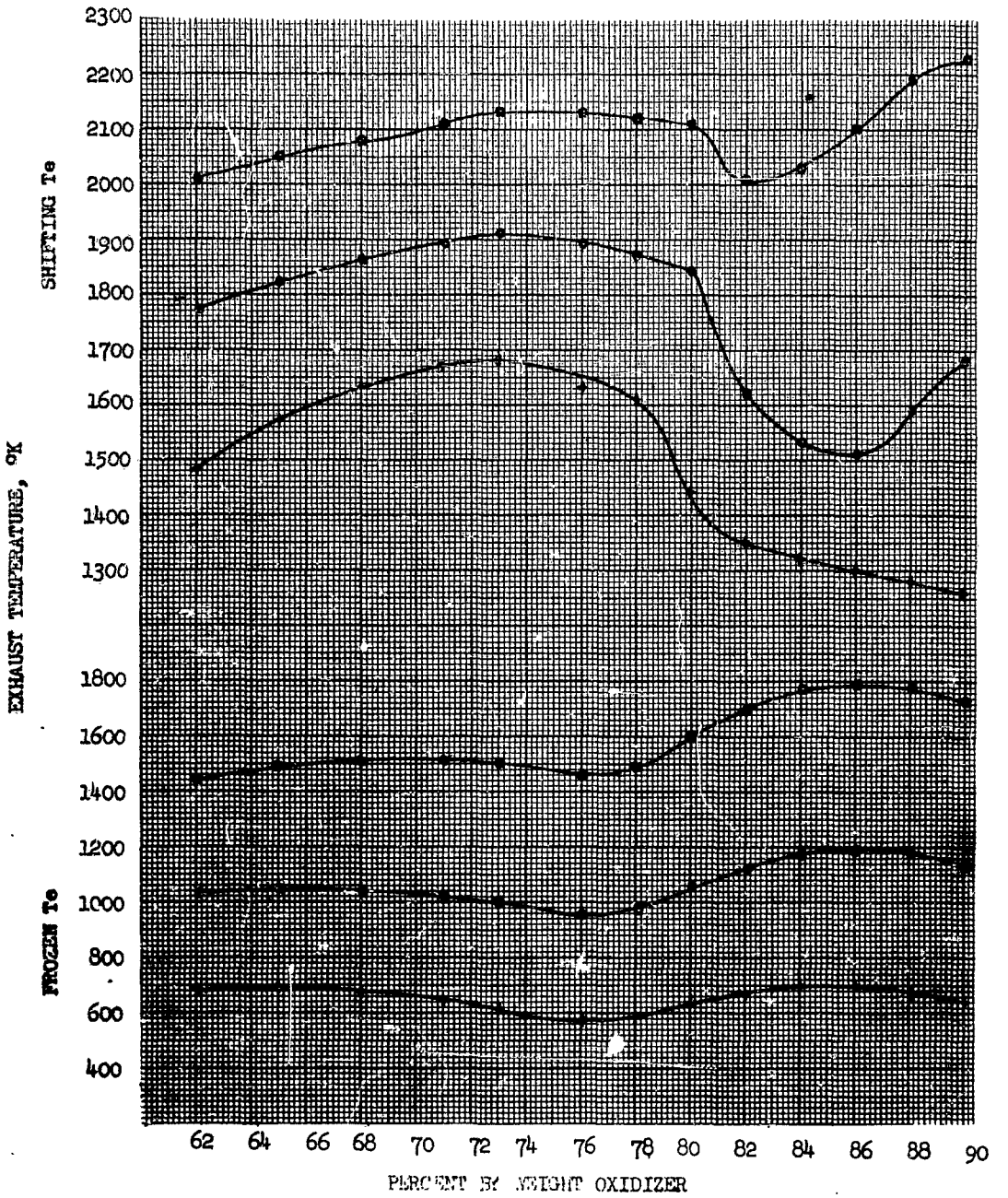
pc = 1000 psi



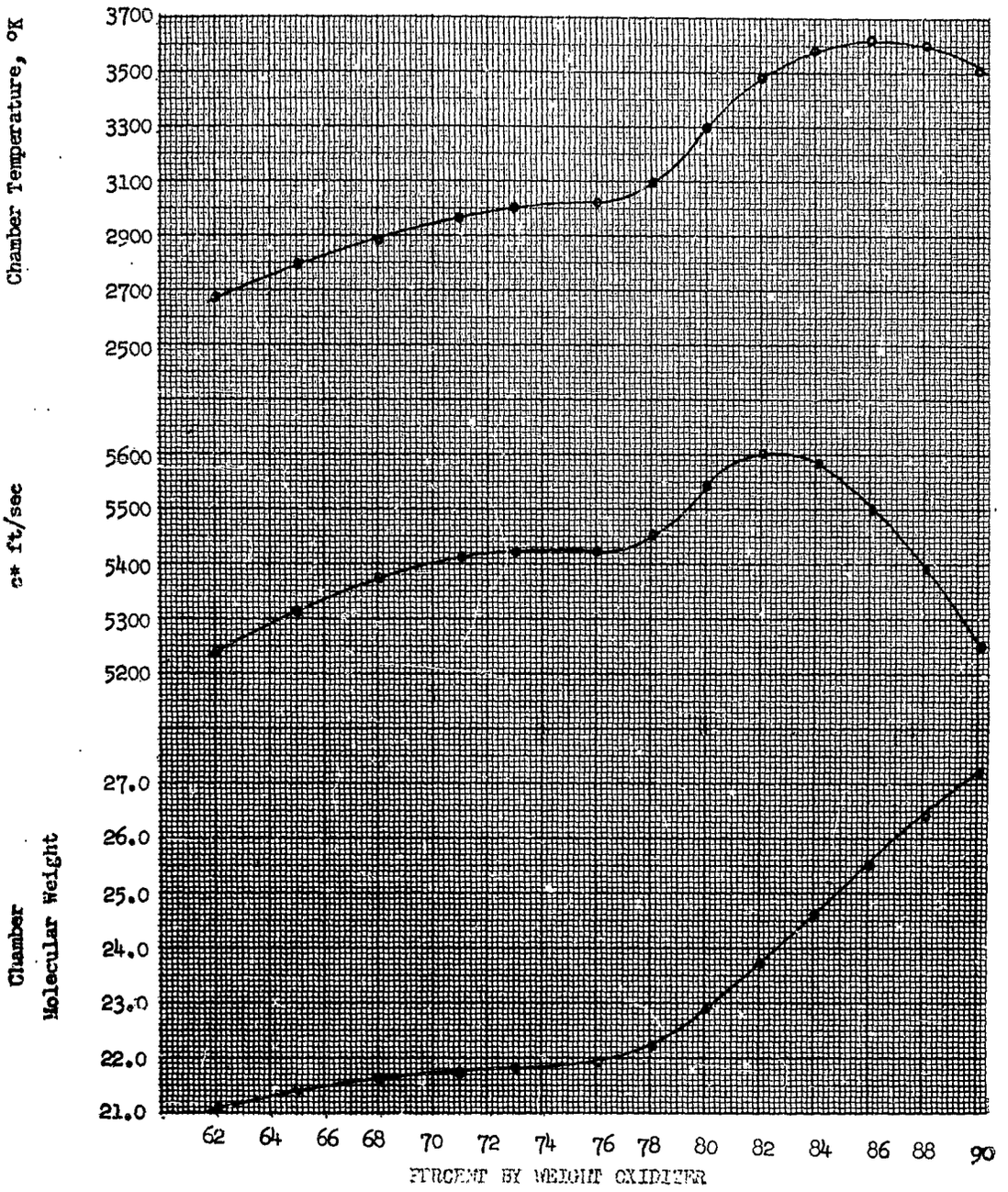
PENTABORANE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 179

p_c = 1000 psi

□ p_c/p_e=68 O p_c/p_e=500 + p_c/p_e=5000

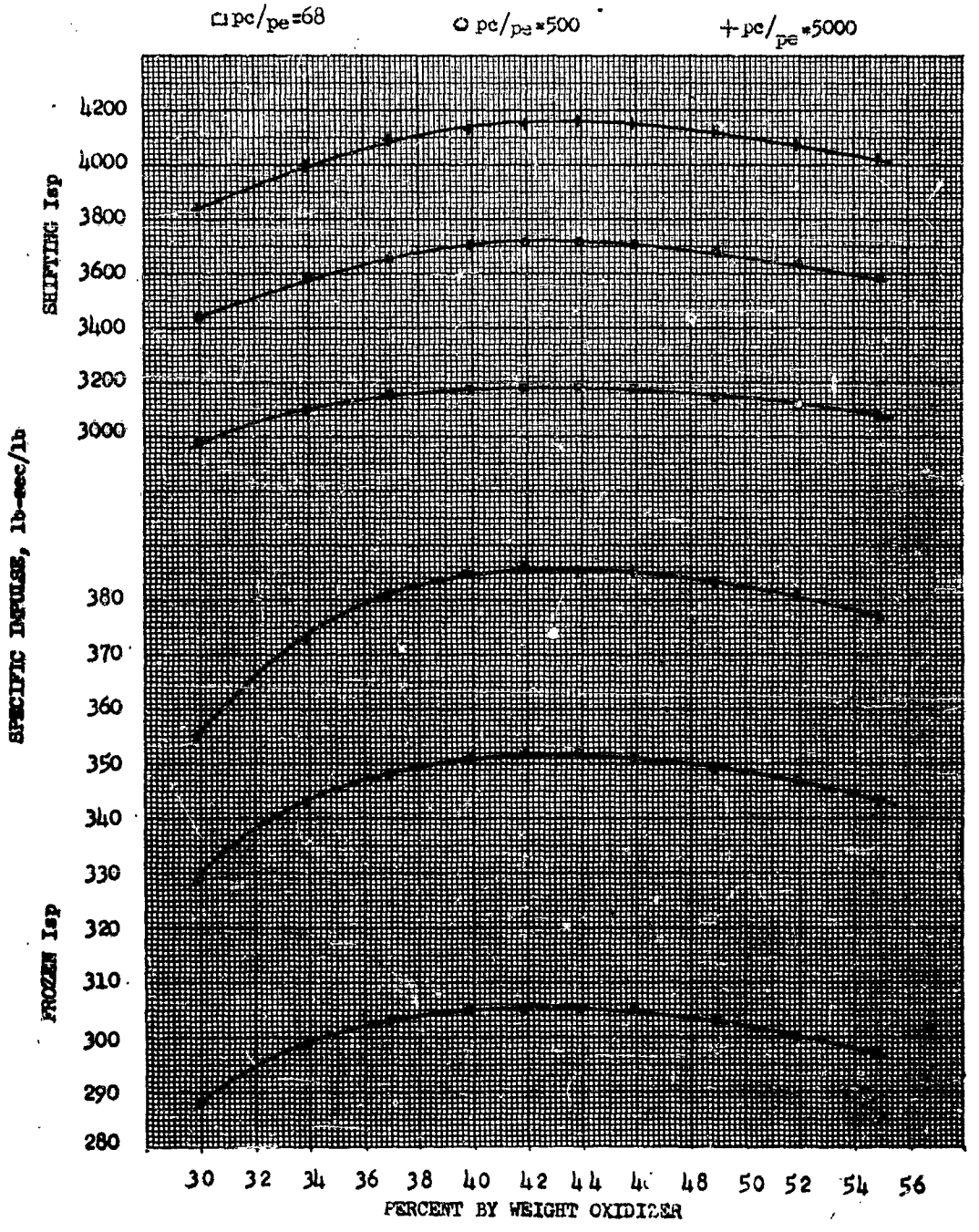


PENTABORANE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 180

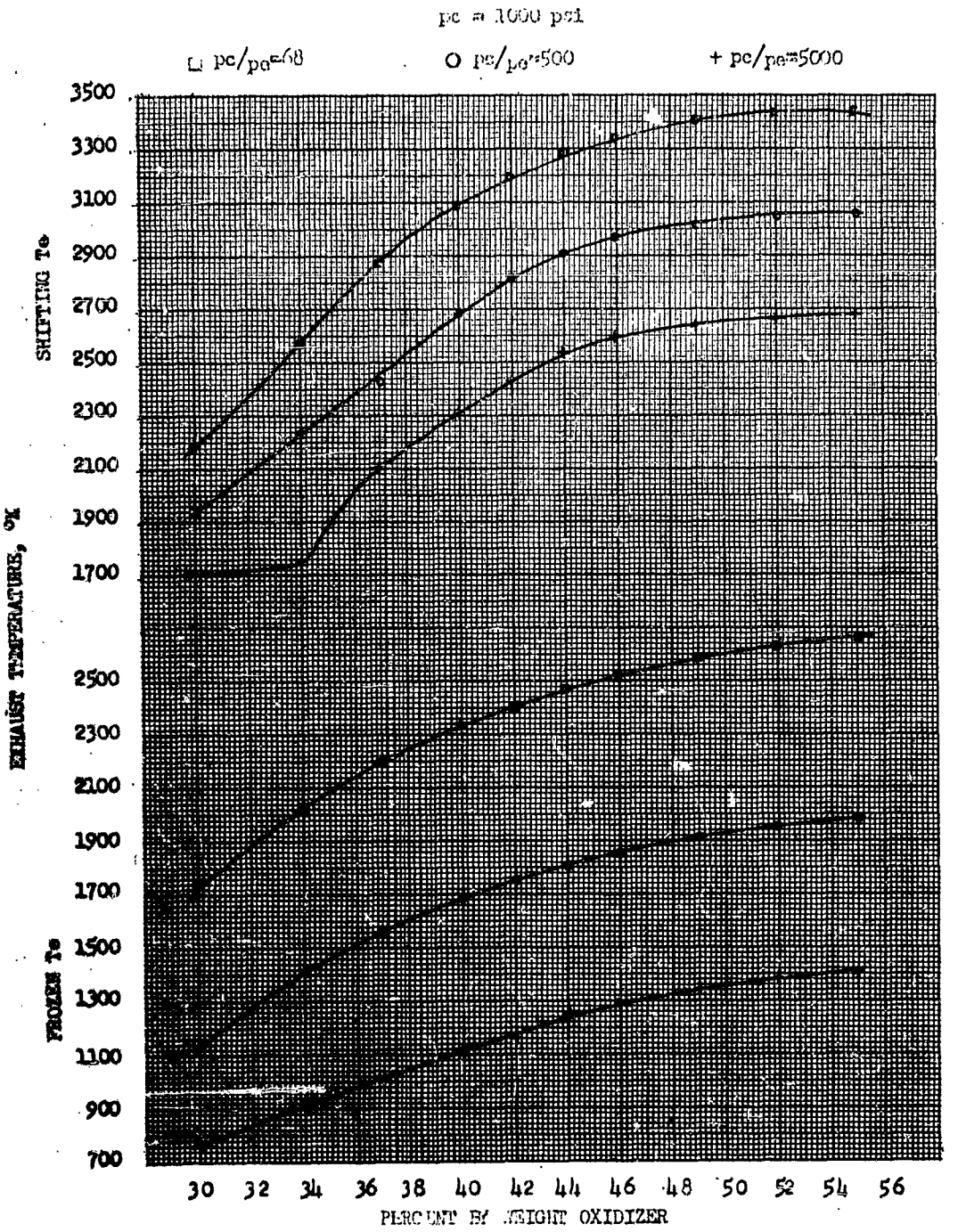


ALUMINUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 181

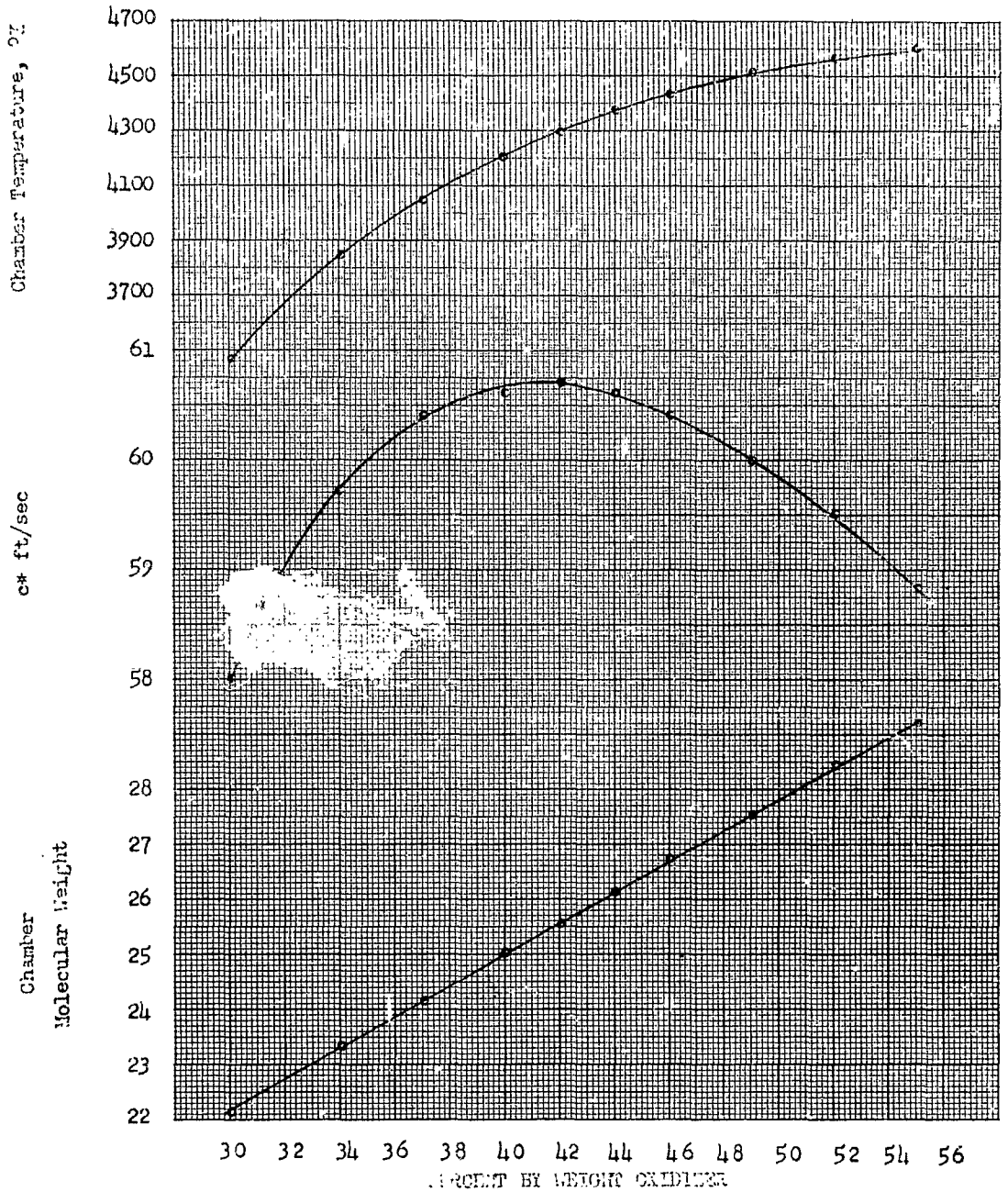
pc = 1000 psi



ALUMINUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 182



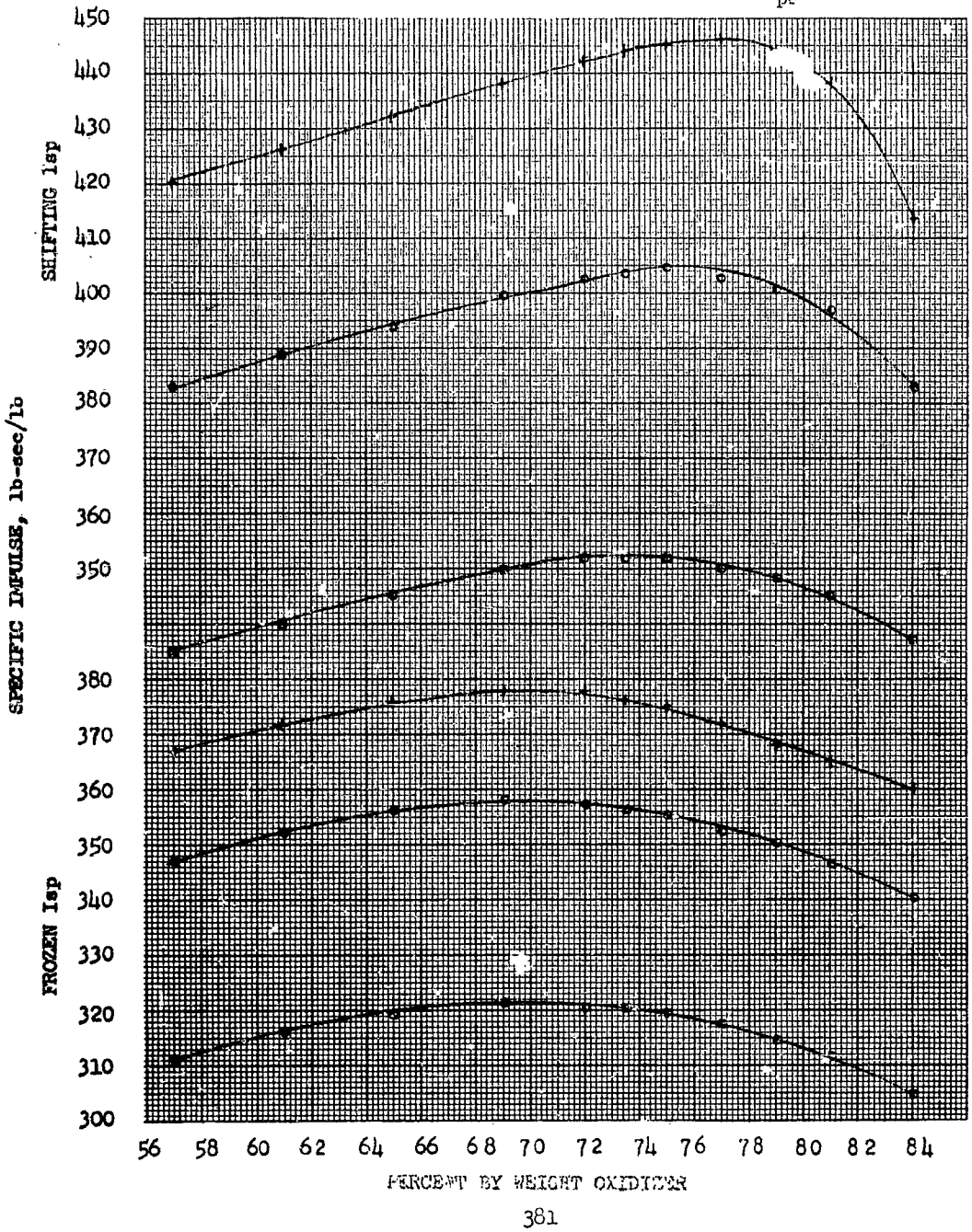
ALUMINUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 183



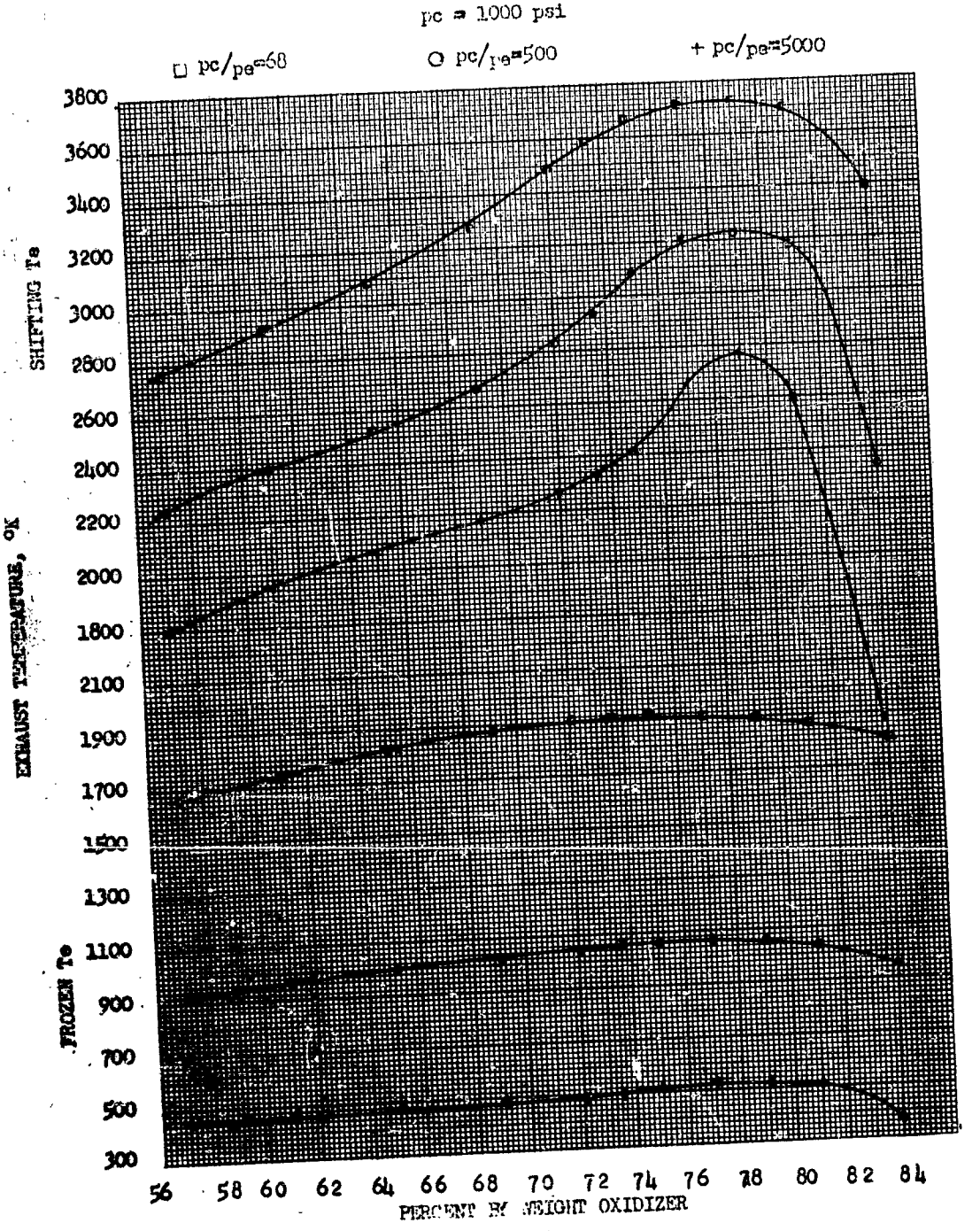
ALUMINUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 184

p_c = 1000 psi

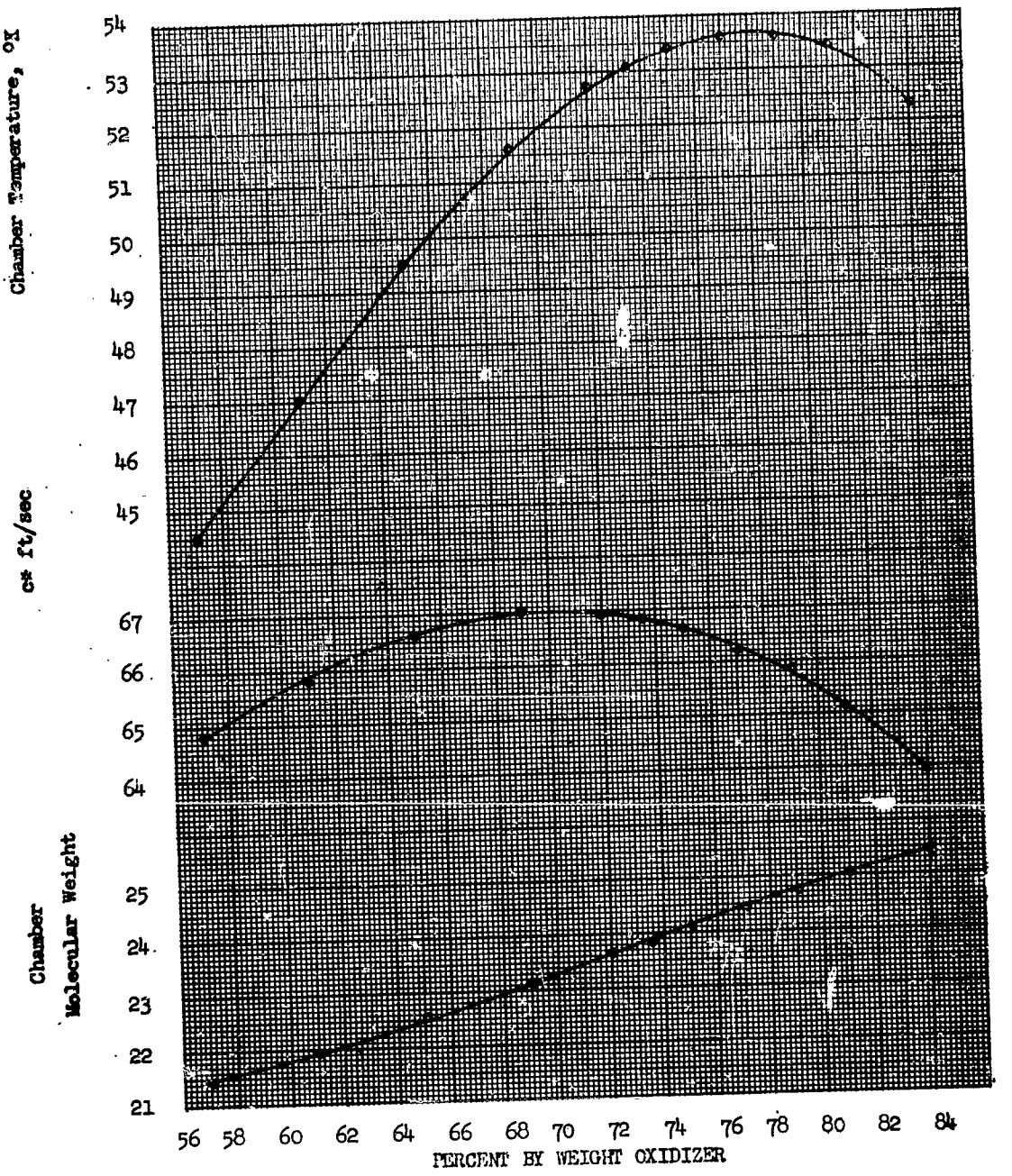
□ p_c/p_e=68 ○ p_c/p_e=500 + p_c/p_e=5000



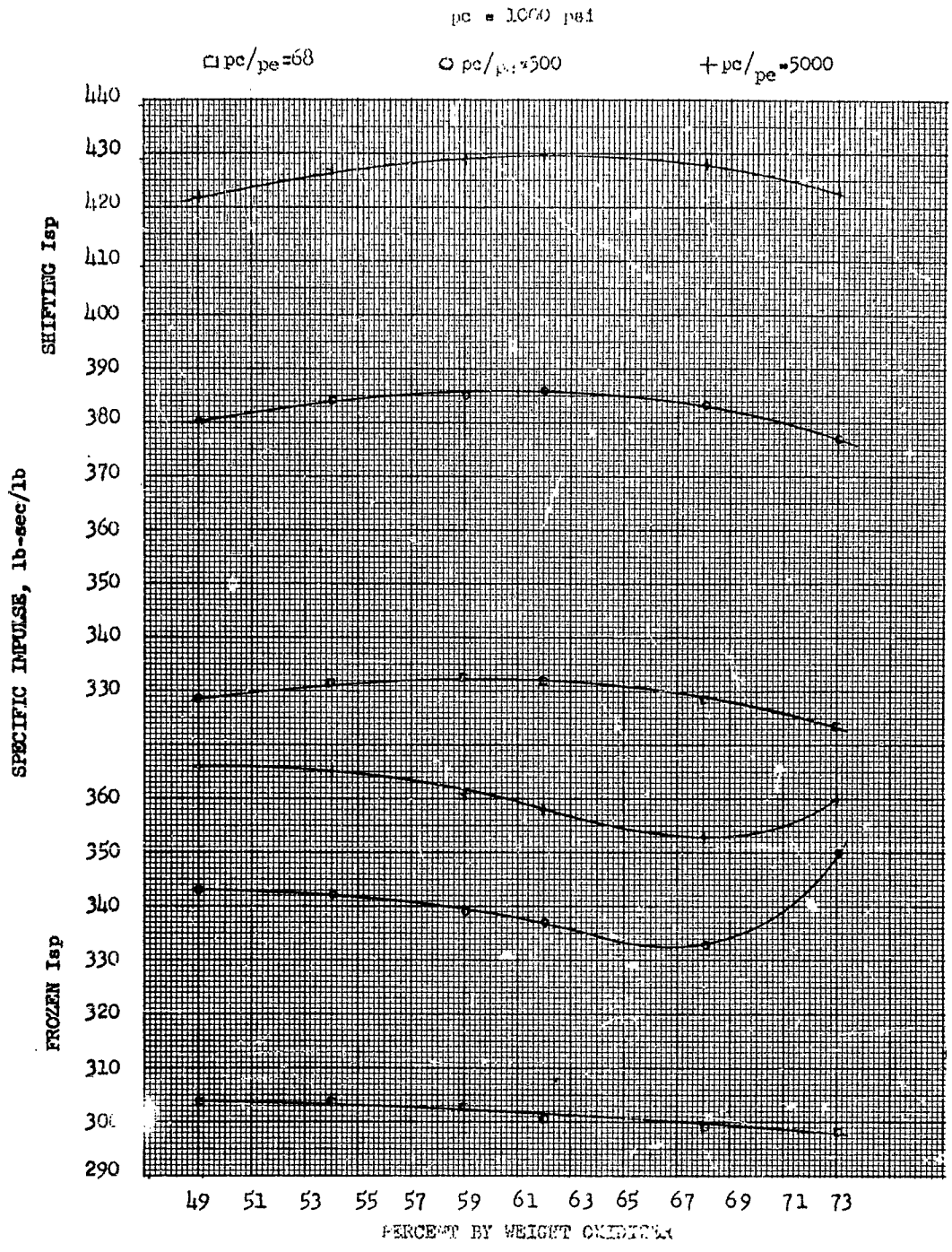
ALUMINUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 185



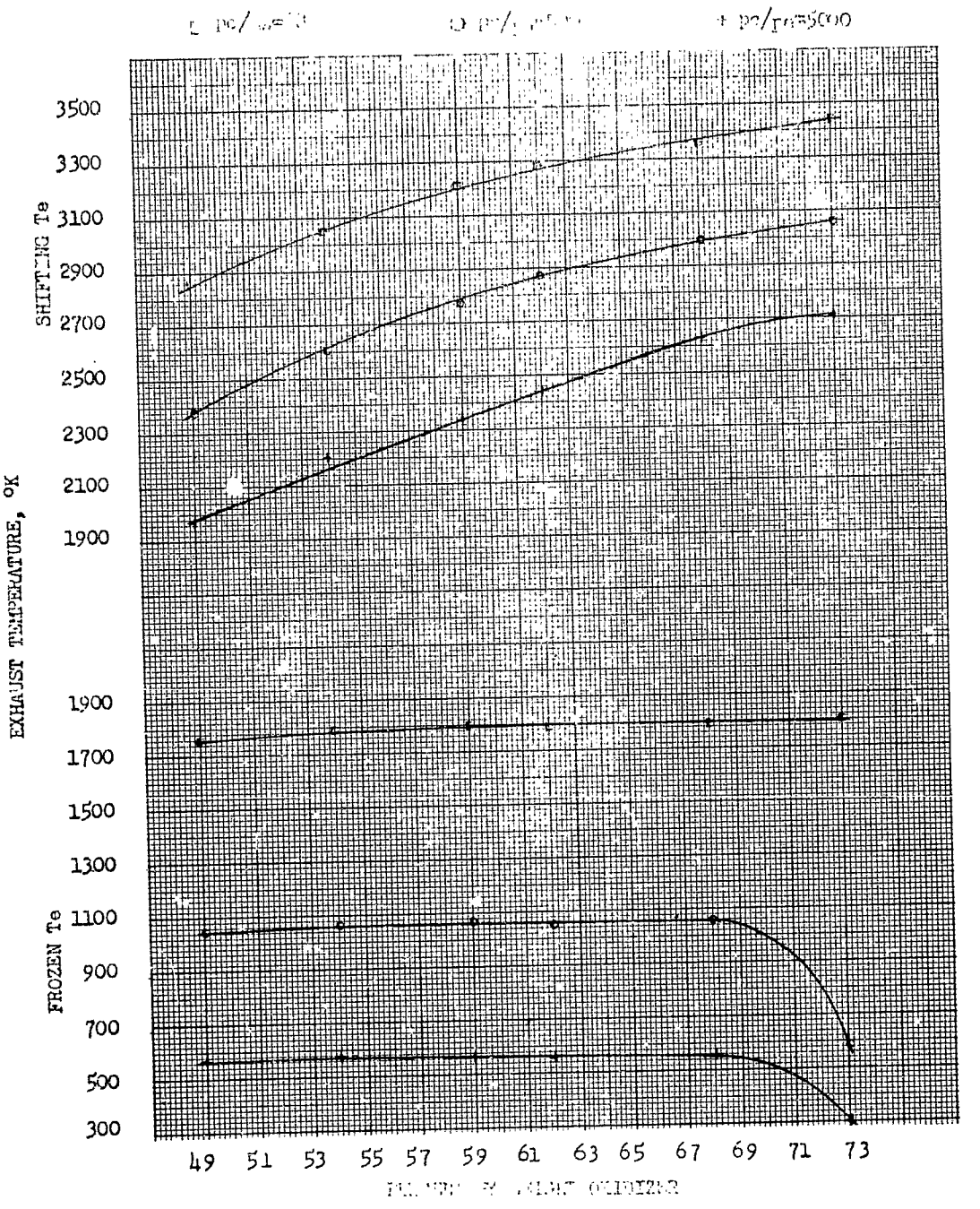
ALUMINUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 186



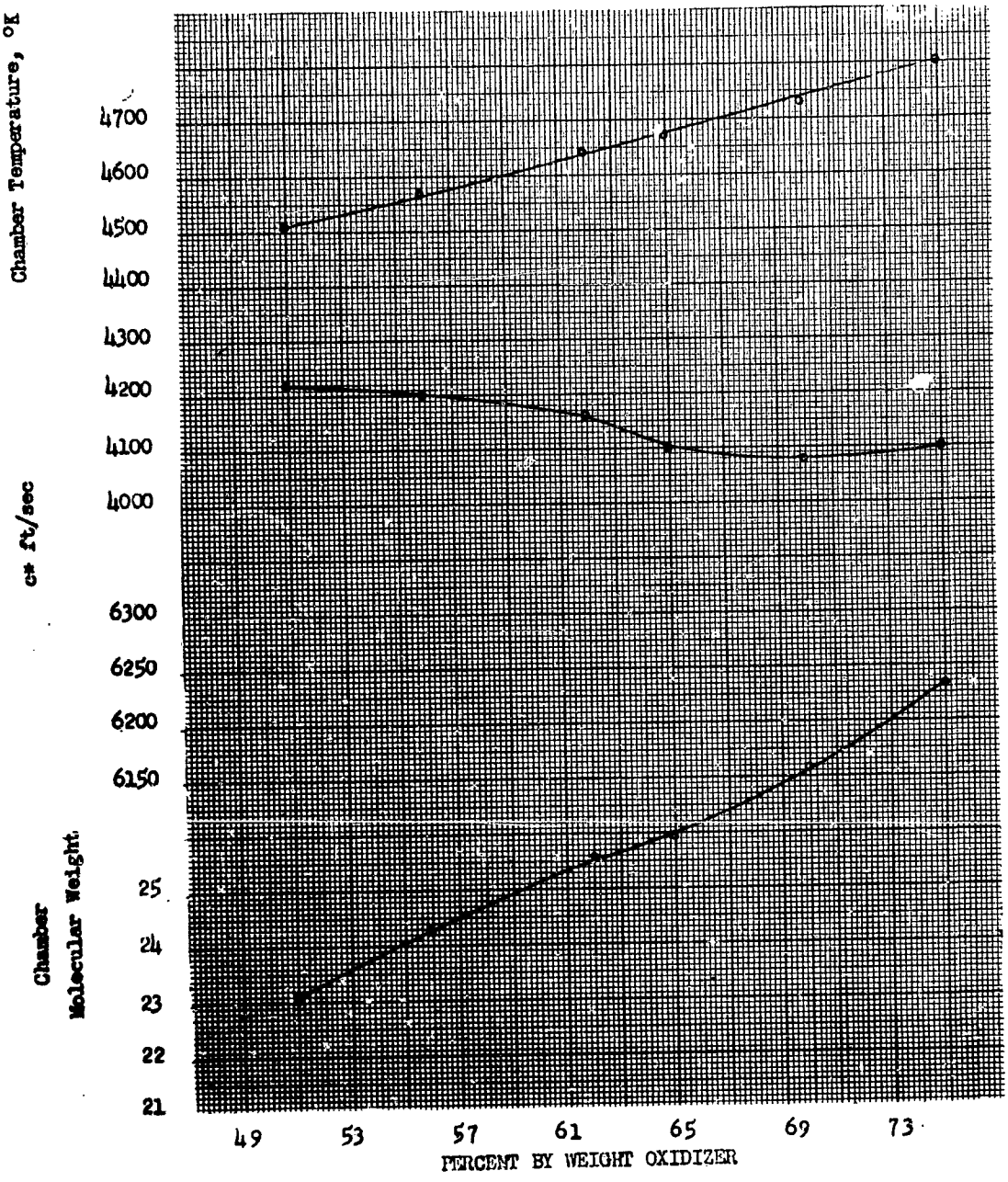
ALUMINUM HYDRIDE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 187



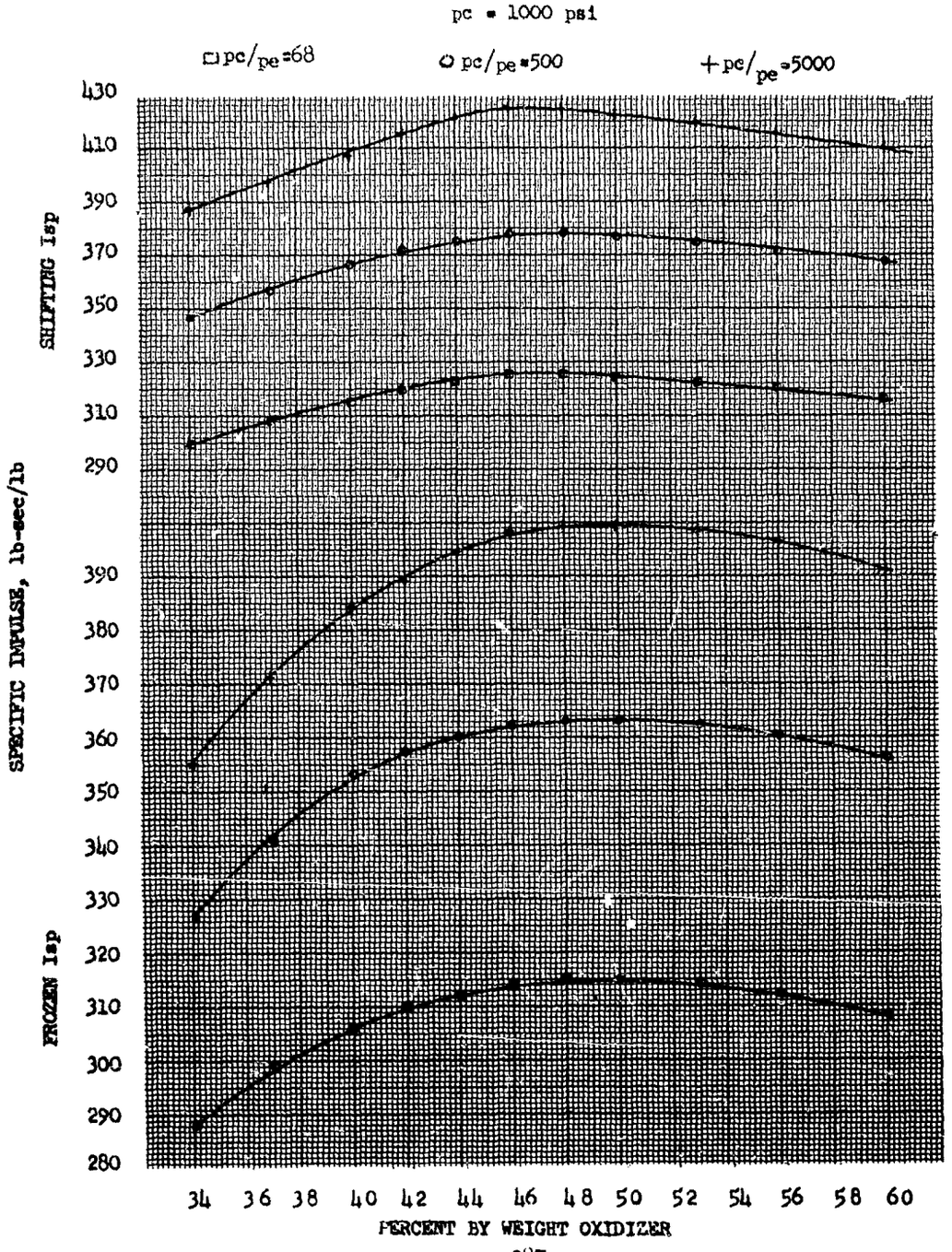
ALUMINUM HYDRIDE – [illegible] PERFORMANCE CURVES FIGURE 188



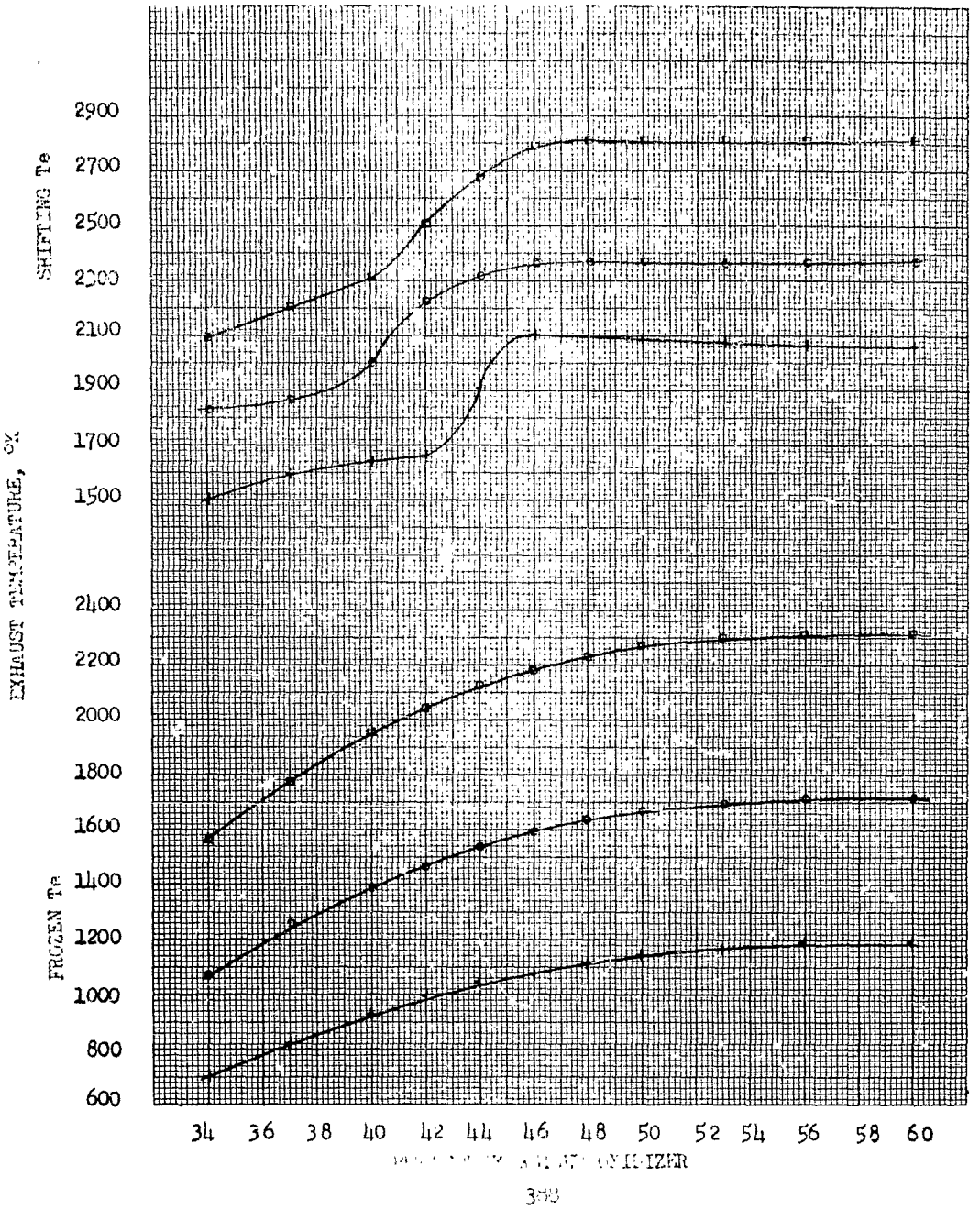
ALUMINUM HYDRIDE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 189



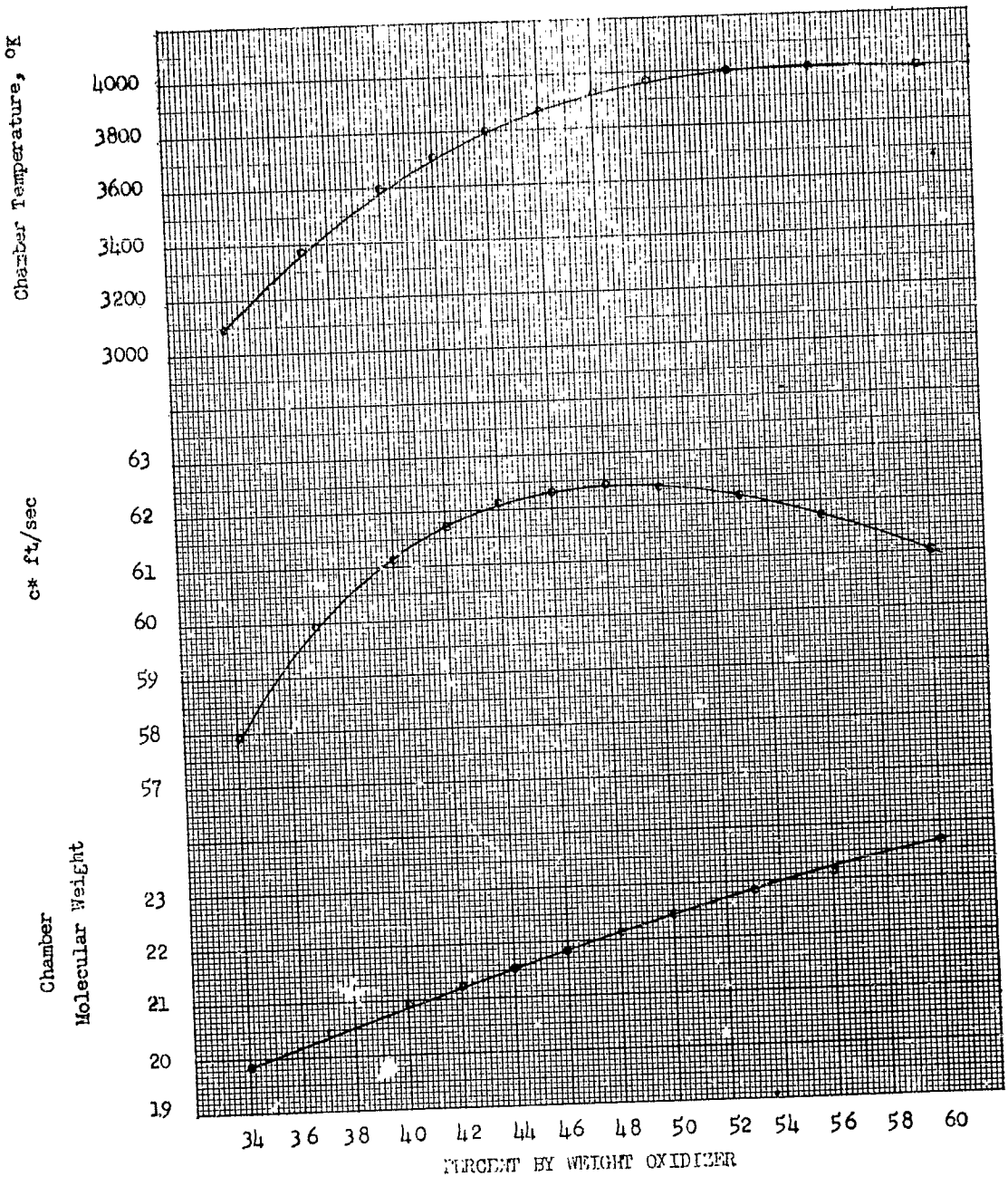
ALUMINUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 190



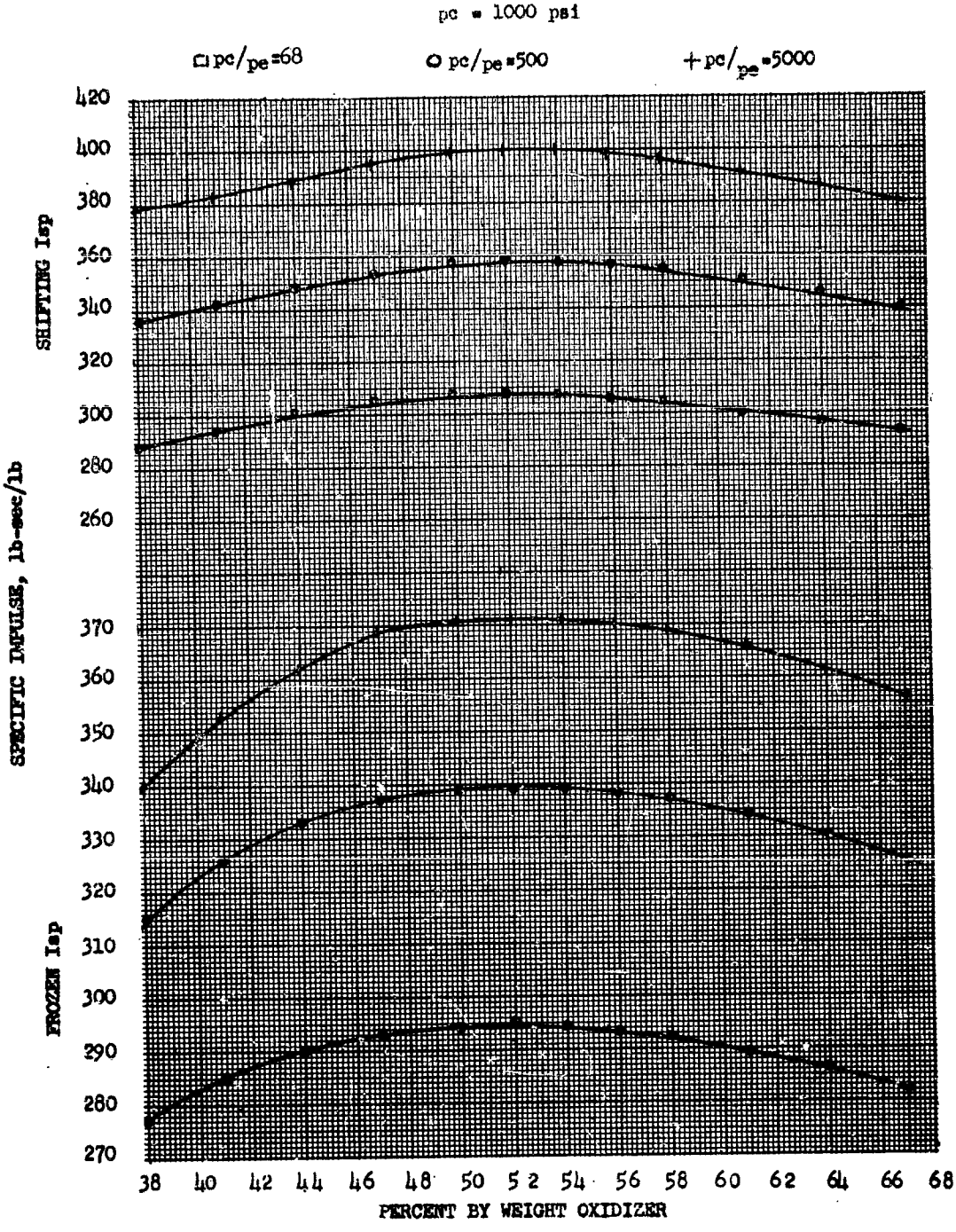
ALUMINUM HYDRIDE – HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 191



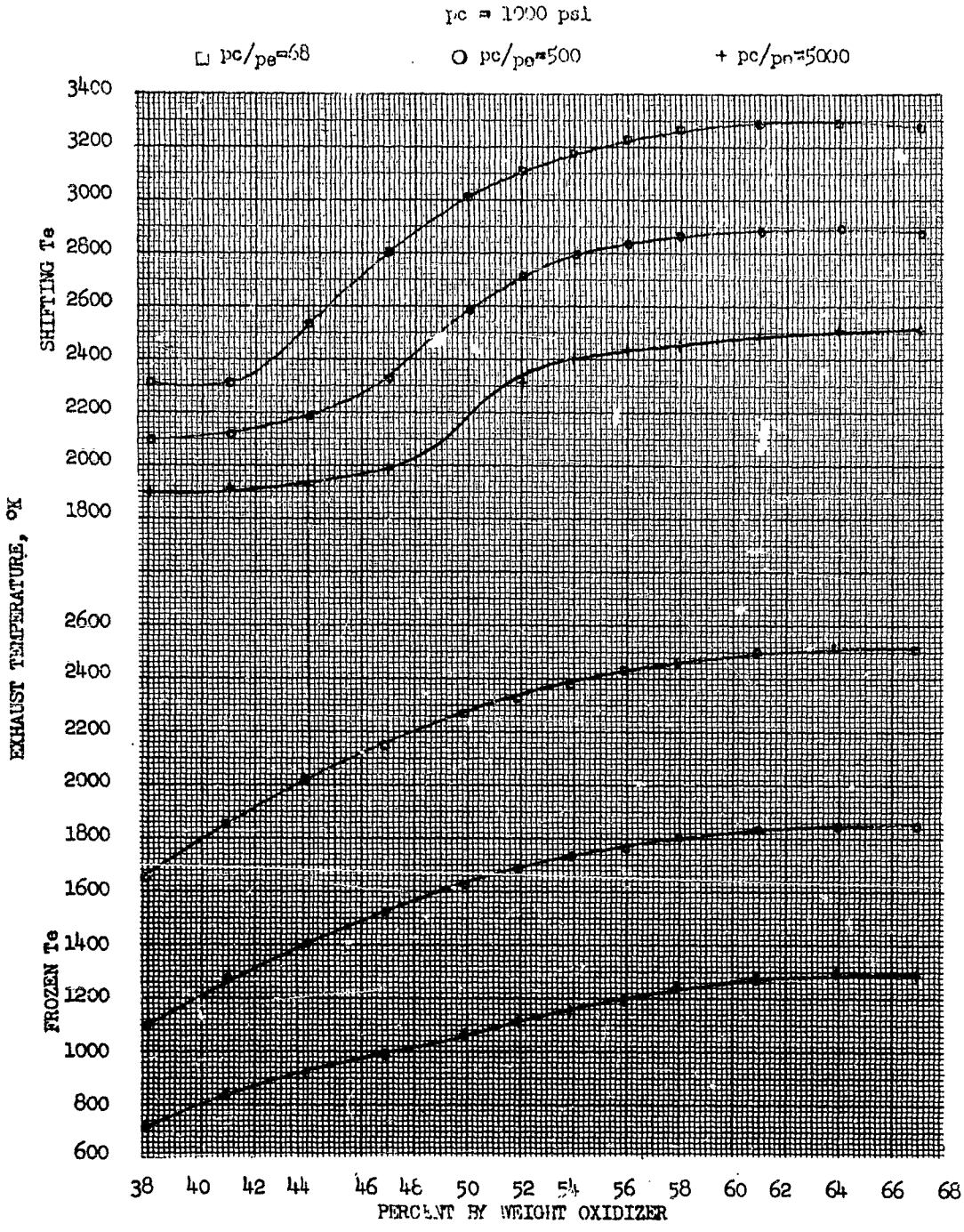
ALUMINUM HYDRIDE – HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 192



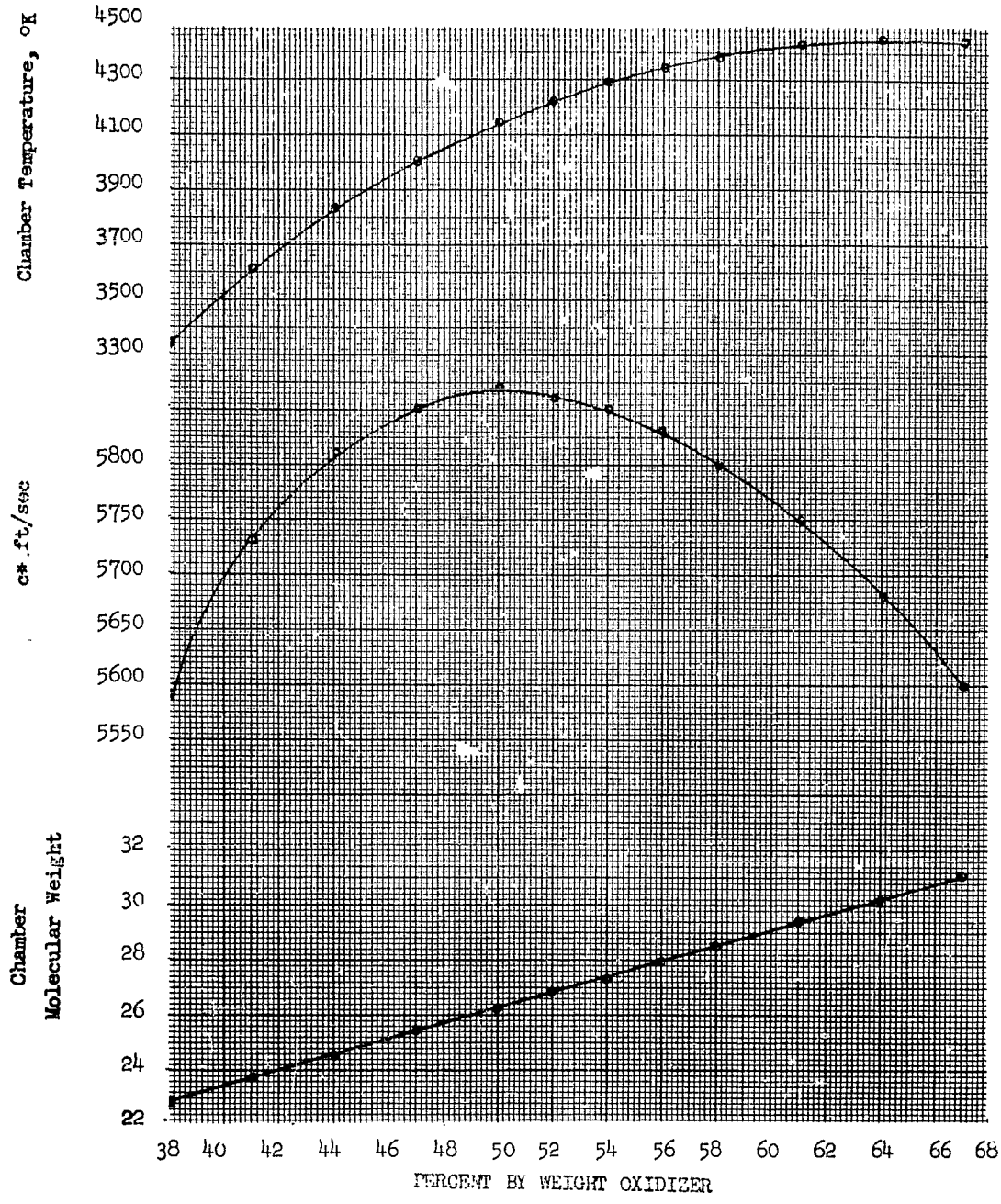
ALUMINUM HYDRIDE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 193



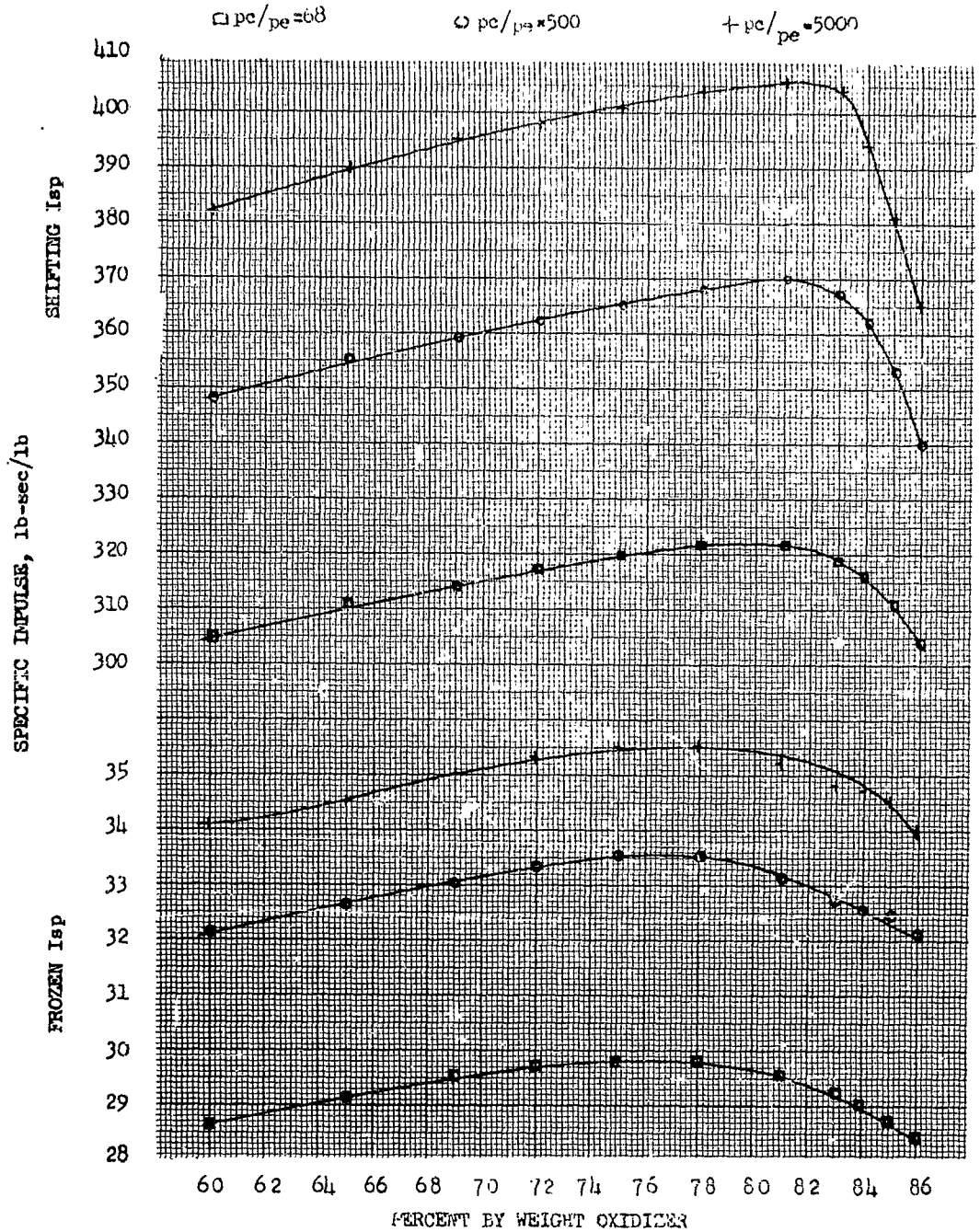
ALUMINUM HYDRIDE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 194



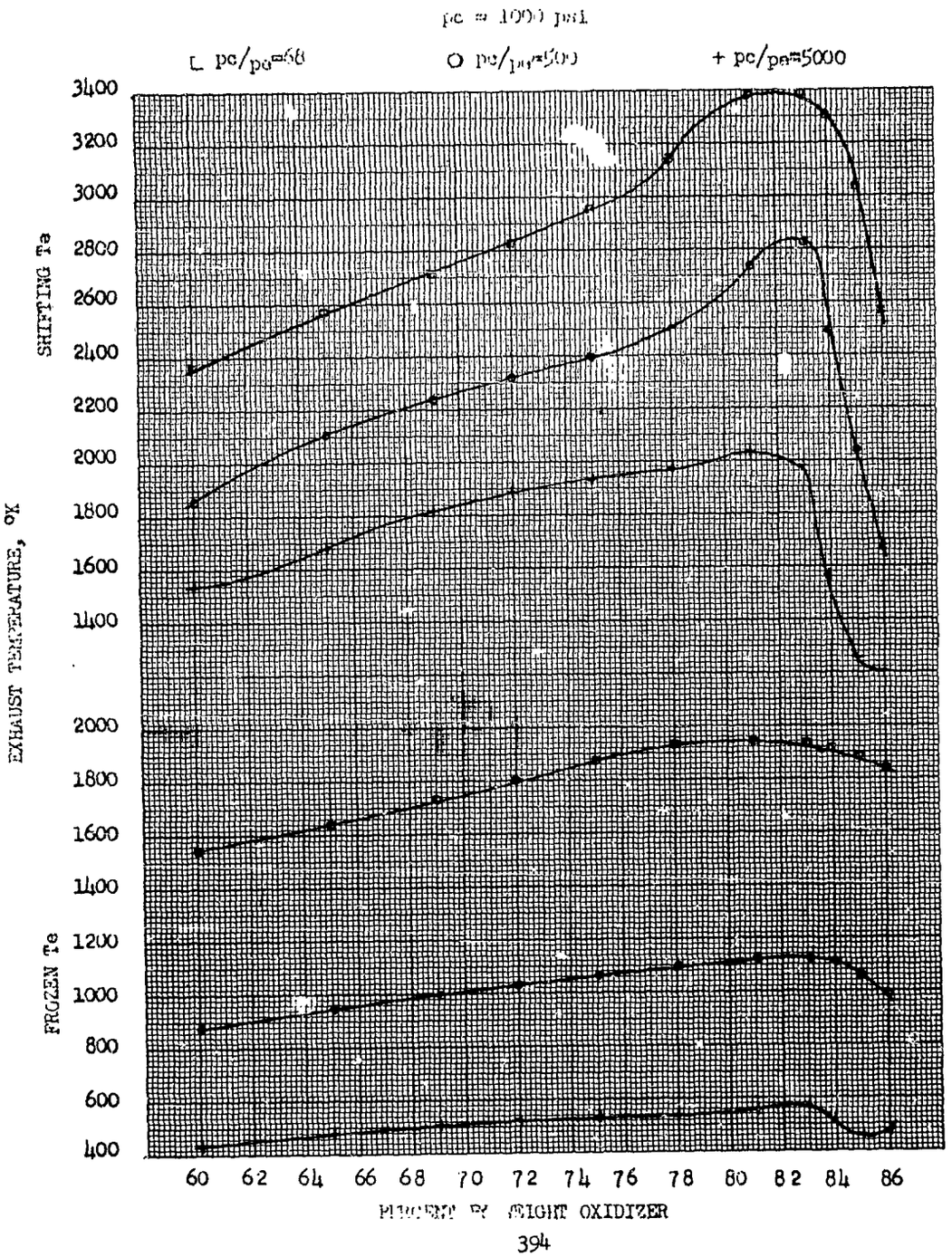
ALUMINUM HYDRIDE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 195



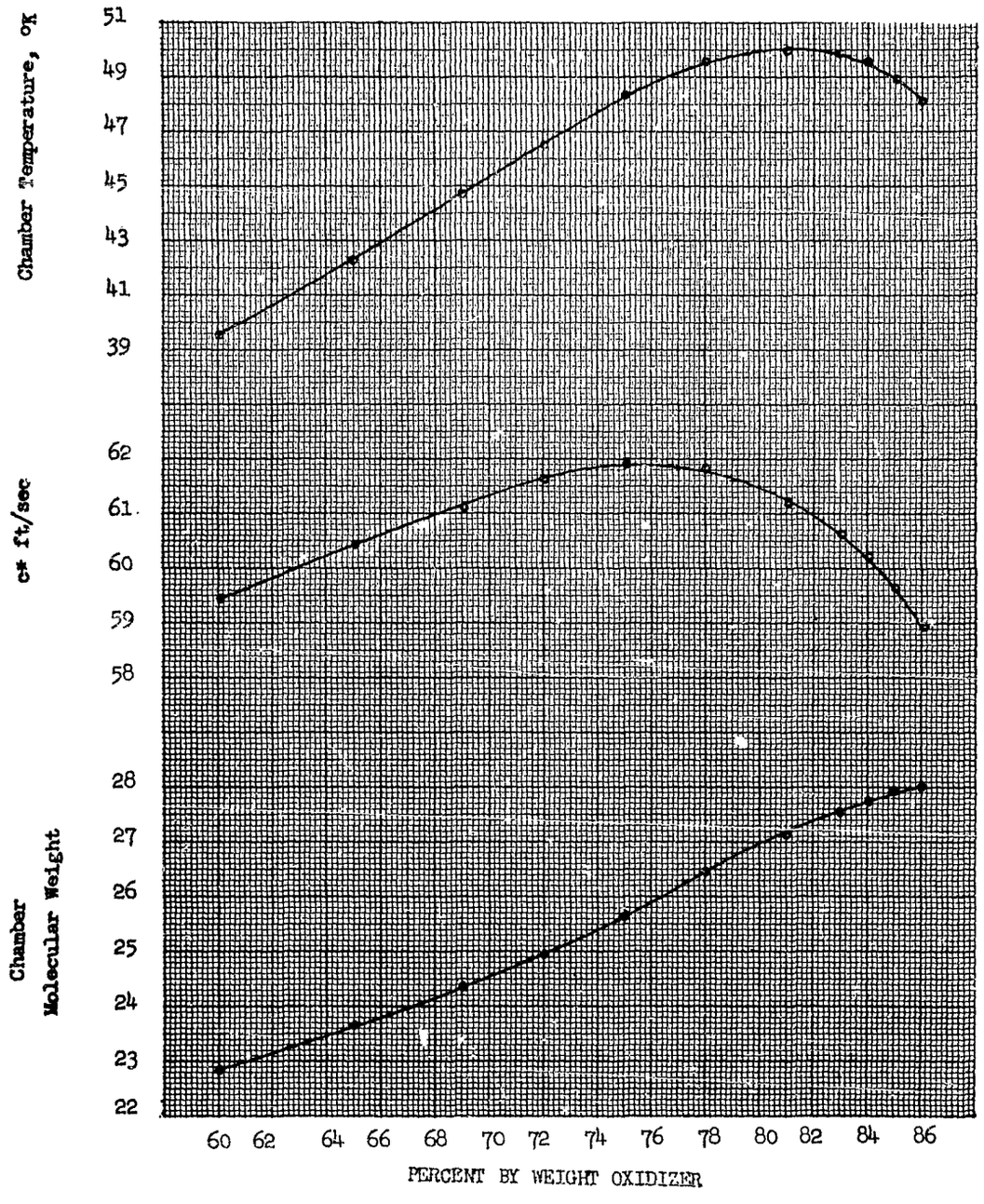
ALUMINUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 196



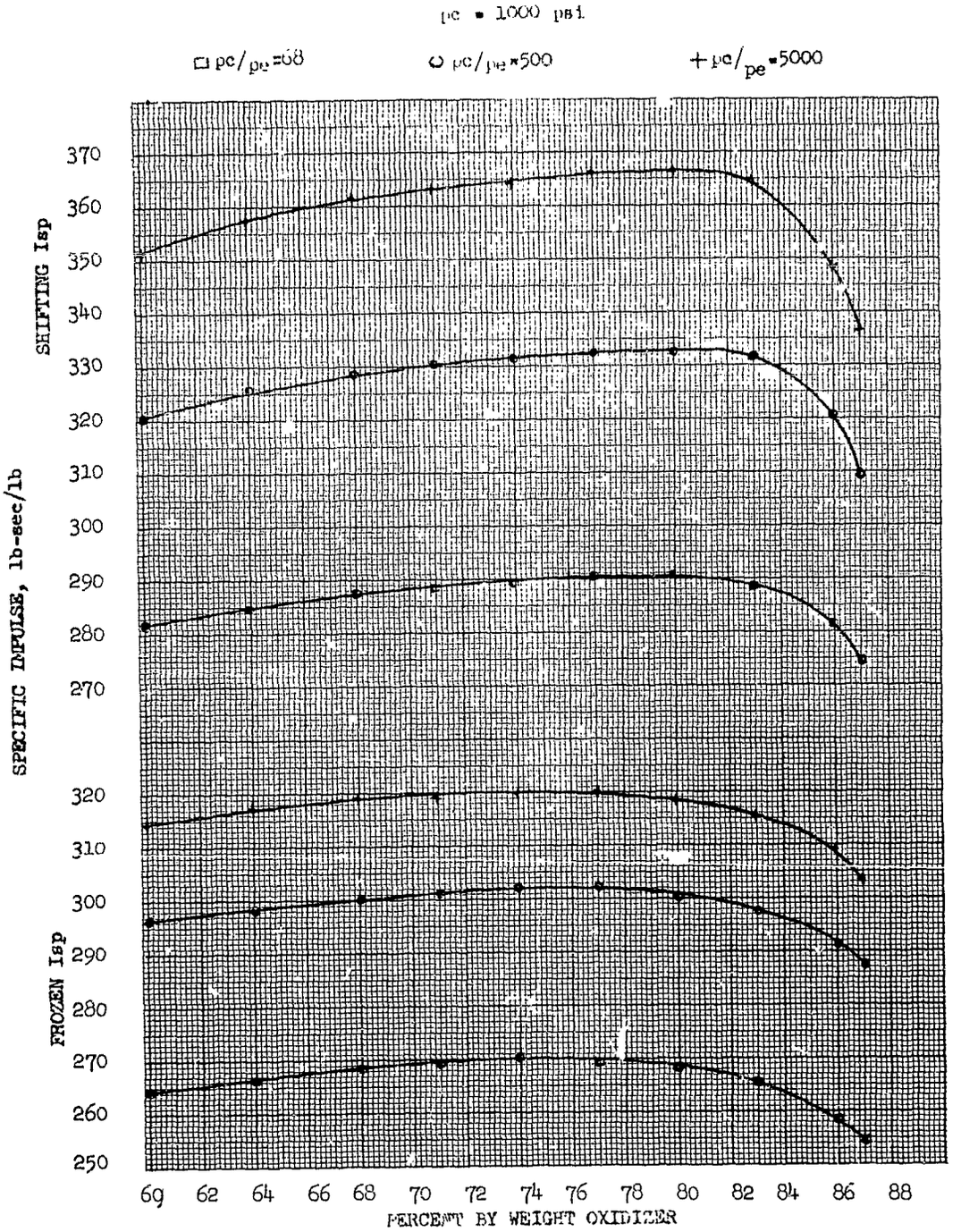
ALUMINUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 197



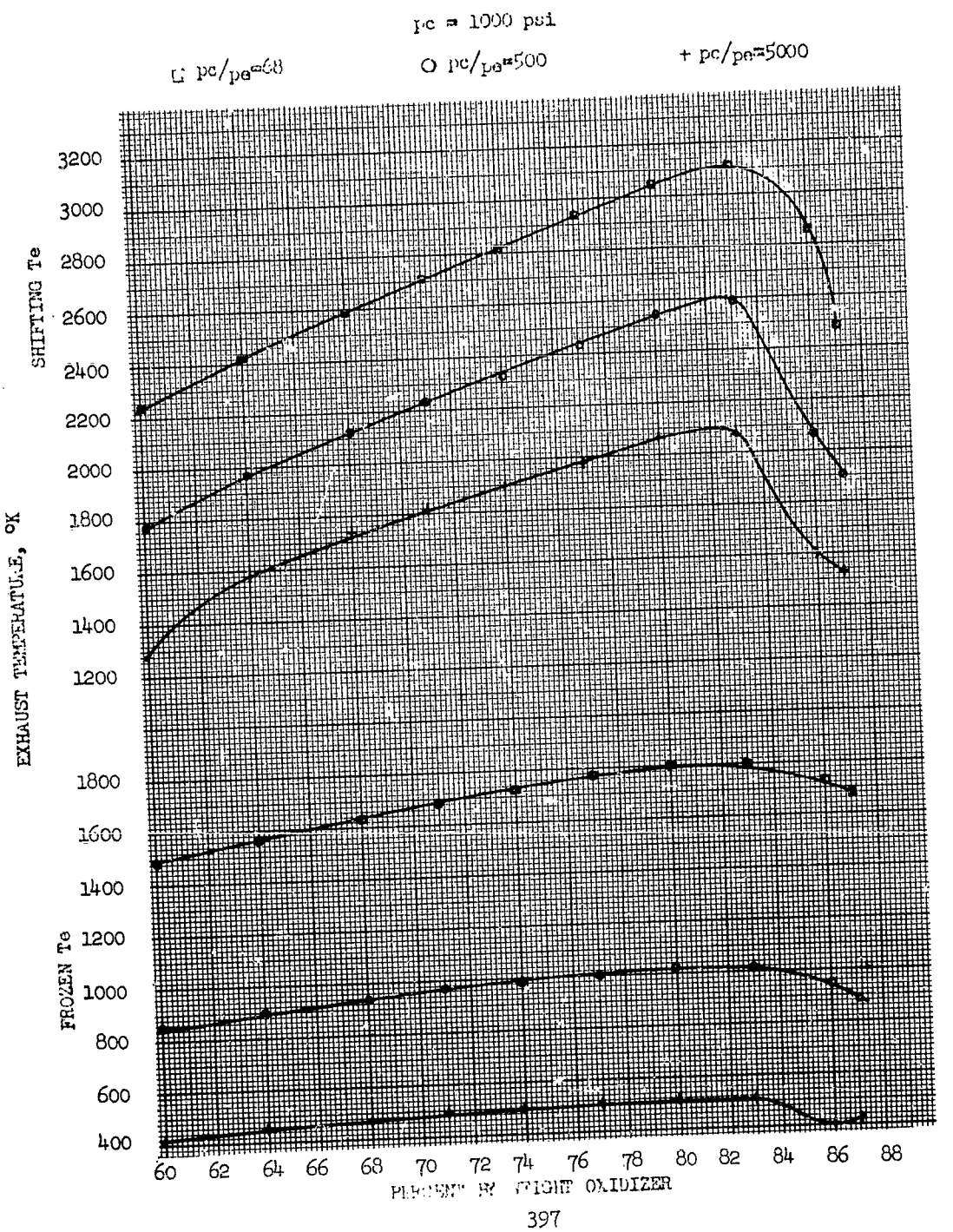
ALUMINUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 198



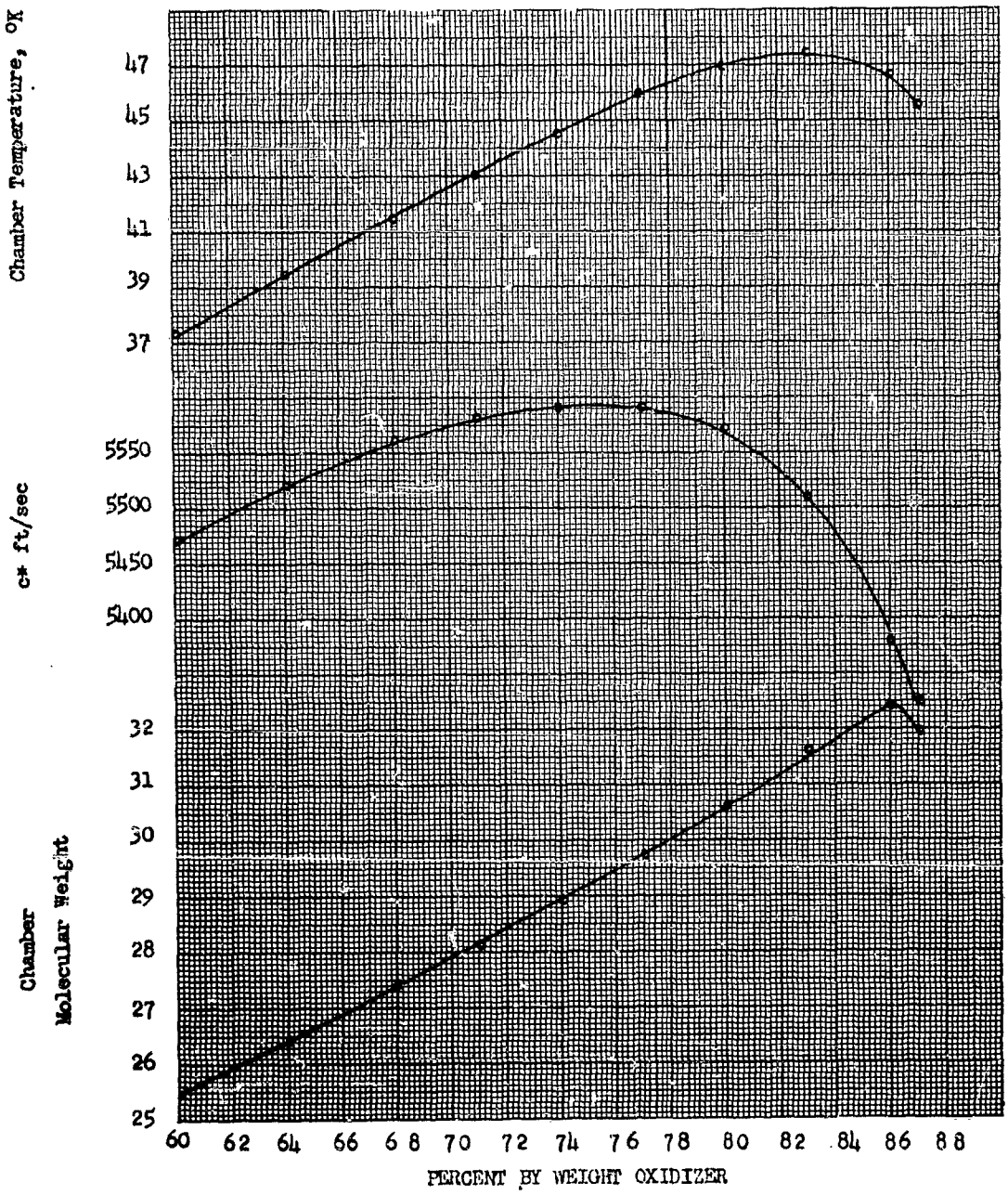
ALUMINUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 199



ALUMINUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 200

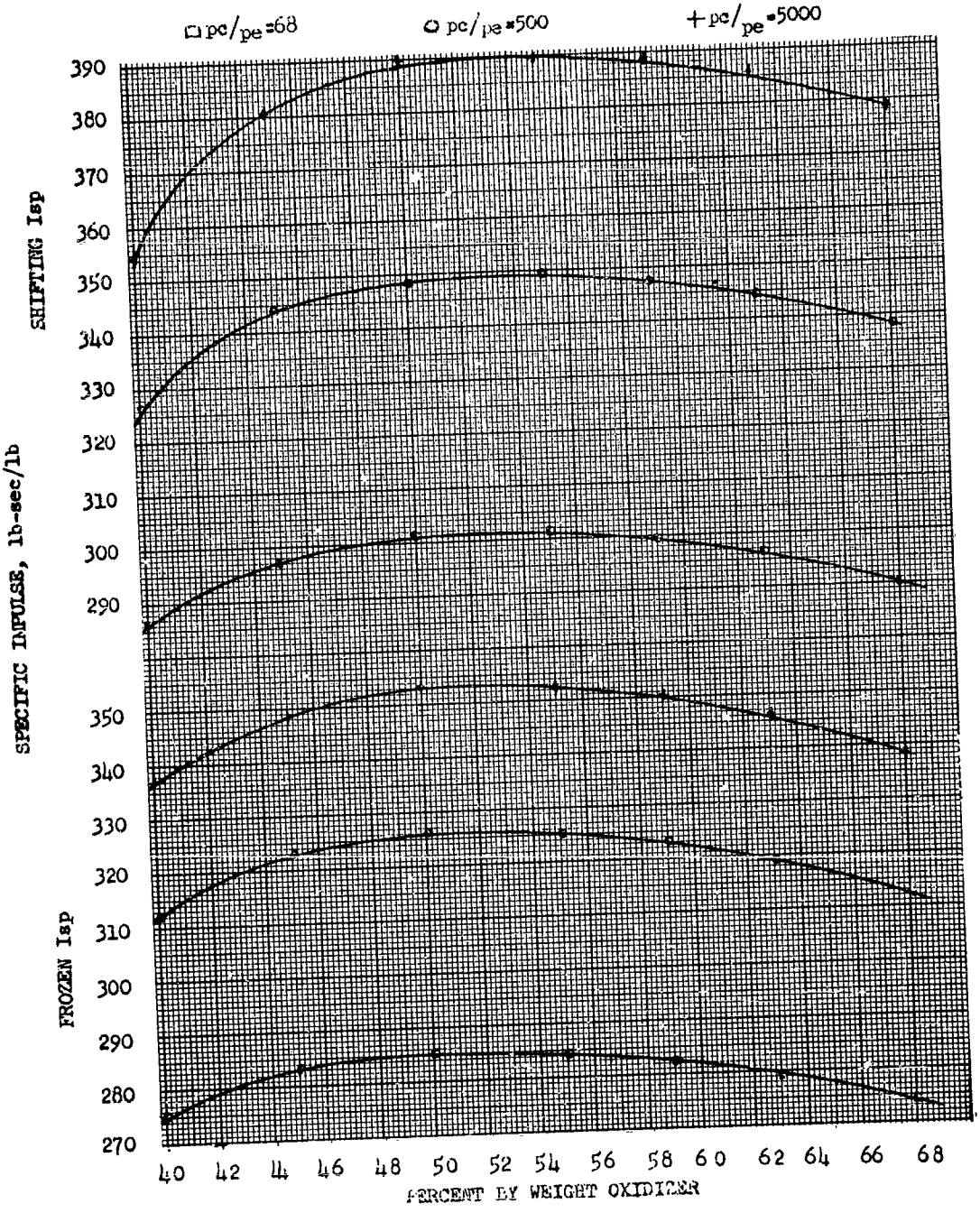


ALUMINUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 201



ALUMINUM HYDRIDE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 202

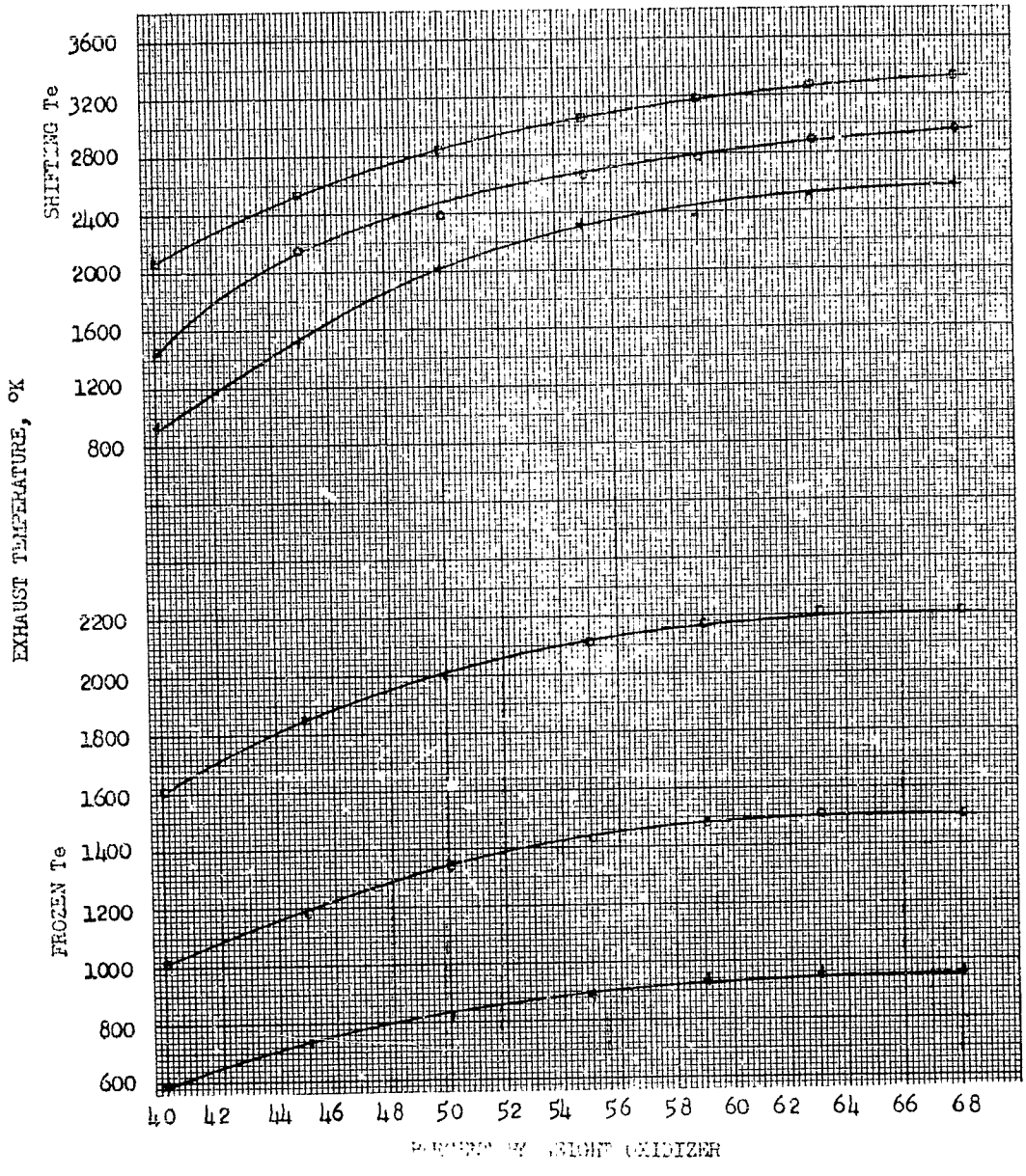
p_c = 1000 psi



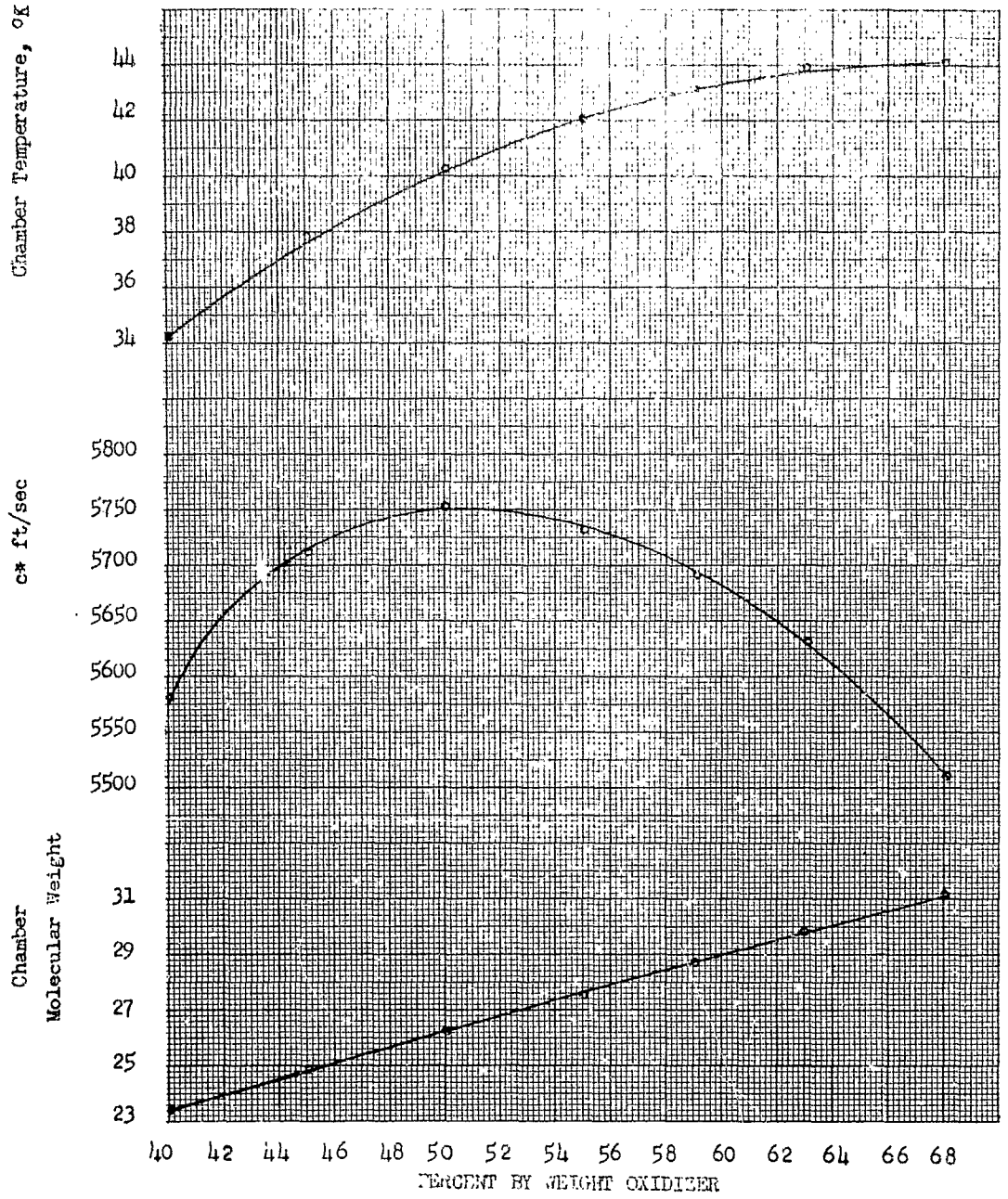
ALUMINUM HYDRIDE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 203

$\varepsilon = 10$, p_e psi

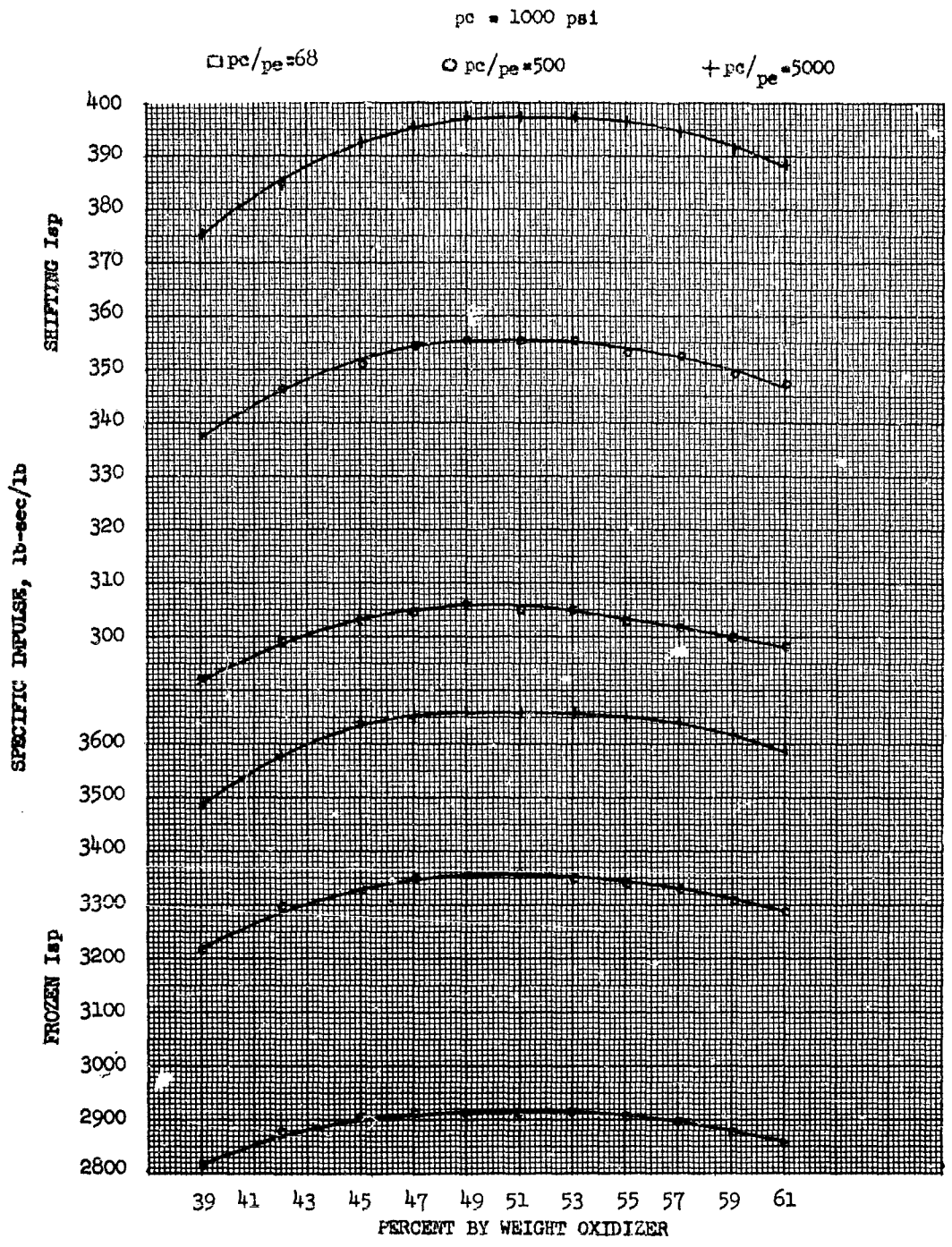
△ $p_c/p_e=500$ ○ $p_c/p_e=1000$ + $p_c/p_e=5000$



ALUMINUM HYDRIDE – [illegible] FIGURE 204



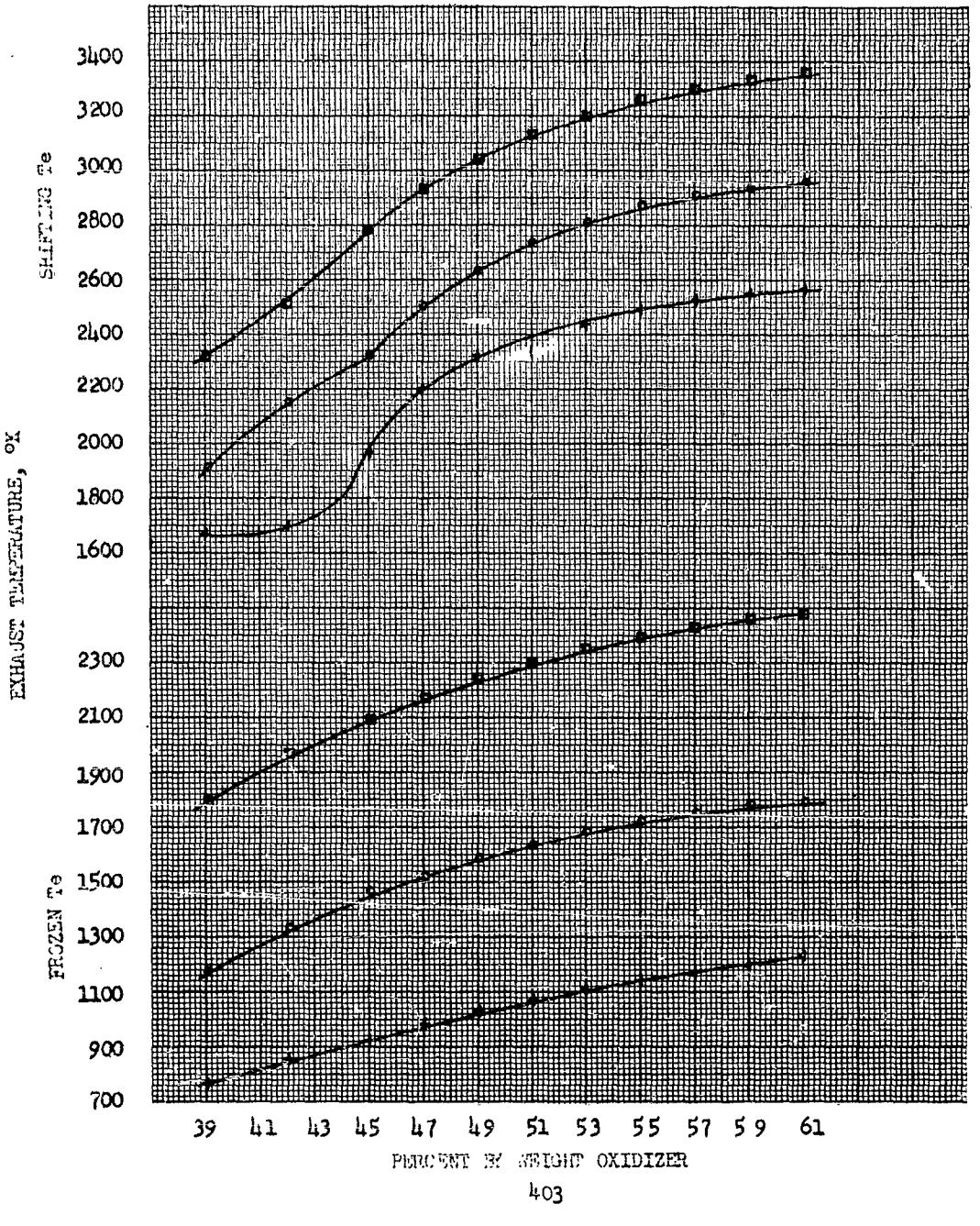
ALUMINUM HYDRIDE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 205



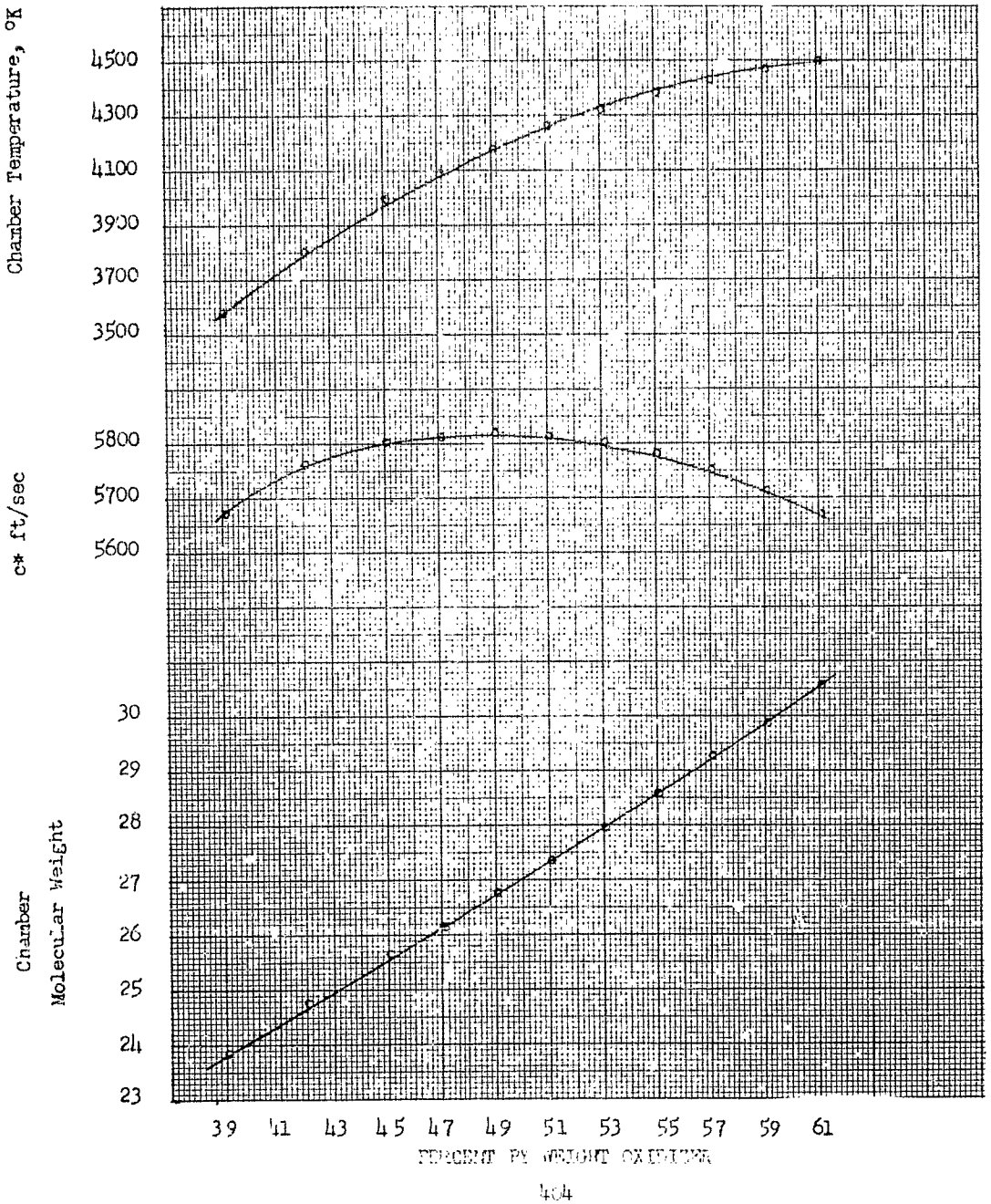
ALUMINUM HYDRIDE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 206

pc = 1000 psi

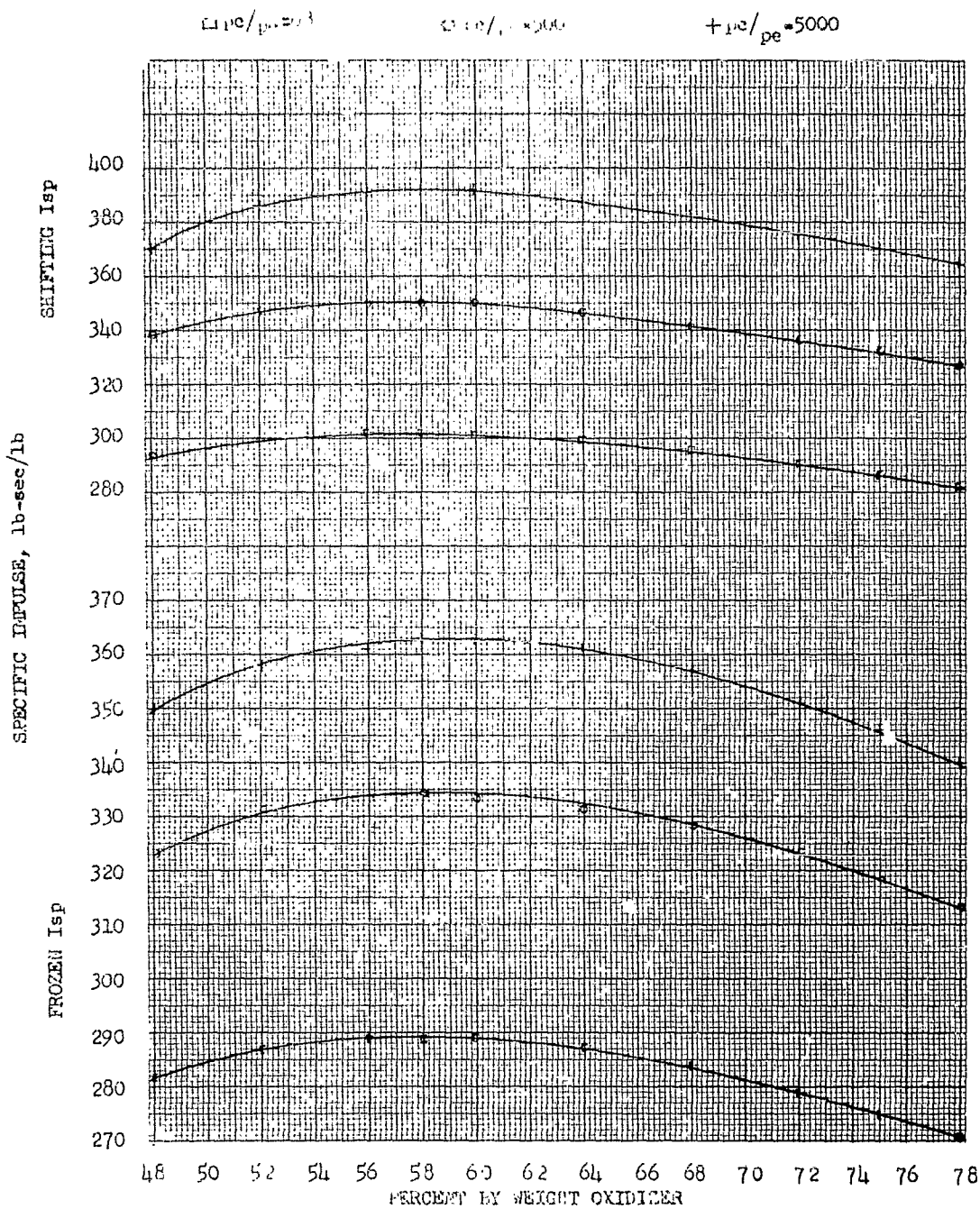
△ pe/pa=68 O pe/pe=500 + pe/pe=5000



ALUMINUM HYDRIDE - [illegible] PERCHLORATE PERFORMANCE CURVES FIGURE 207



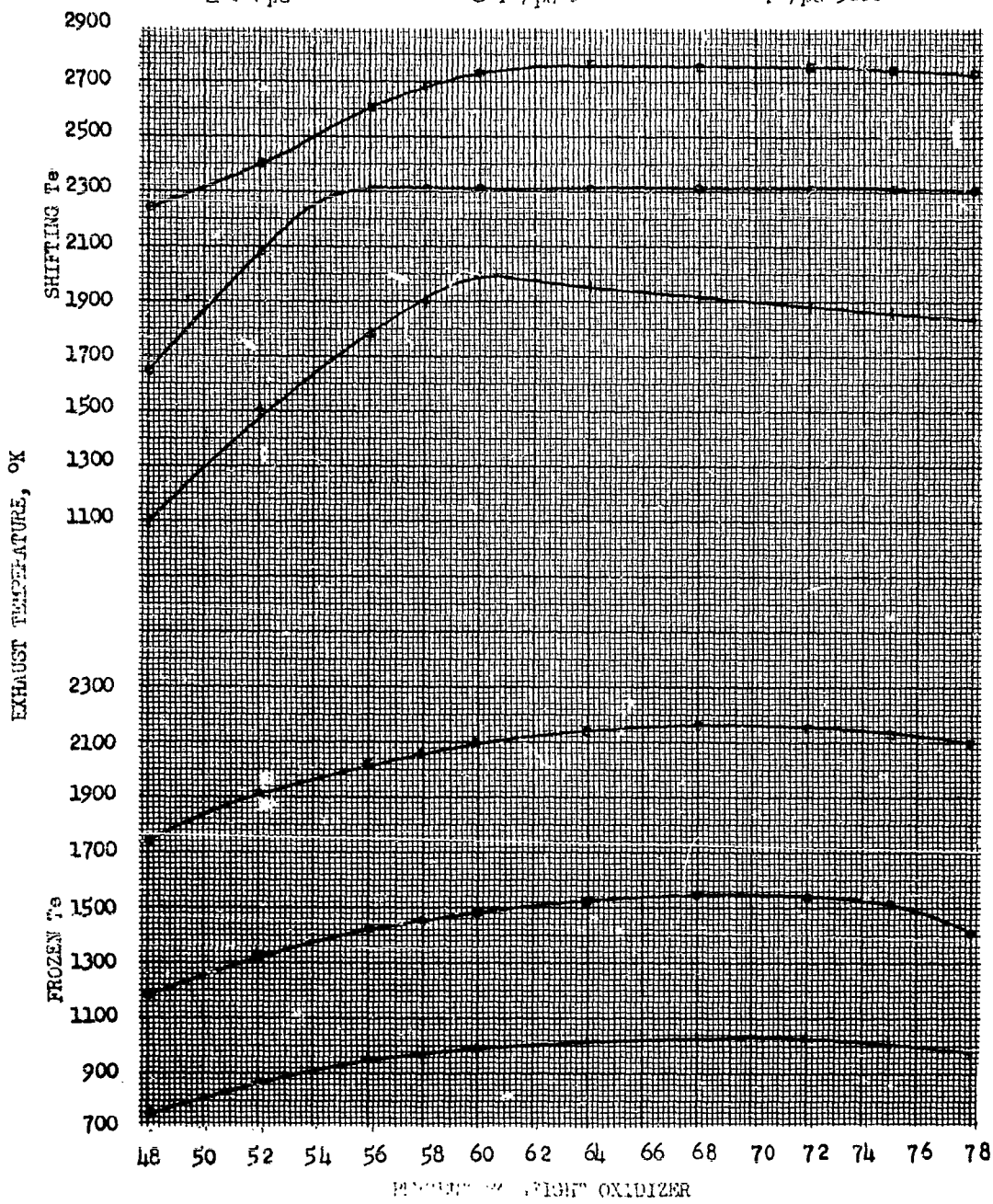
ALUMINUM HYDRIDES - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 208

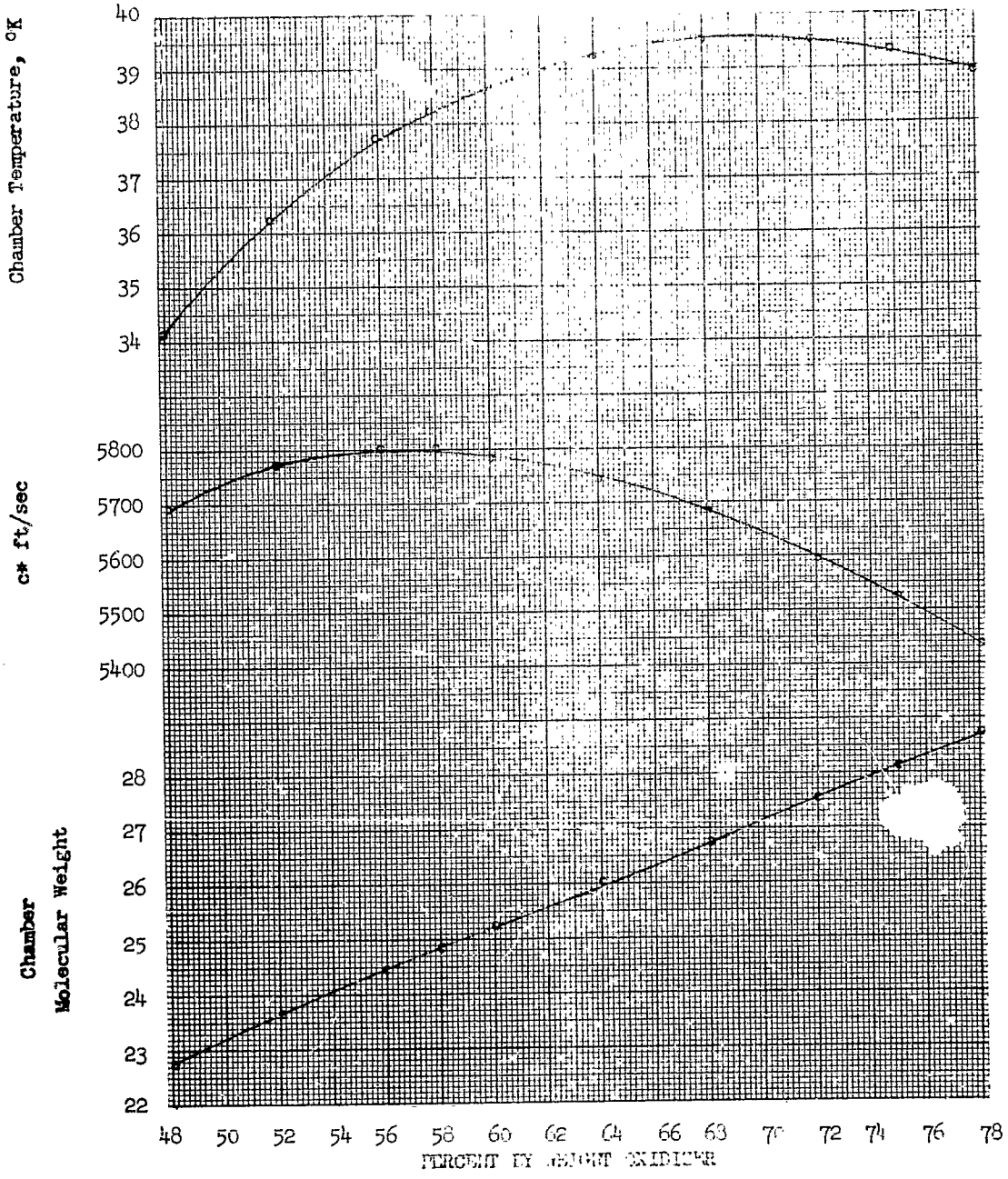


ALUMINUM HYDRIDE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 209

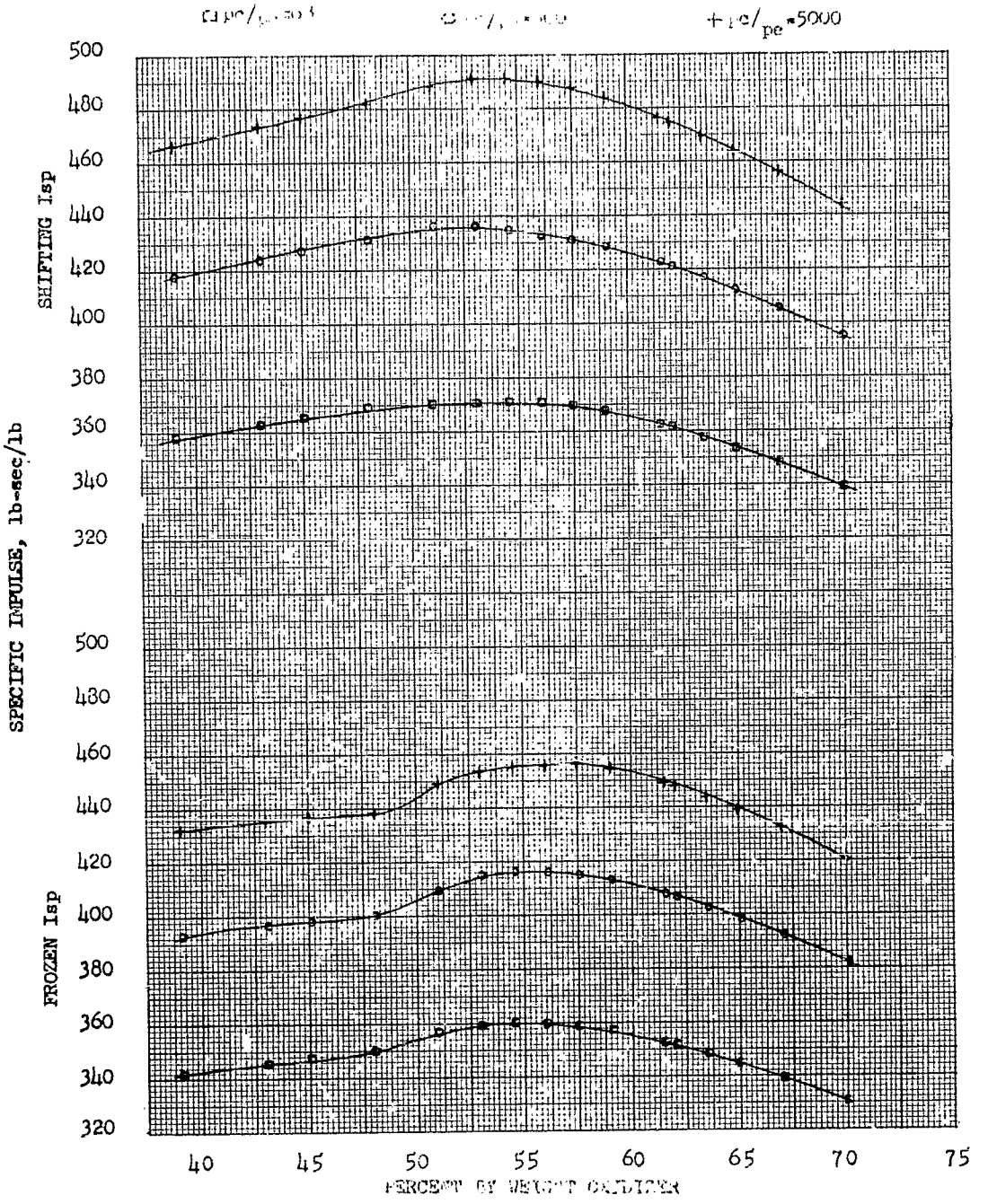
p_c = 1000 psi

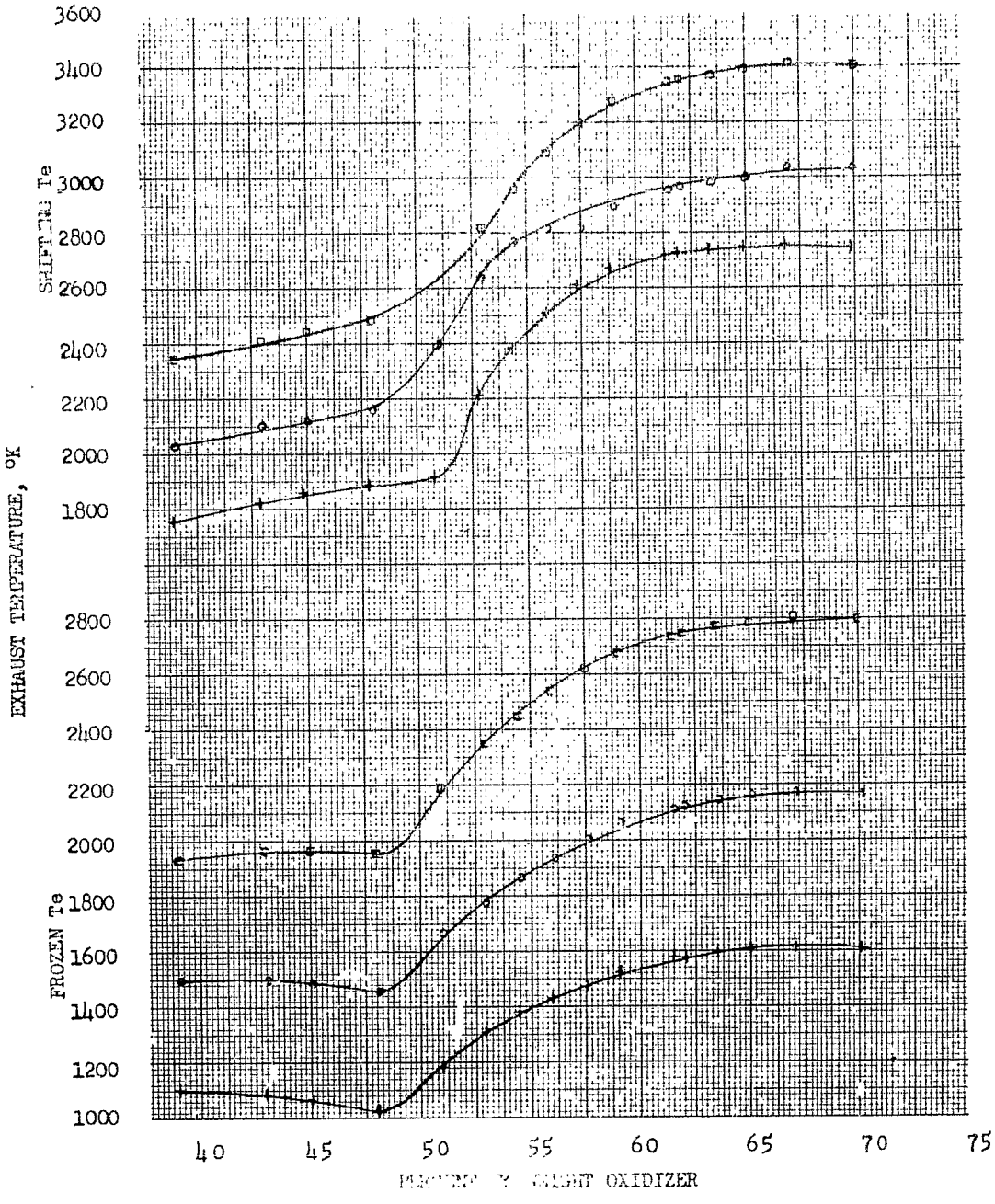
△ p_c/p_e=68 O p_c/p_e=500 + p_c/p_e=5000



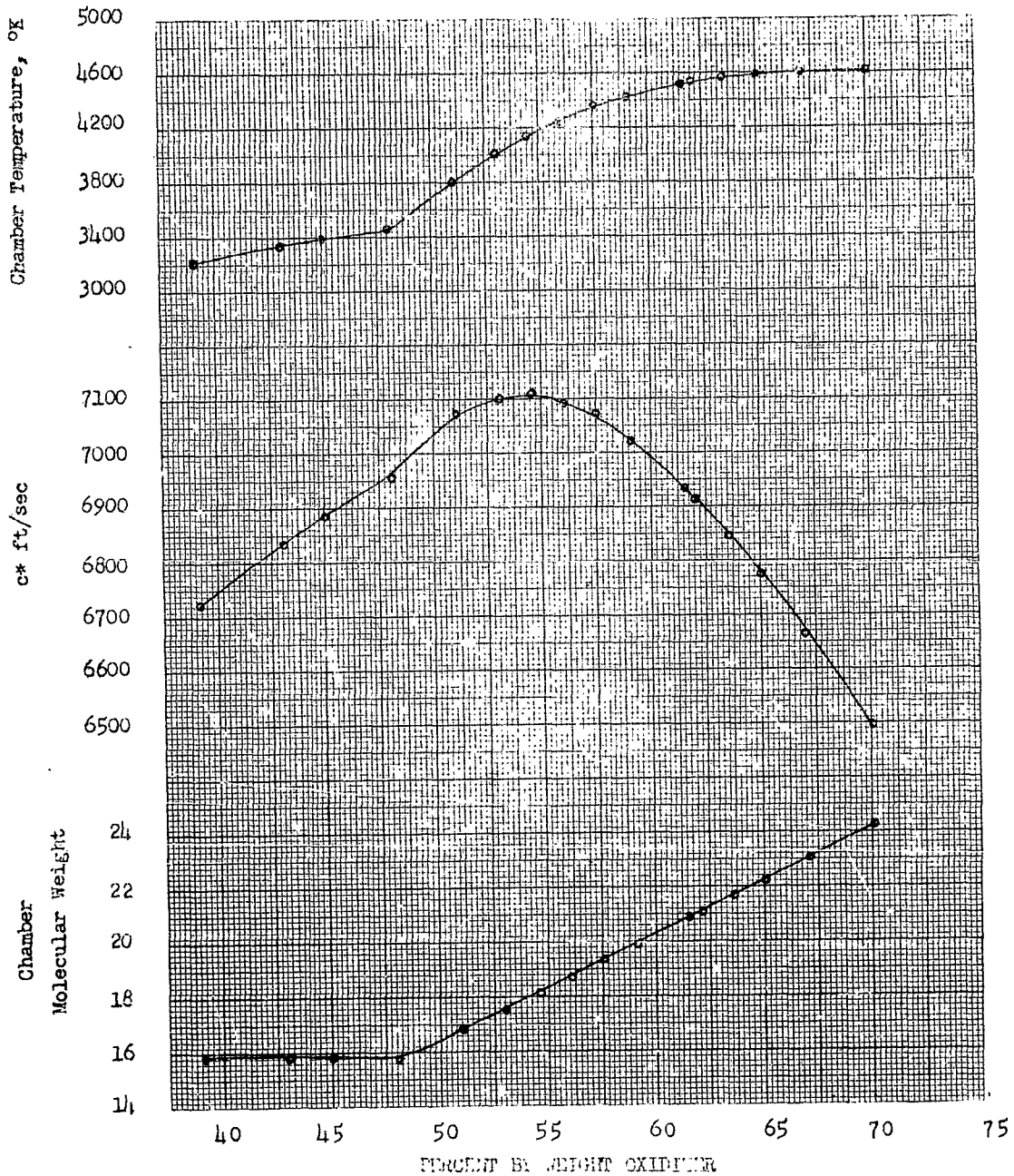

Chamber Temperature, °K
40
39
38
37
36
35
34
c* ft/sec
5800
5700
5600
5500
5400
Chamber Molecular Weight
28
27
26
25
24
23
22
48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78
PERCENT BY WEIGHT OXIDIZER

BERYLLIUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 211



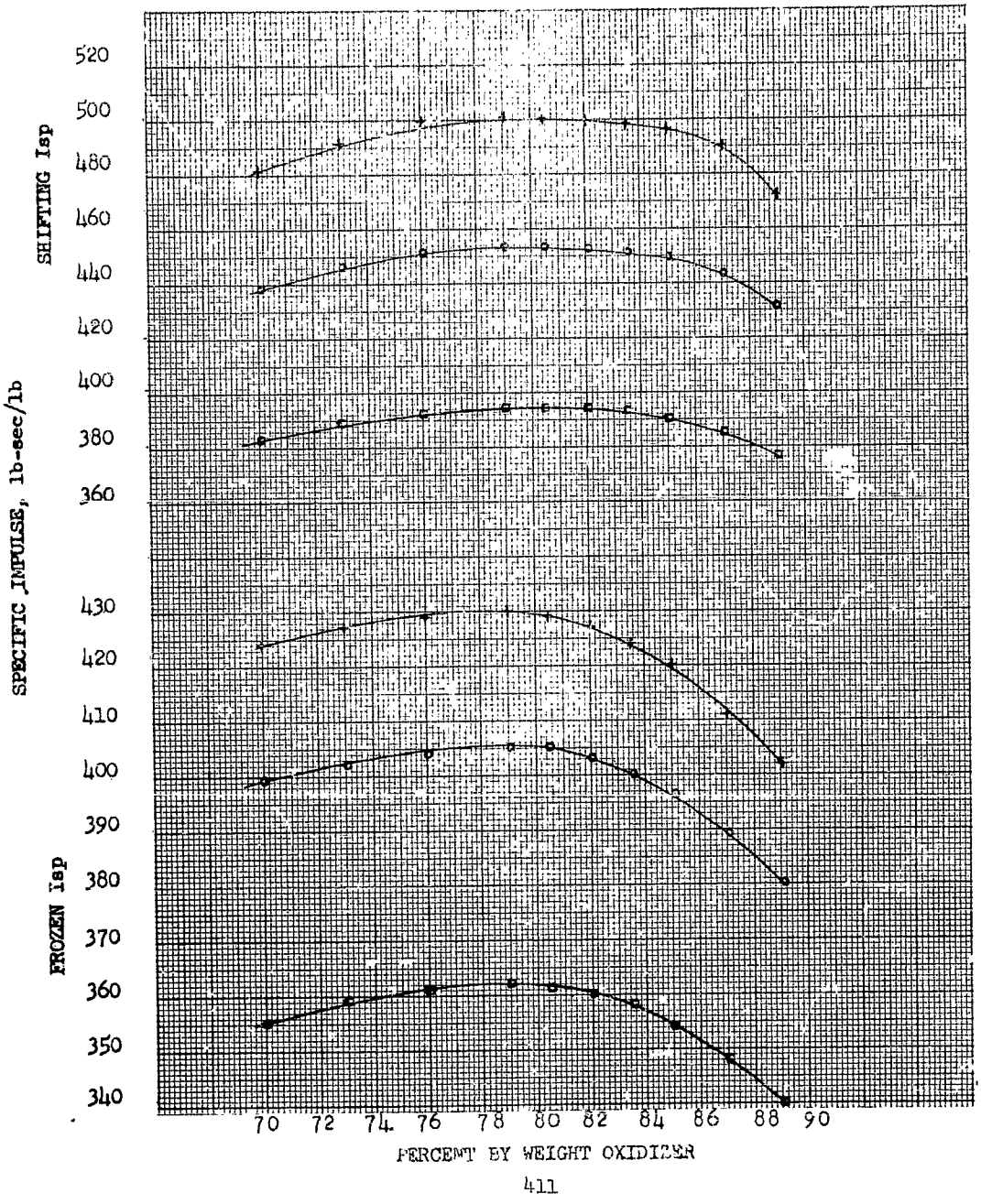

EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
40
45
50
55
60
65
70
75
PERCENT BY WEIGHT OXIDIZER

BERYLLIUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 213

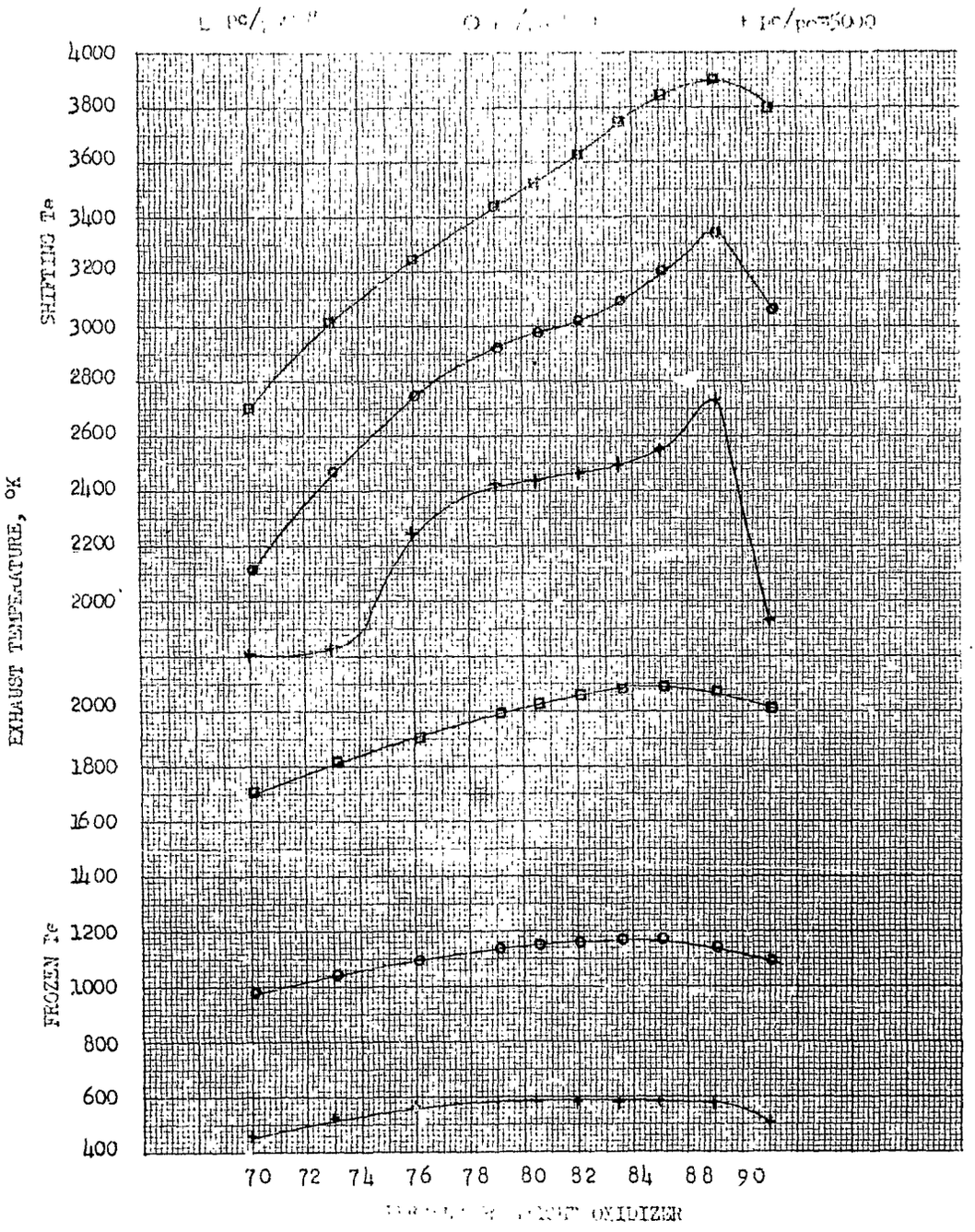


BERYLLIUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 211

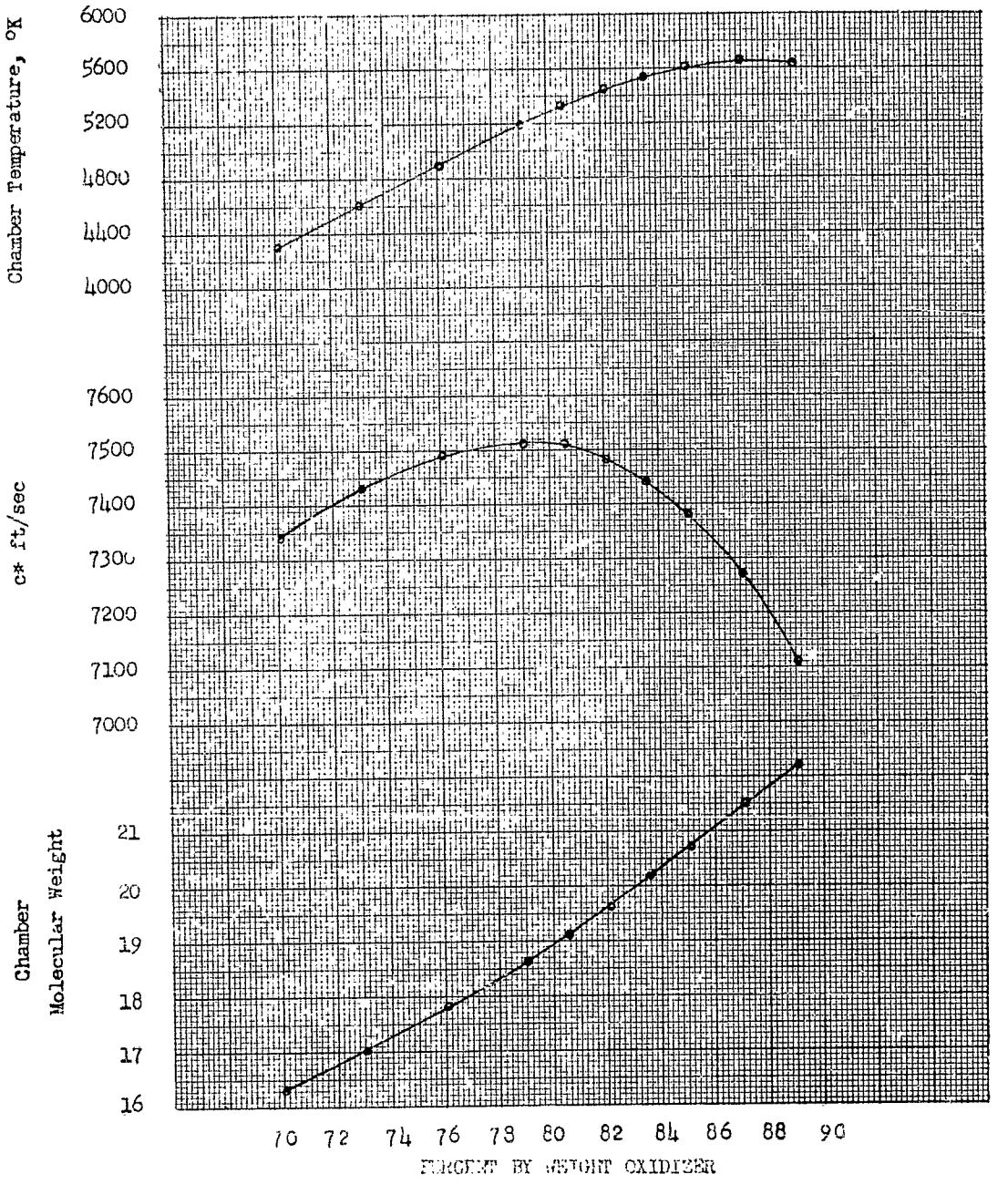
□ p_c/p_e=500 ○ p_c/p_e=1000 + p_c/p_e=5000



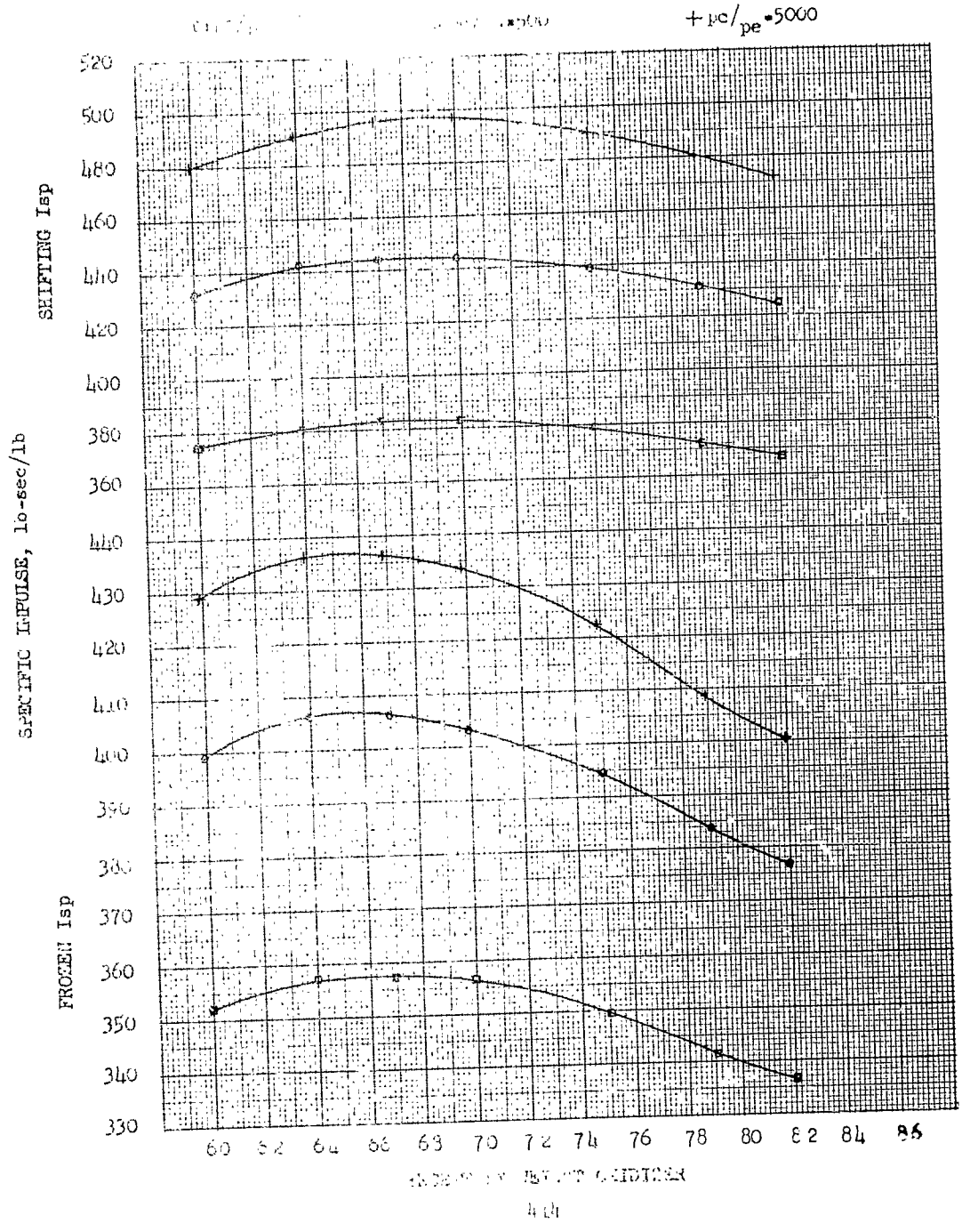
BERYLLIUM HYDRIDE - [illegible] CURVES FIGURE 215

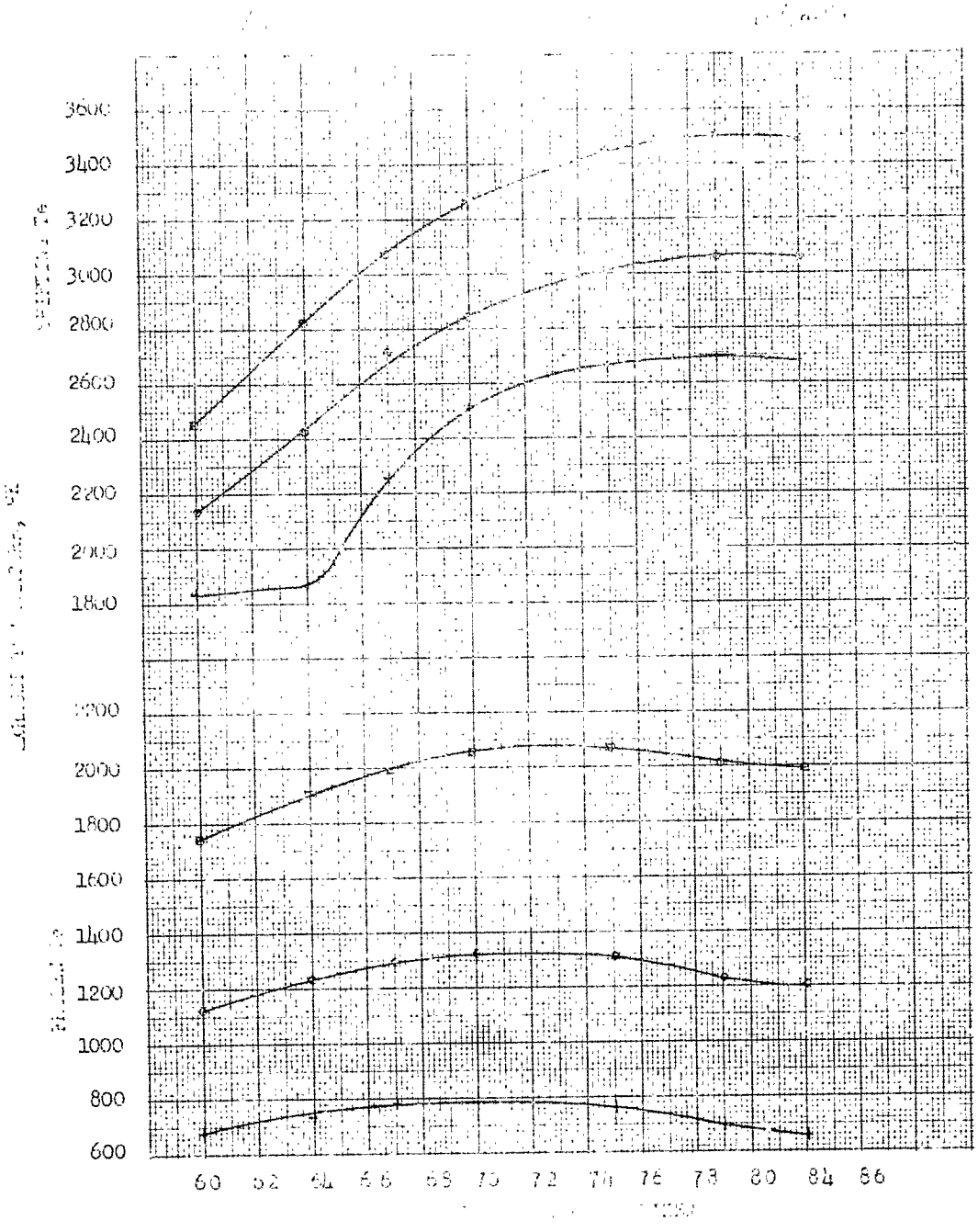


BERYLLIUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 216

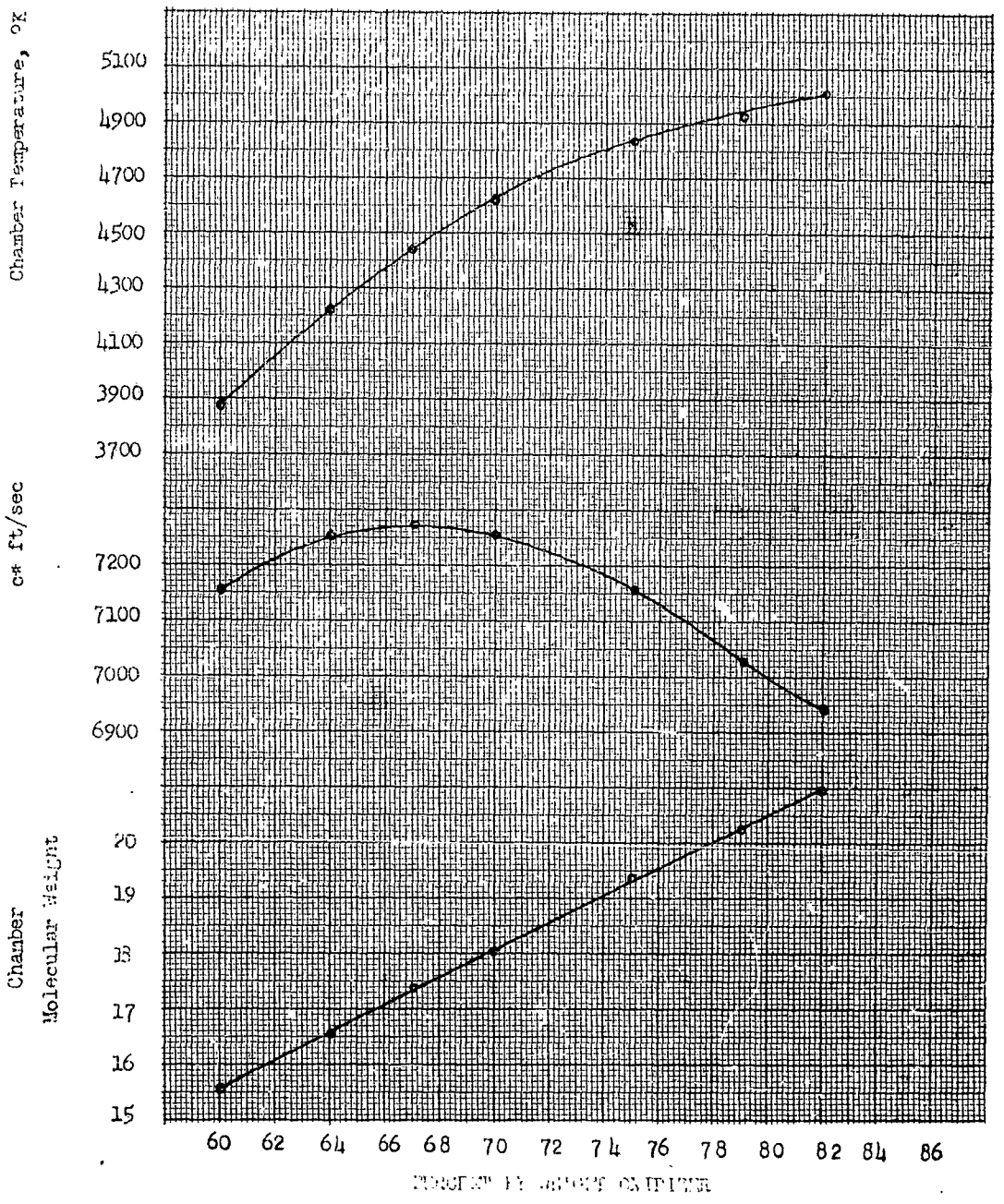


PERFORMANCE CURVES FIGURE 217

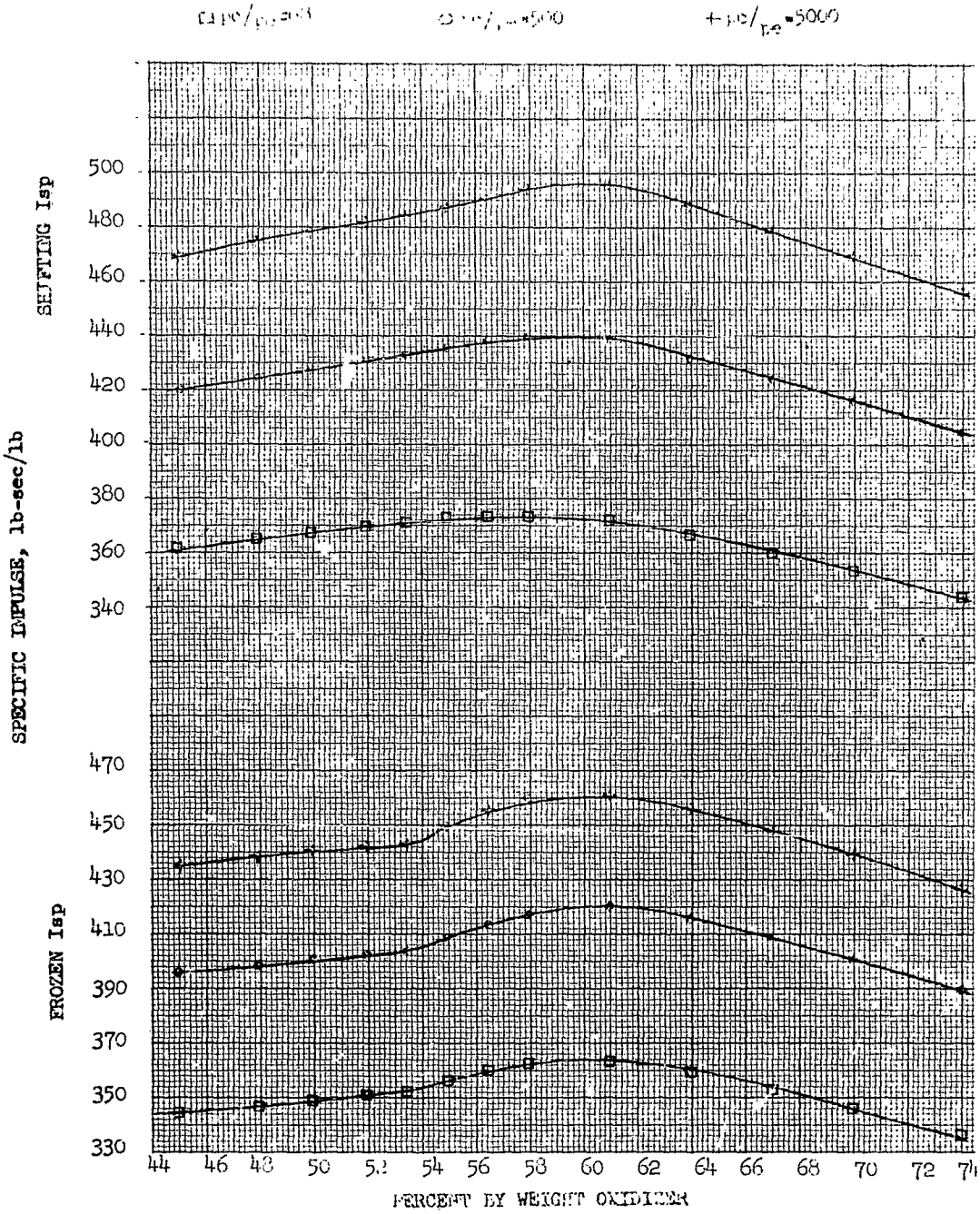


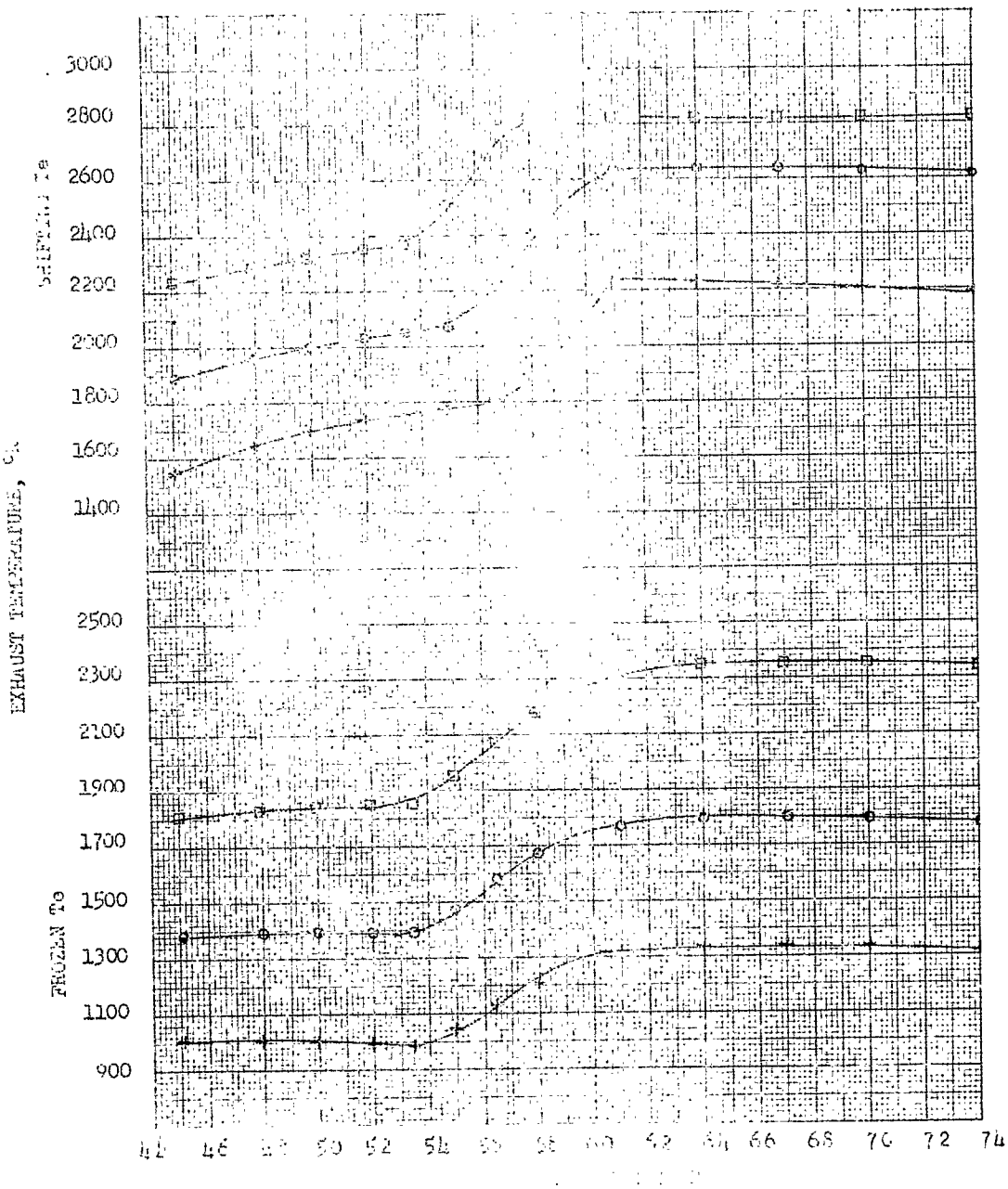

3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
2200
2000
1800
1600
1400
1200
1000
800
600
60
62
64
66
68
70
72
74
76
78
80
82
84
86

BERYLLIUM HYDRIDE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 219



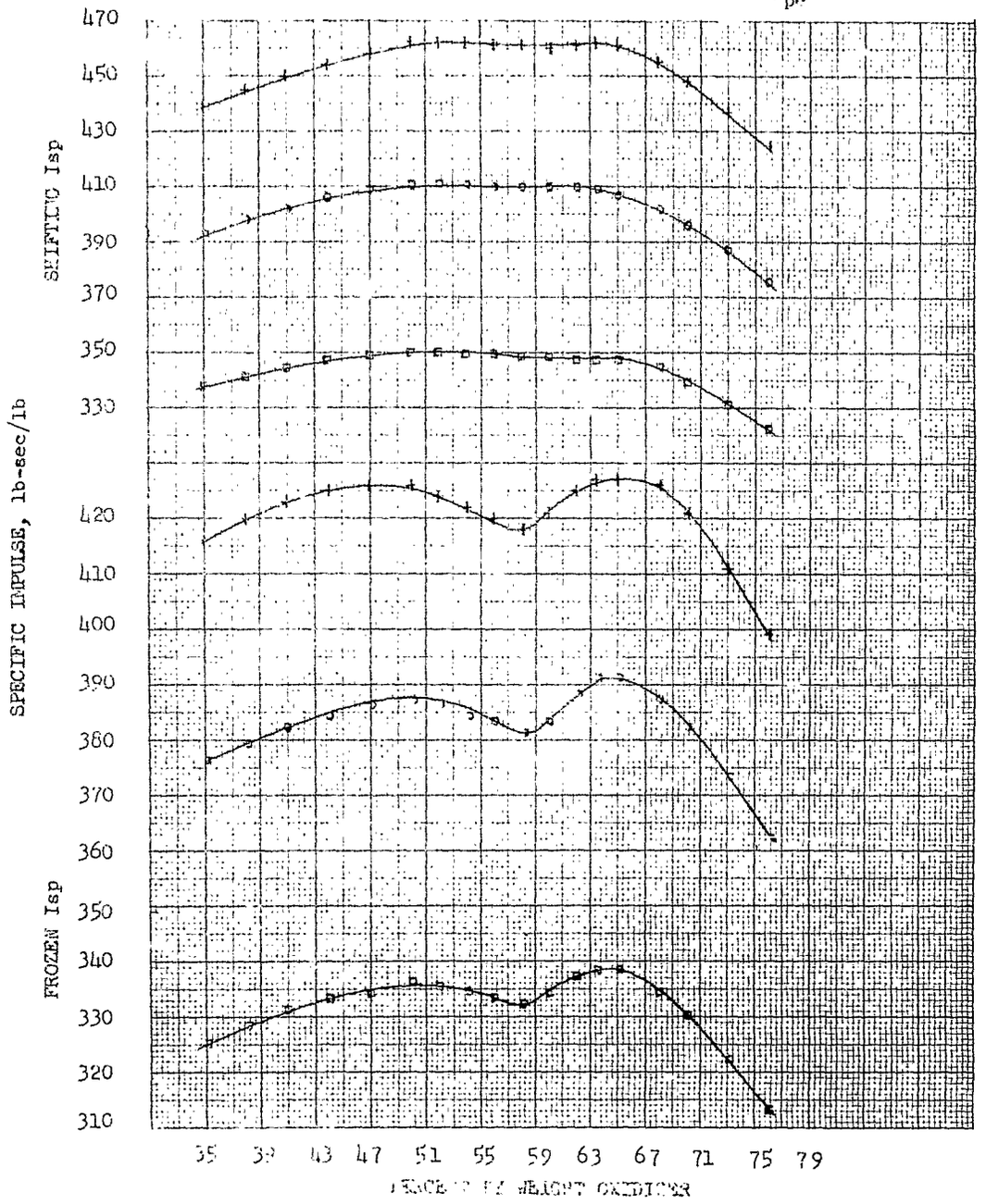
BERYLLIUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 22



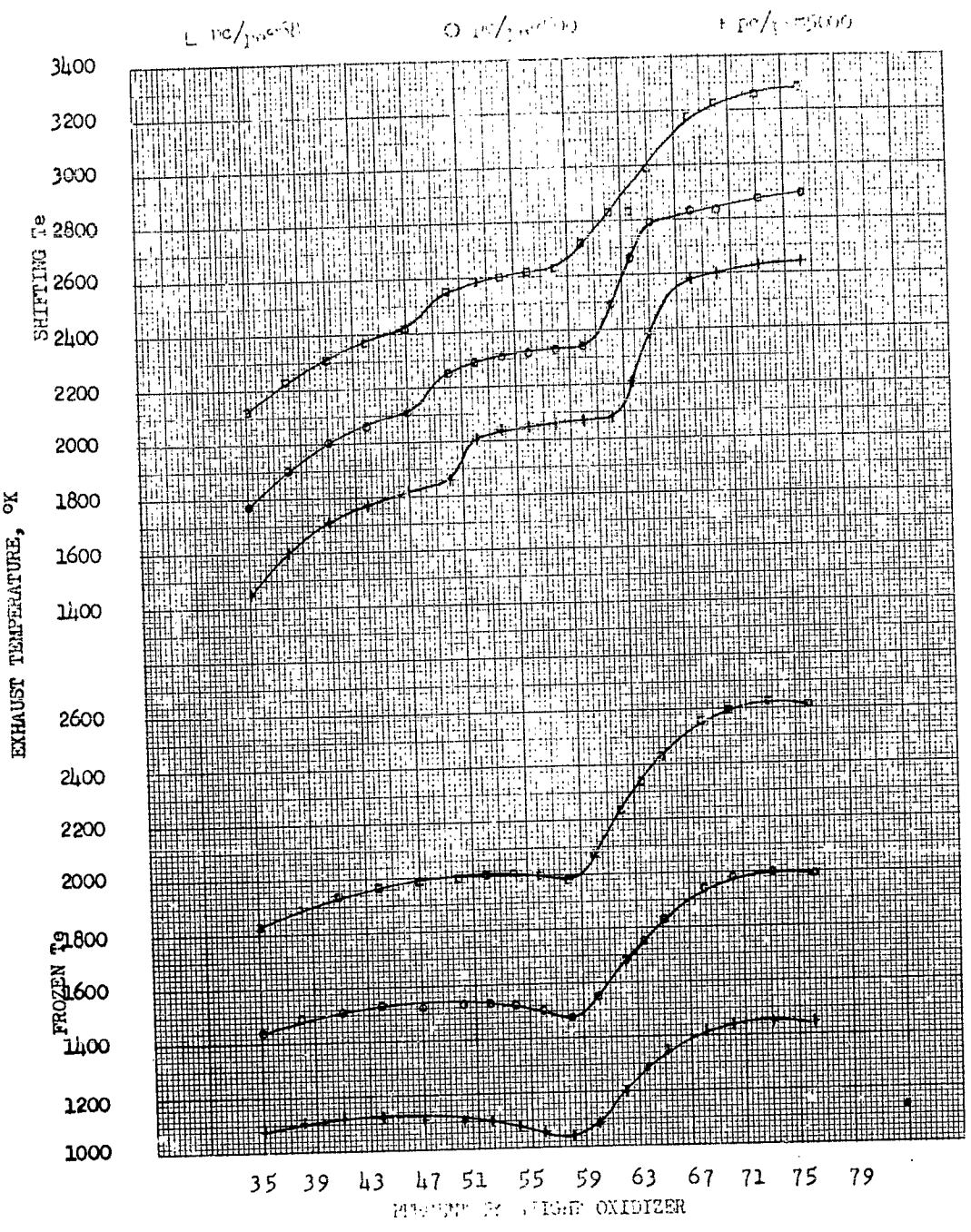

EXHAUST TEMPERATURE, °F
FROZEN Te
3000
2800
2600
2400
2200
2000
1800
1600
1400
2500
2300
2100
1900
1700
1500
1300
1100
900
42
46
50
52
54
66
68
70
72
74

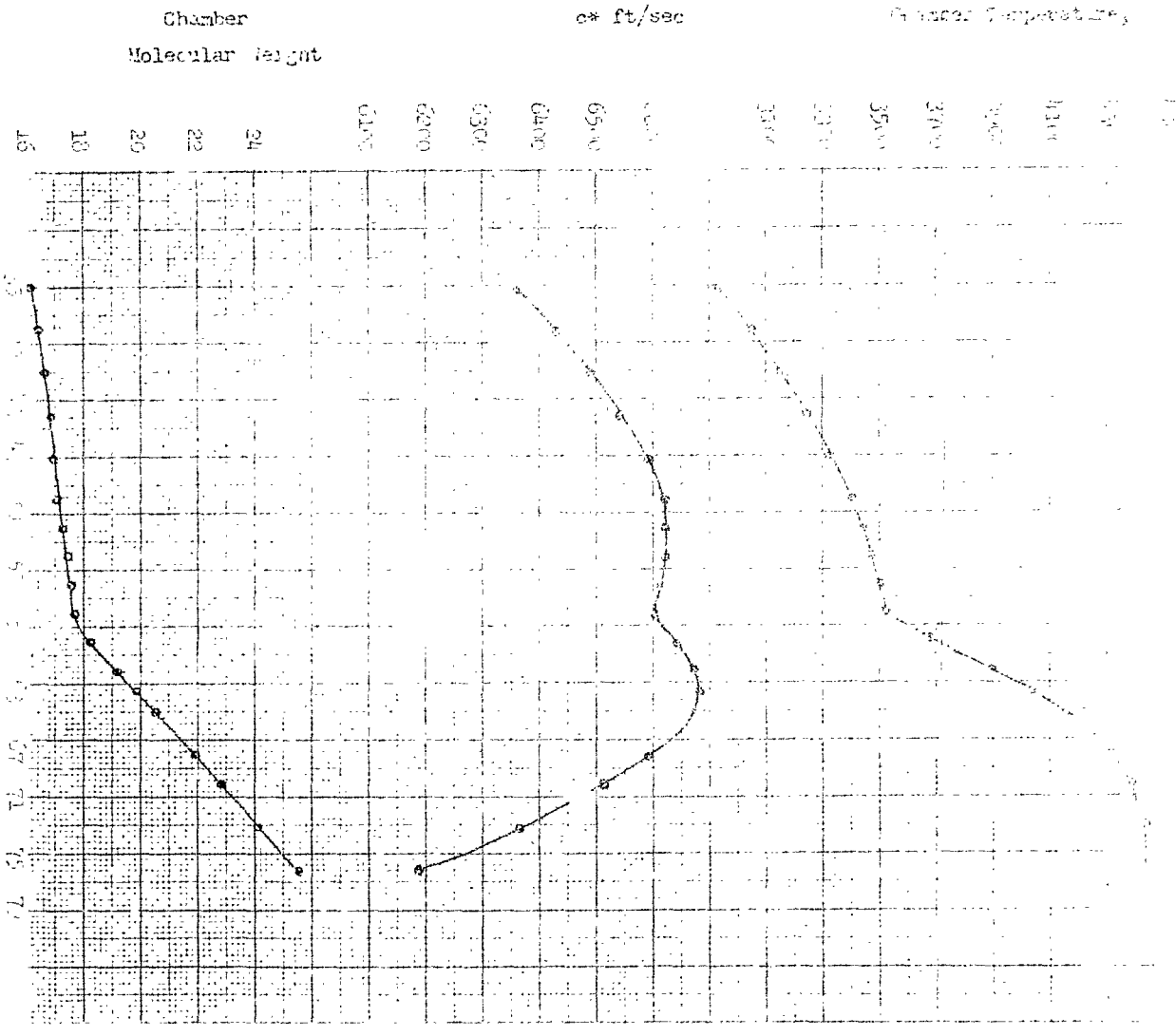
Chamber Temperature, °F
c* ft/sec
Chamber
3600
3400
3200
3000
7100
7000
6900
6800
6700
6600
17
16
15
14
62
64
66
68
70
72
74

BERYLLIUM HYDRIDE - LITHIUM BOROHYDRIDE PERFORMANCE CURVES FIGURE 223

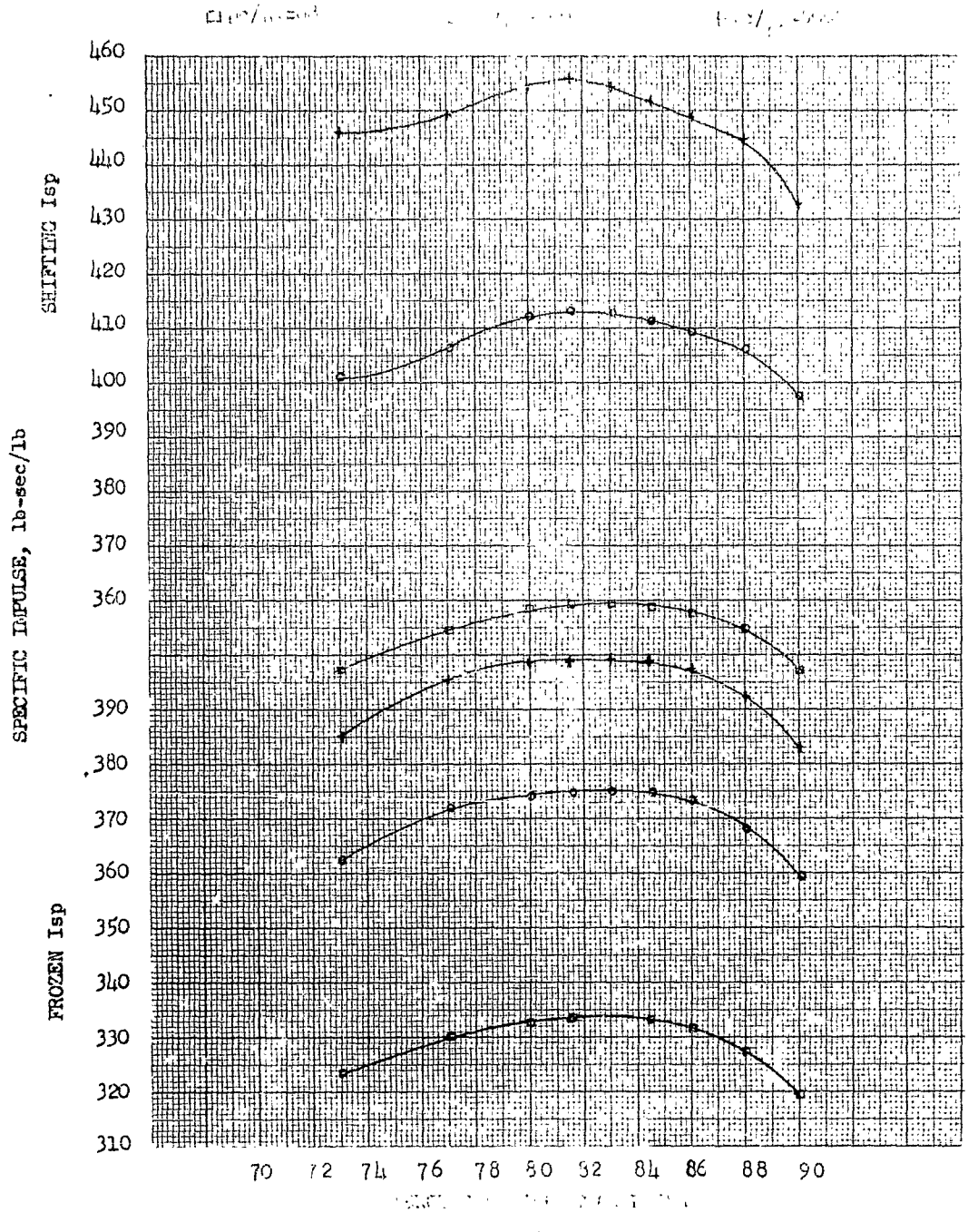


BERYLLIUM HYDRIDE – NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 224

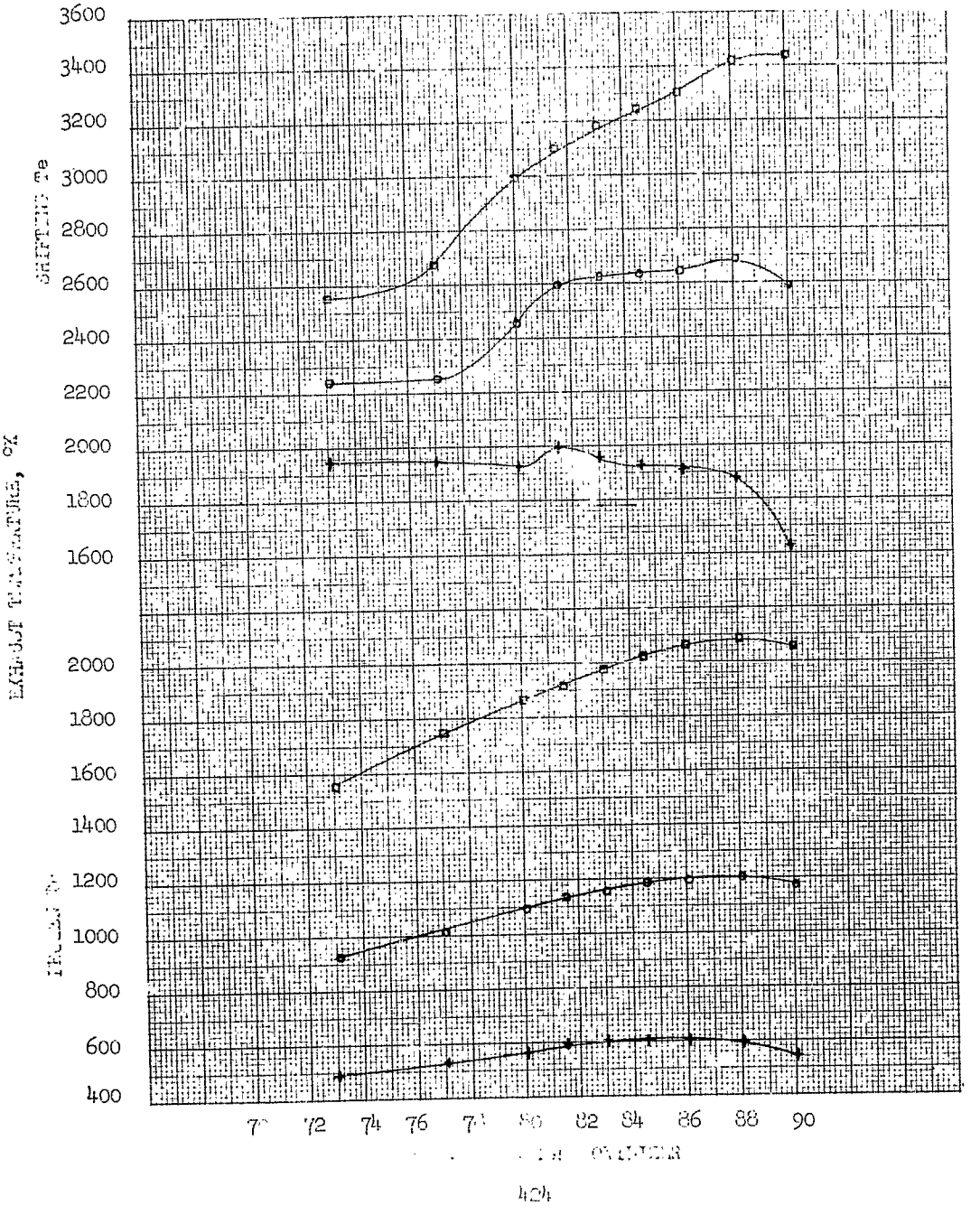


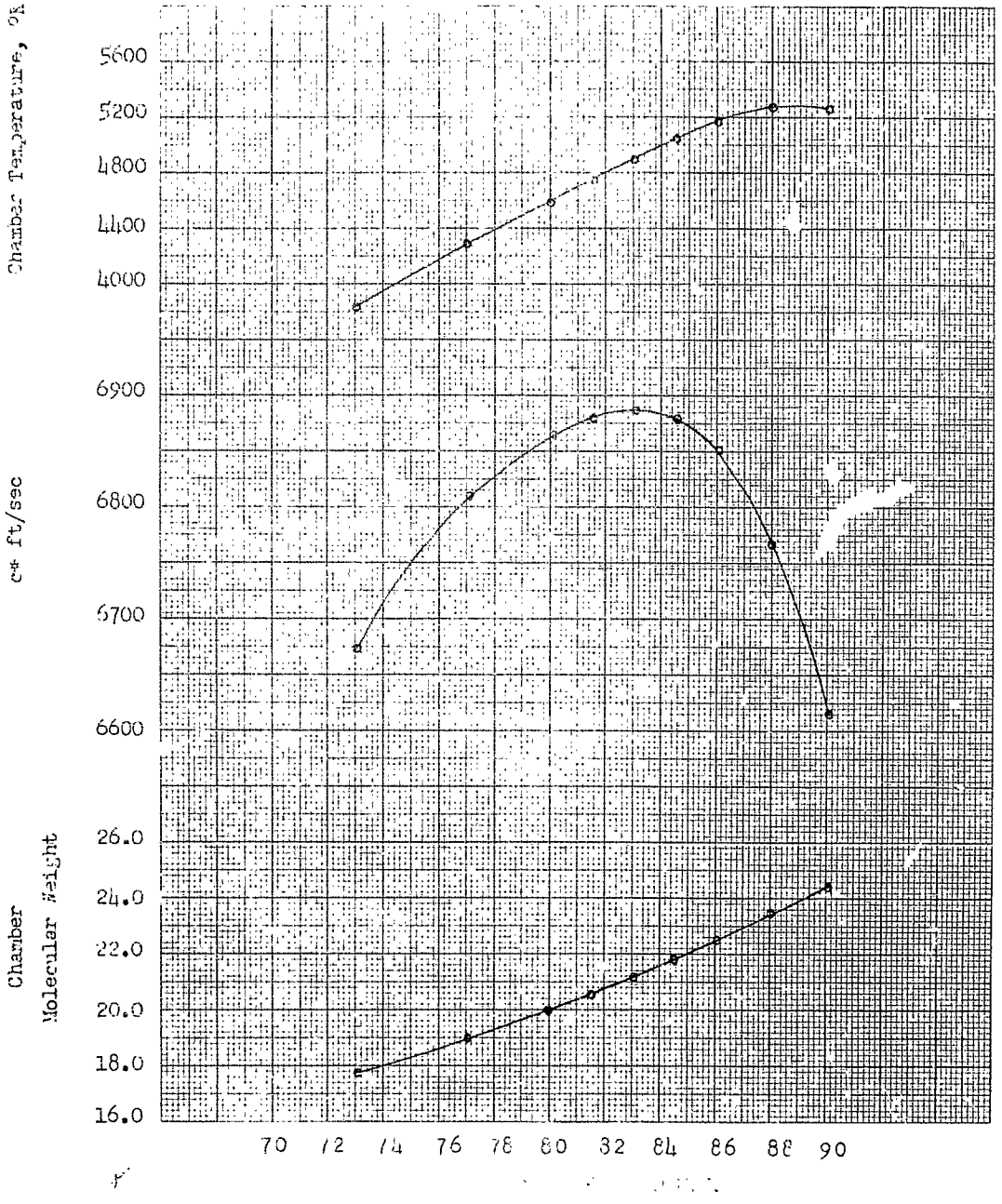

Chamber
Molecular Weight
c* ft/sec
16
18
20
22
24
6100
6200
6300
6400
6500
3400
3500
3600
3700
3800
3900
70
72
74
76

BERYLLIUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 226

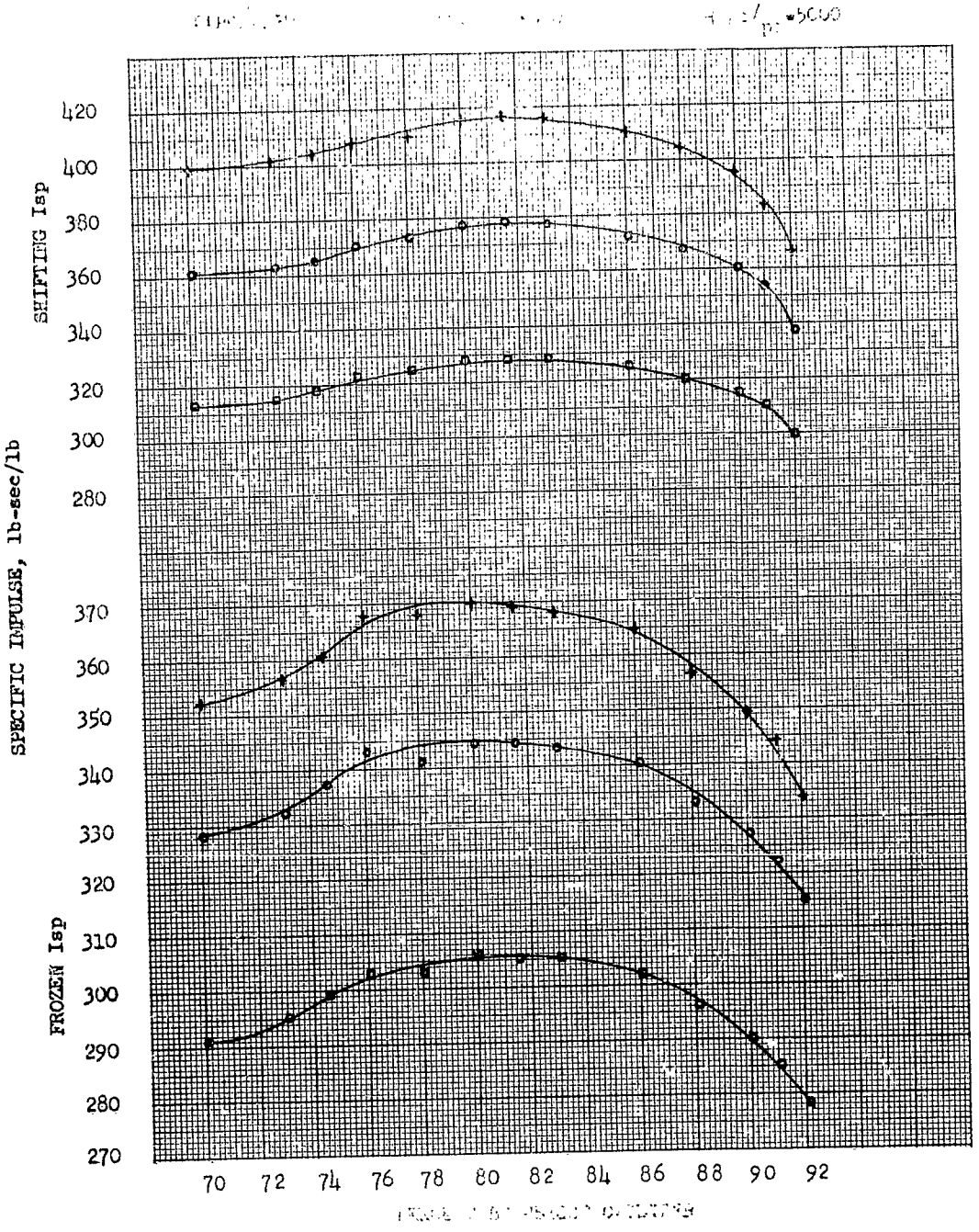


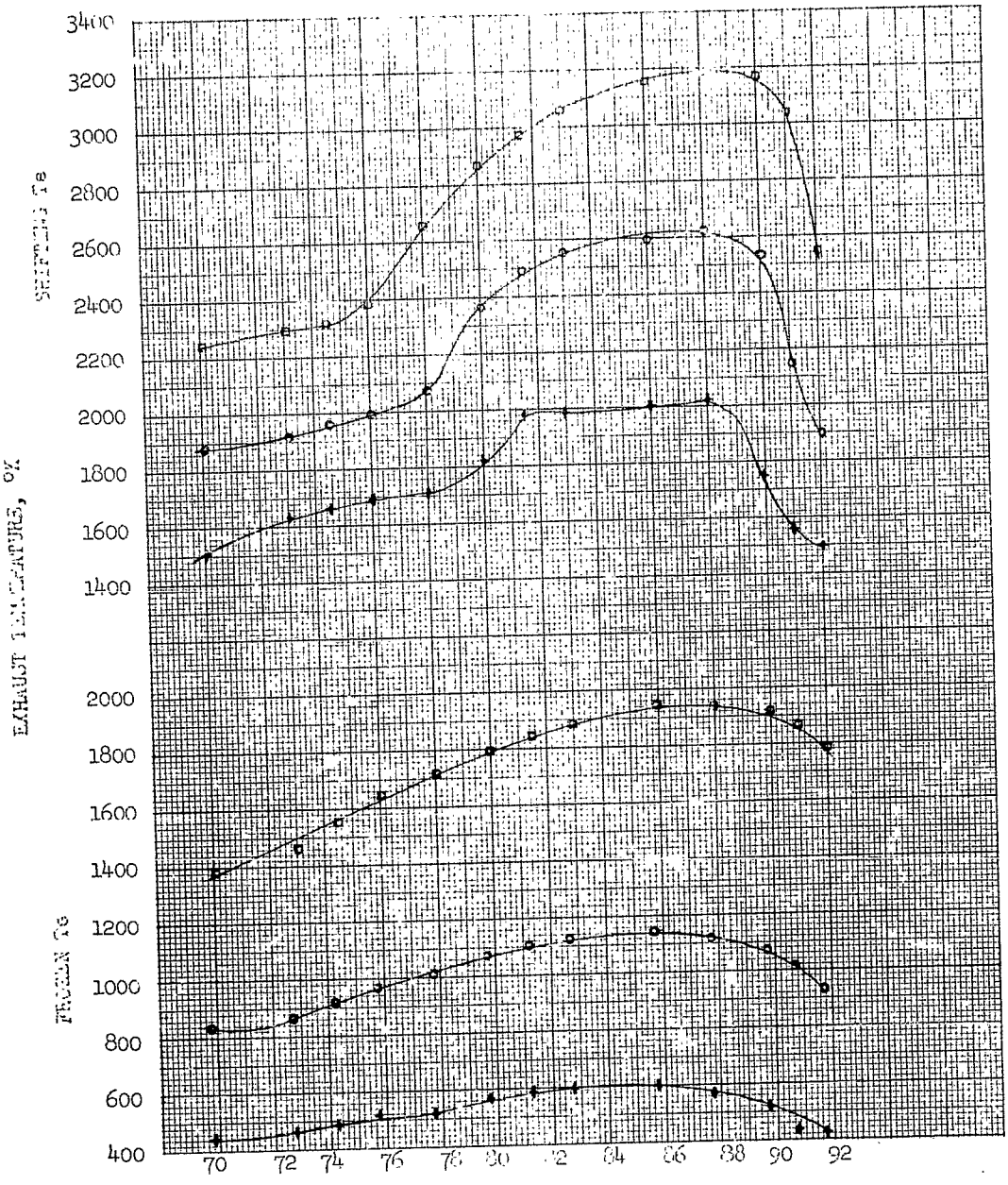
BERYLLIUM HYDRIDE - BORON TRIFLUORIDE PERFORMANCE CURVES FIGURE 27

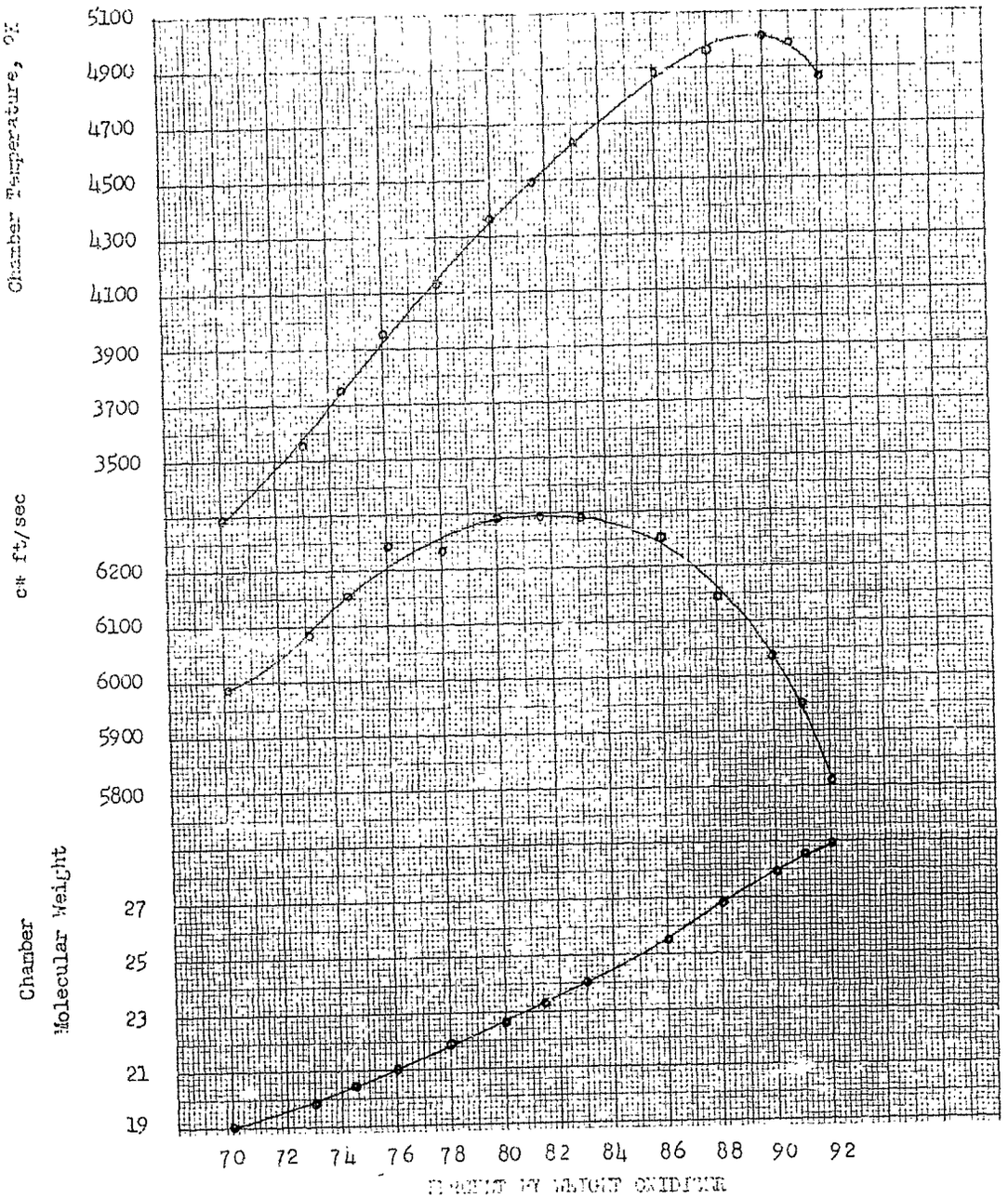



Chamber Temperature, °K
5600
5200
4800
4400
4000
c* ft/sec
6900
6800
6700
6600
Chamber Molecular Weight
26.0
24.0
22.0
20.0
18.0
16.0
70 72 74 76 78 80 82 84 86 88 90

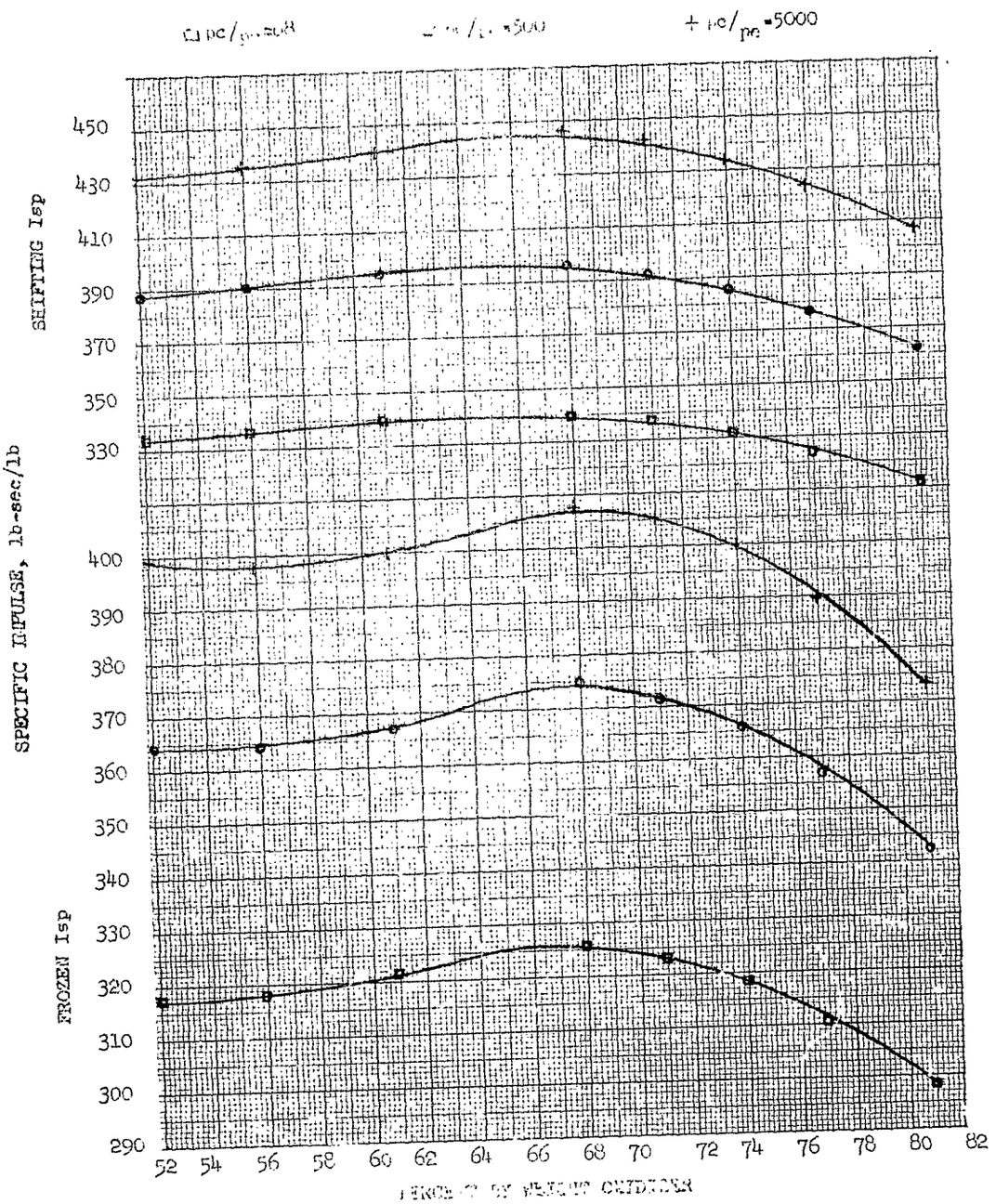
BERYLLIUM HYDRIDE - OXYGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 229



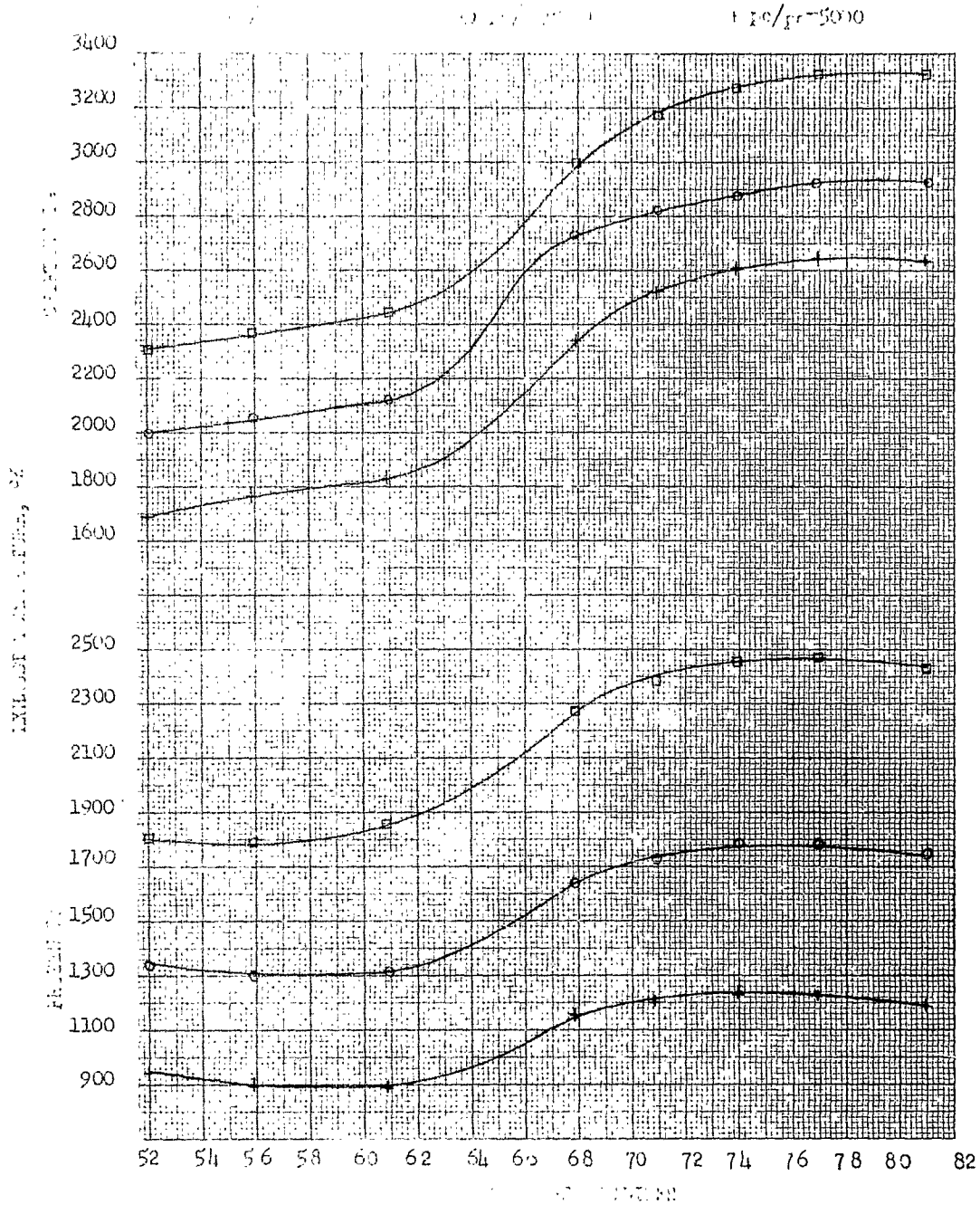

EXHAUST TEMPERATURE, °F
SHEPPARD °F
FRICTION °F
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
2000
1800
1600
1400
1200
1000
800
600
400
70
72
74
76
78
80
82
84
86
88
90
92

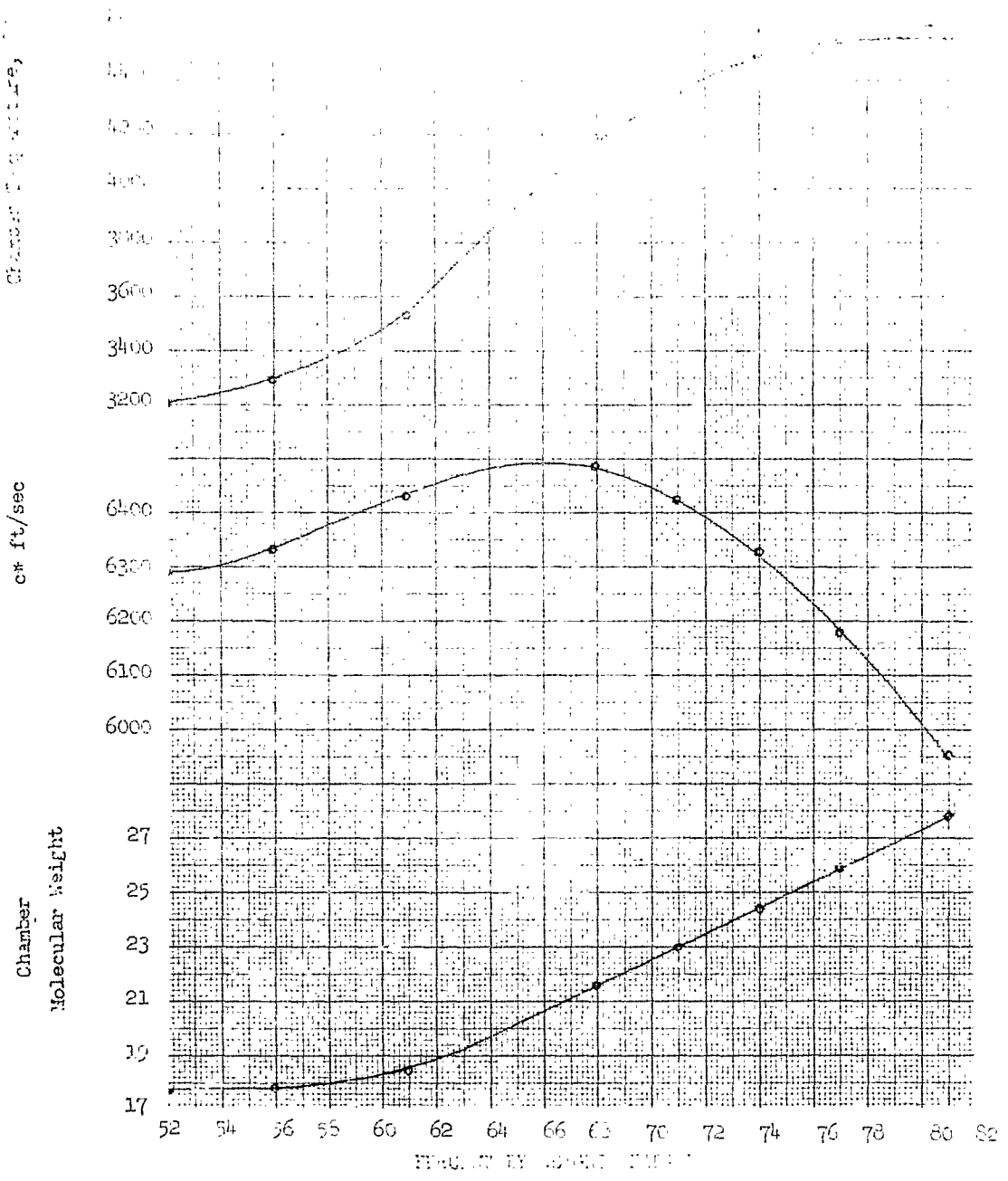

Chamber Temperature, °K
5100
4900
4700
4500
4300
4100
3900
3700
3500
c* ft/sec
6200
6100
6000
5900
5800
Chamber Molecular Weight
27
25
23
21
19
70 72 74 76 78 80 82 84 86 88 90 92

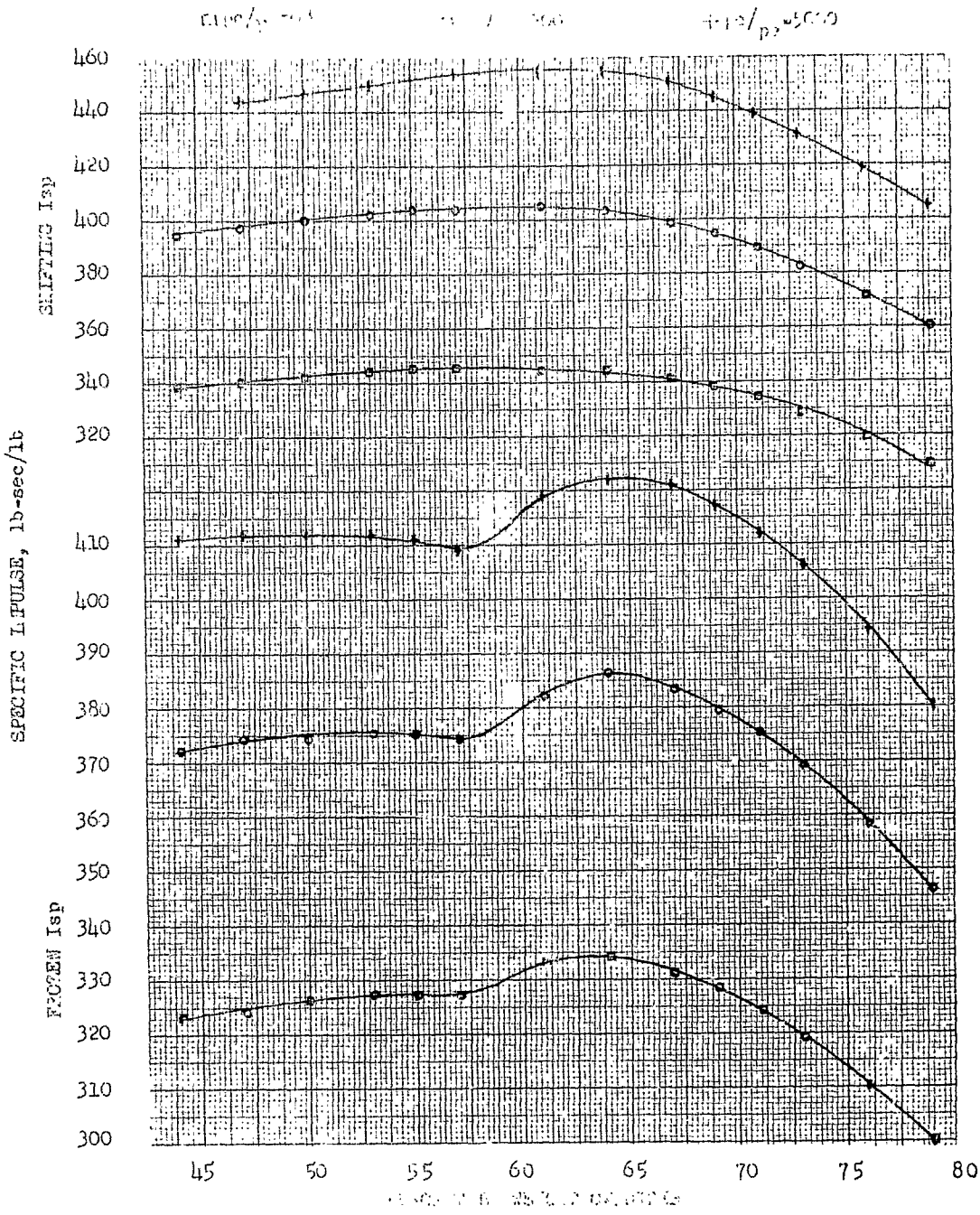
BERYLLIUM HYDRIDE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 232



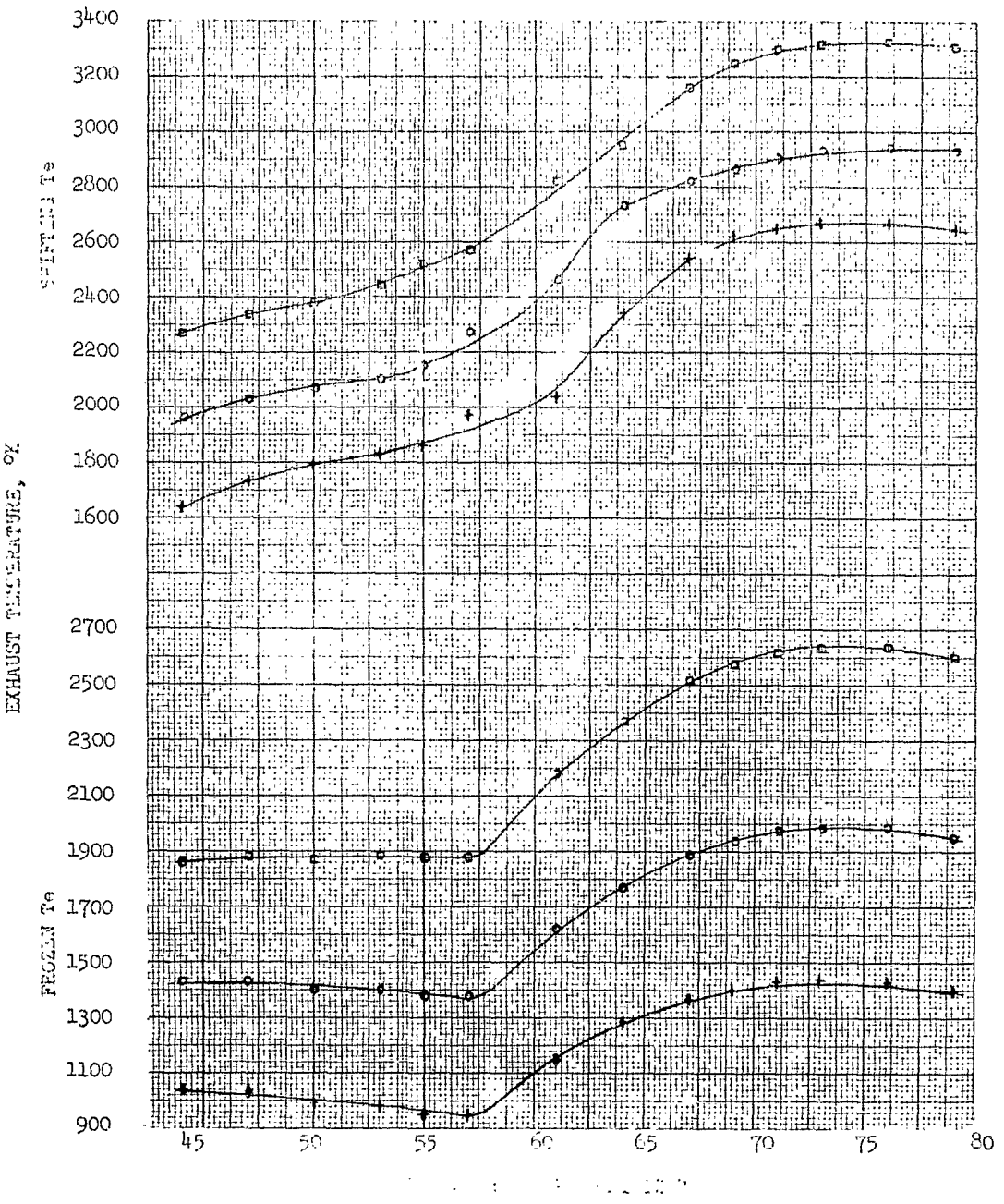
PERFORMANCE CURVES FIGURE 233

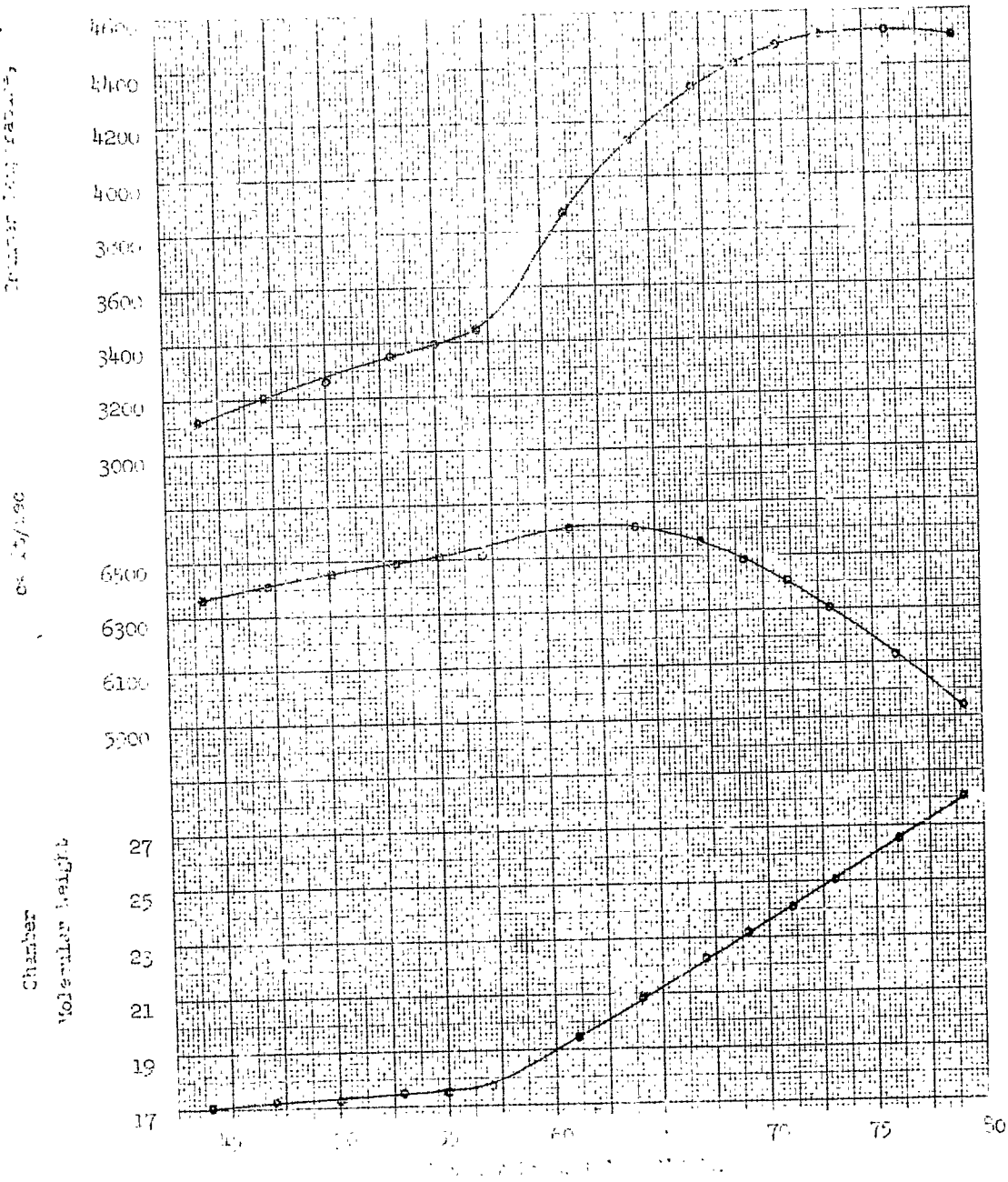


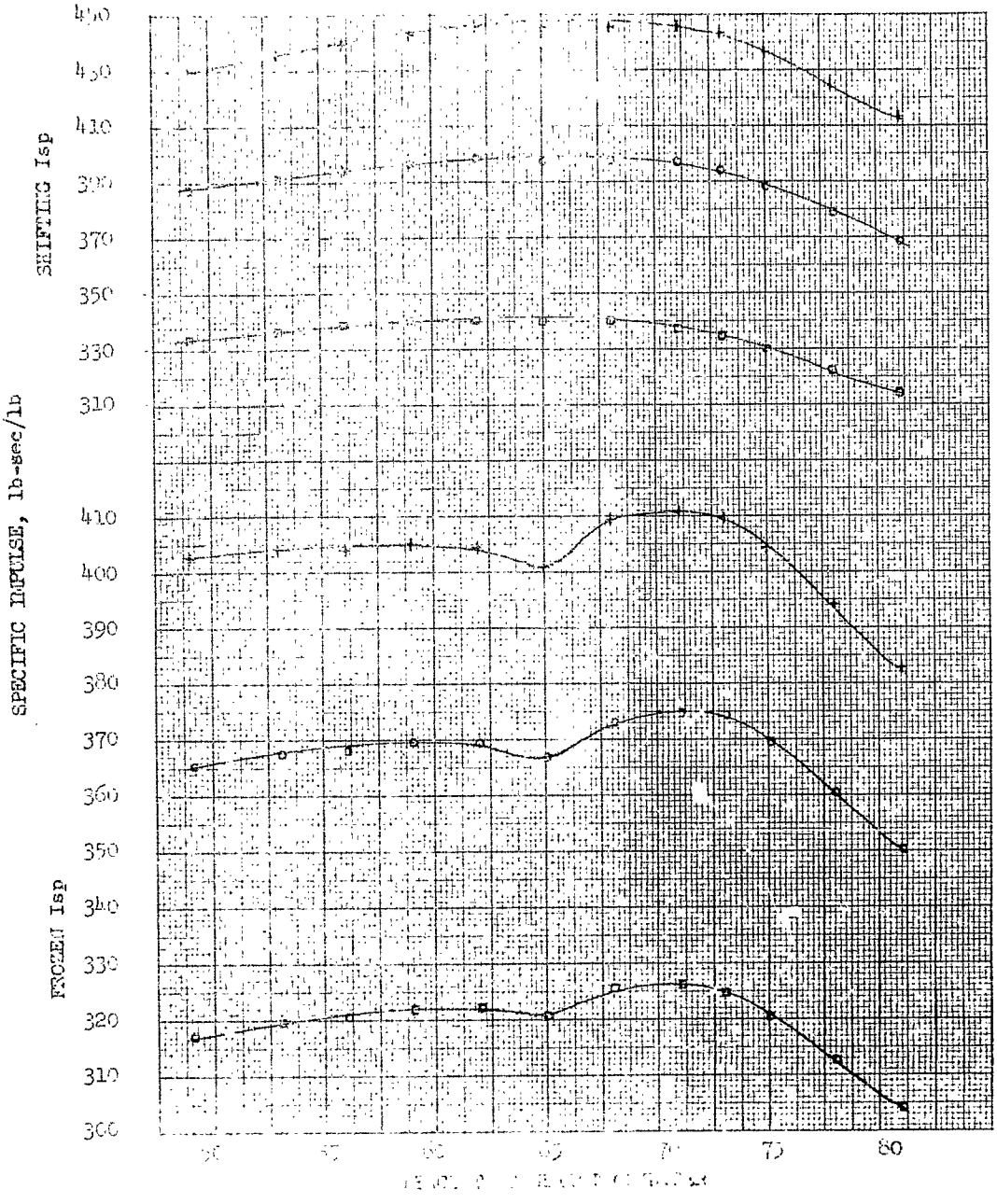

c* ft/sec
6400
6300
6200
6100
6000
Chamber
Molecular Weight
27
25
23
21
19
17
52
54
56
58
60
62
64
66
68
70
72
74
76
78
80
82

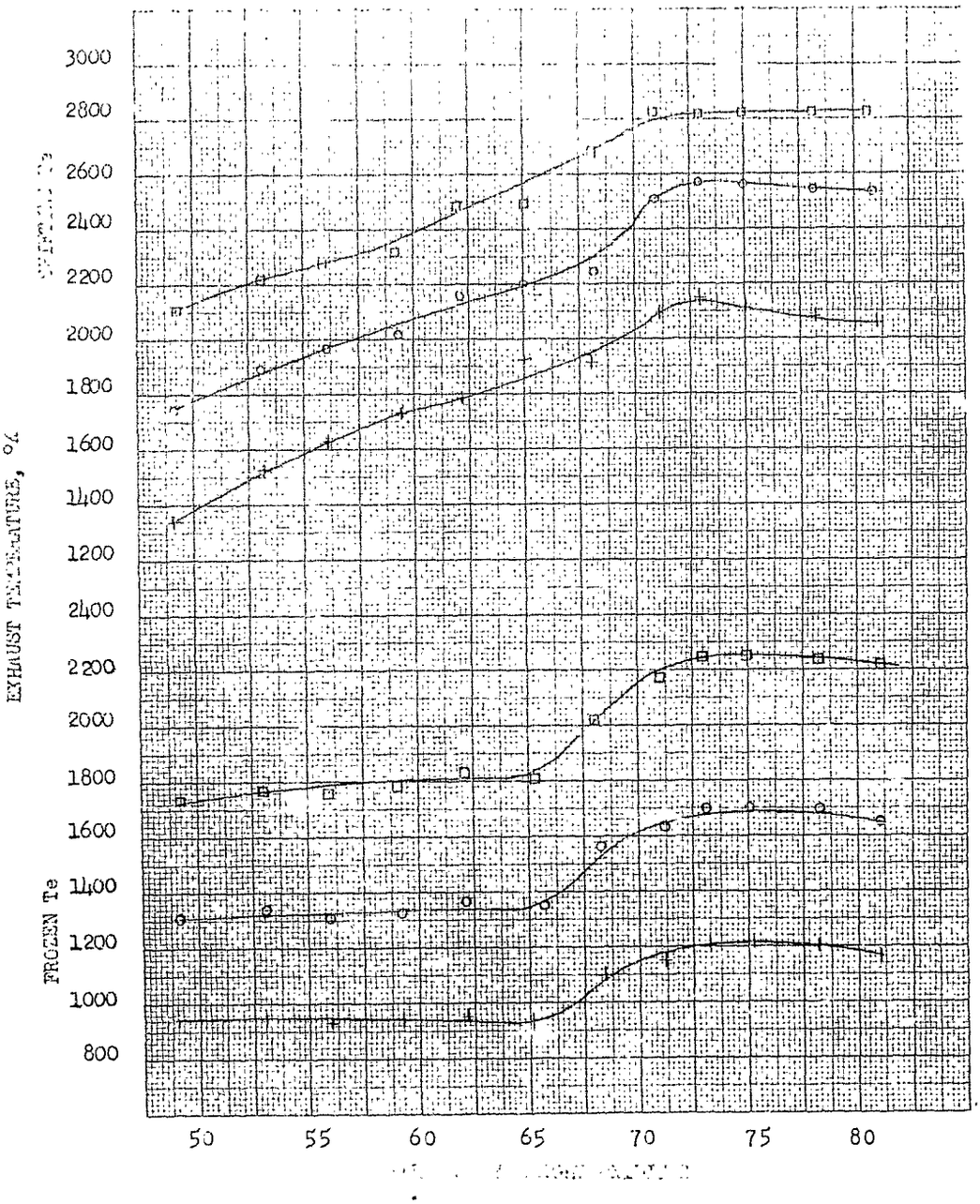

SHIFTING Isp
FROZEN Isp
SPECIFIC IMPULSE, lb-sec/lb
460
440
420
400
380
360
340
320
410
400
390
380
370
360
350
340
330
320
310
300
45
50
55
60
65
70
75
80

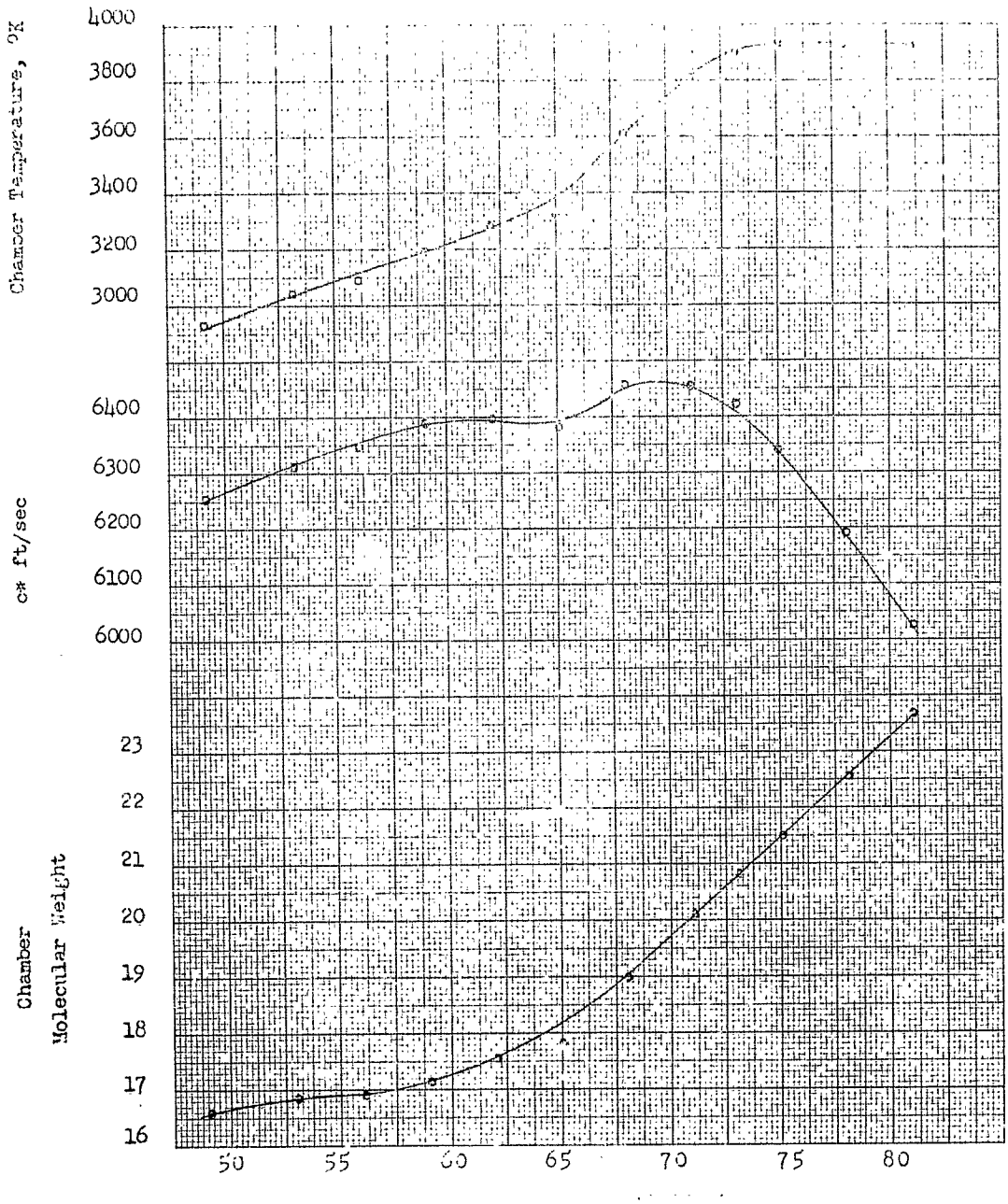
BERYLLIUM HYDRIDE - [illegible] EQUILIBRIUM CURVES FIGURE 4.30

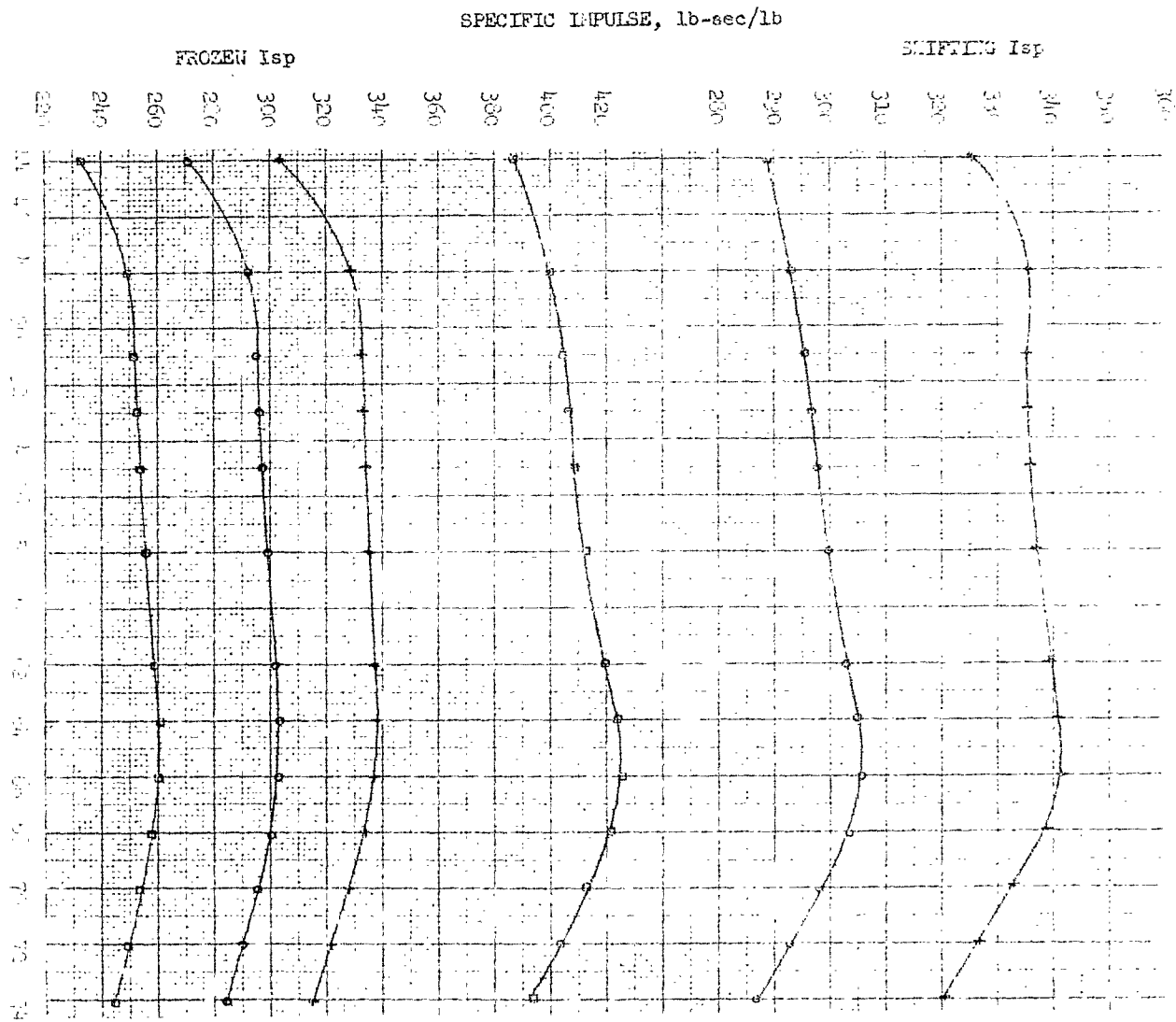



4400
4200
4000
3800
3600
3400
3200
3000
6500
6300
6100
5900
27
25
23
21
19
17
70
75
80

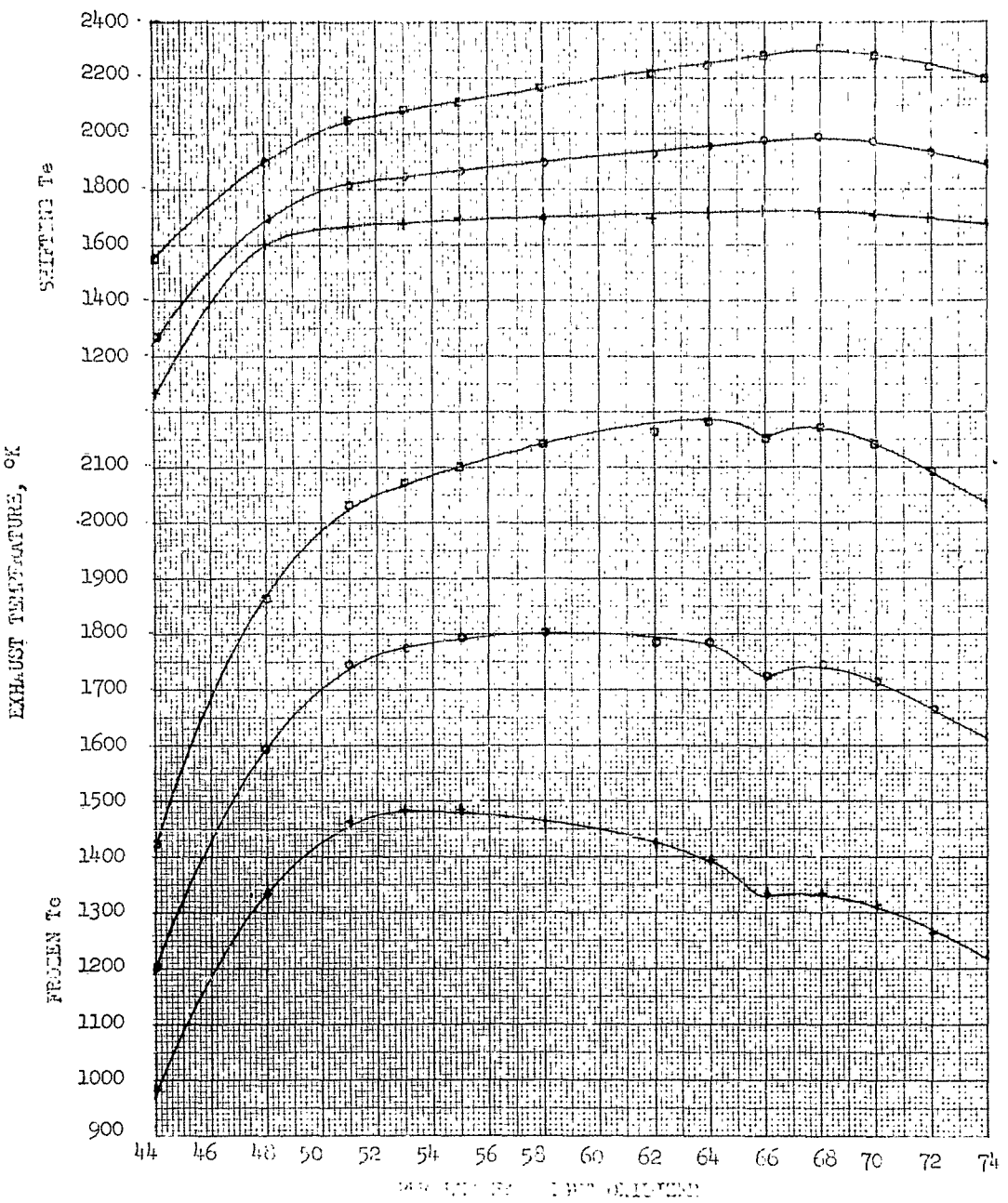

SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
450
430
410
390
370
350
330
310
410
400
390
380
370
360
350
340
330
320
310
300
70
80

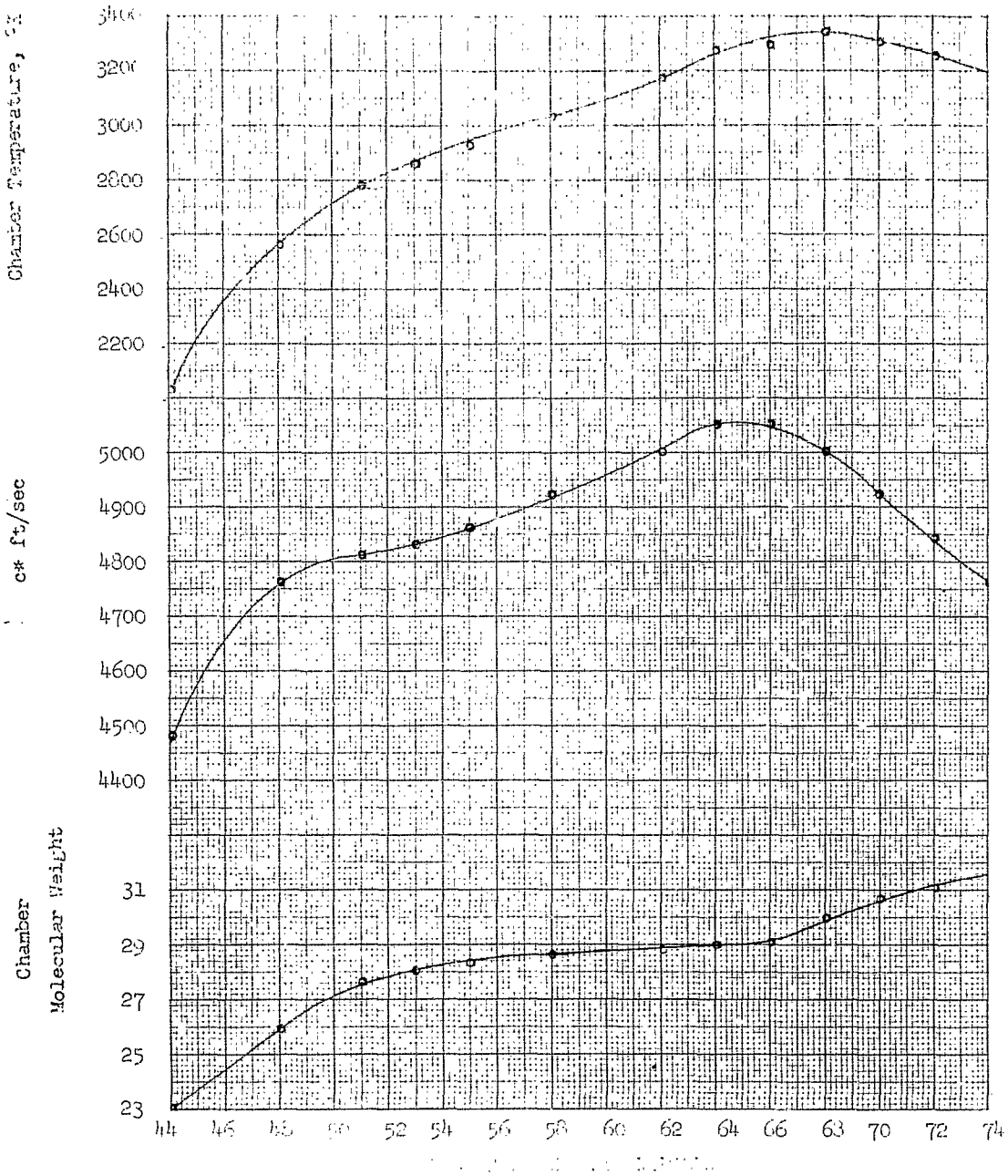

EXHAUST TEMPERATURE, °K
FROZEN Te
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
2400
2200
2000
1800
1600
1400
1200
1000
800
50
55
60
65
70
75
80


Chamber Temperature, °K
4000
3800
3600
3400
3200
3000
c* ft/sec
6400
6300
6200
6100
6000
Chamber Molecular Weight
23
22
21
20
19
18
17
16
50
55
60
65
70
75
80


SPECIFIC IMPULSE, lb-sec/lb
FROZEN Isp
SHIFTING Isp

LITHIUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 24




Chamber Temperature, °R
3400
3200
3000
2800
2600
2400
2200
c* ft/sec
5000
4900
4800
4700
4600
4500
4400
Chamber
Molecular Weight
31
29
27
25
23
44
46
48
50
52
54
56
58
60
62
64
66
68
70
72
74

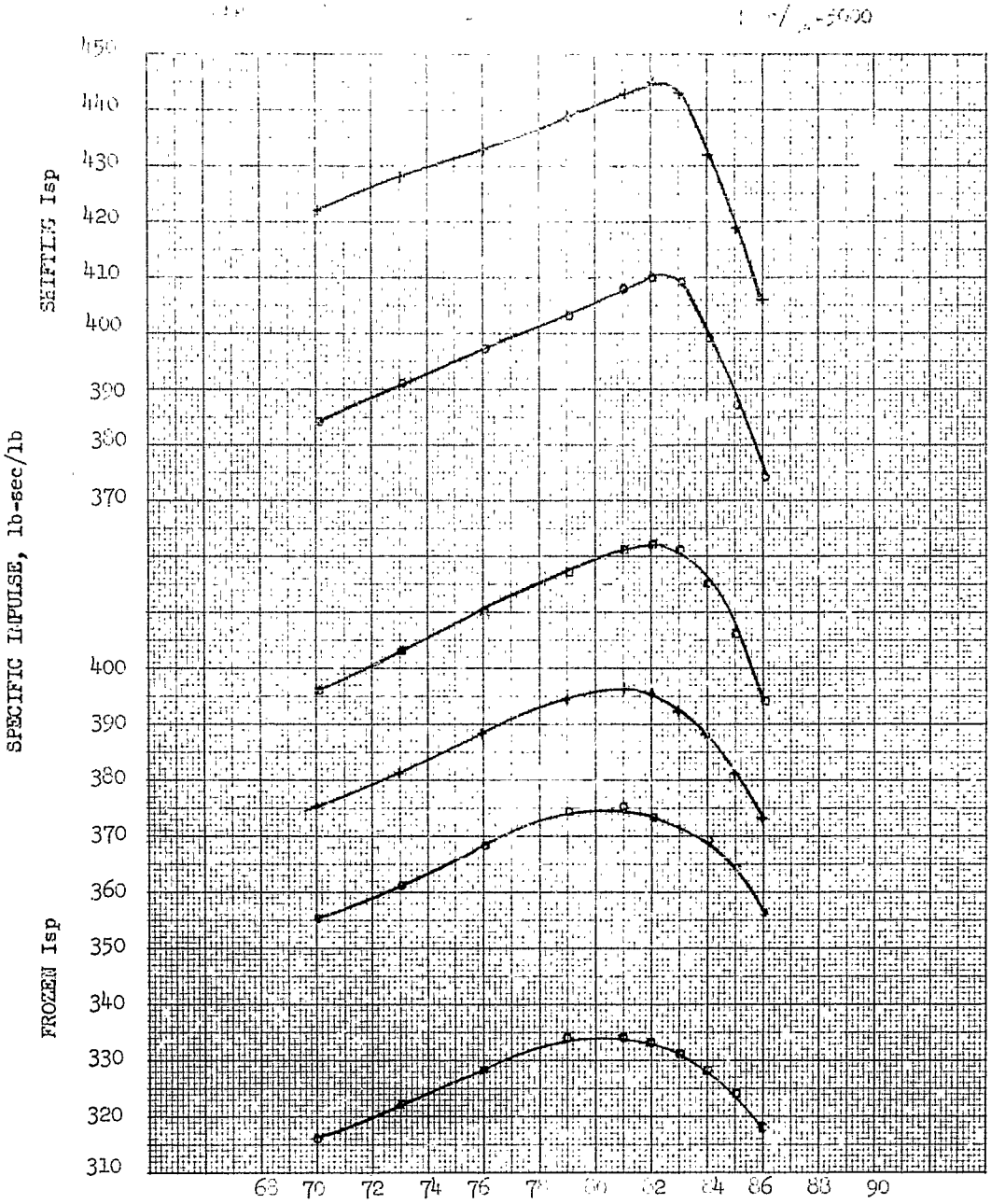
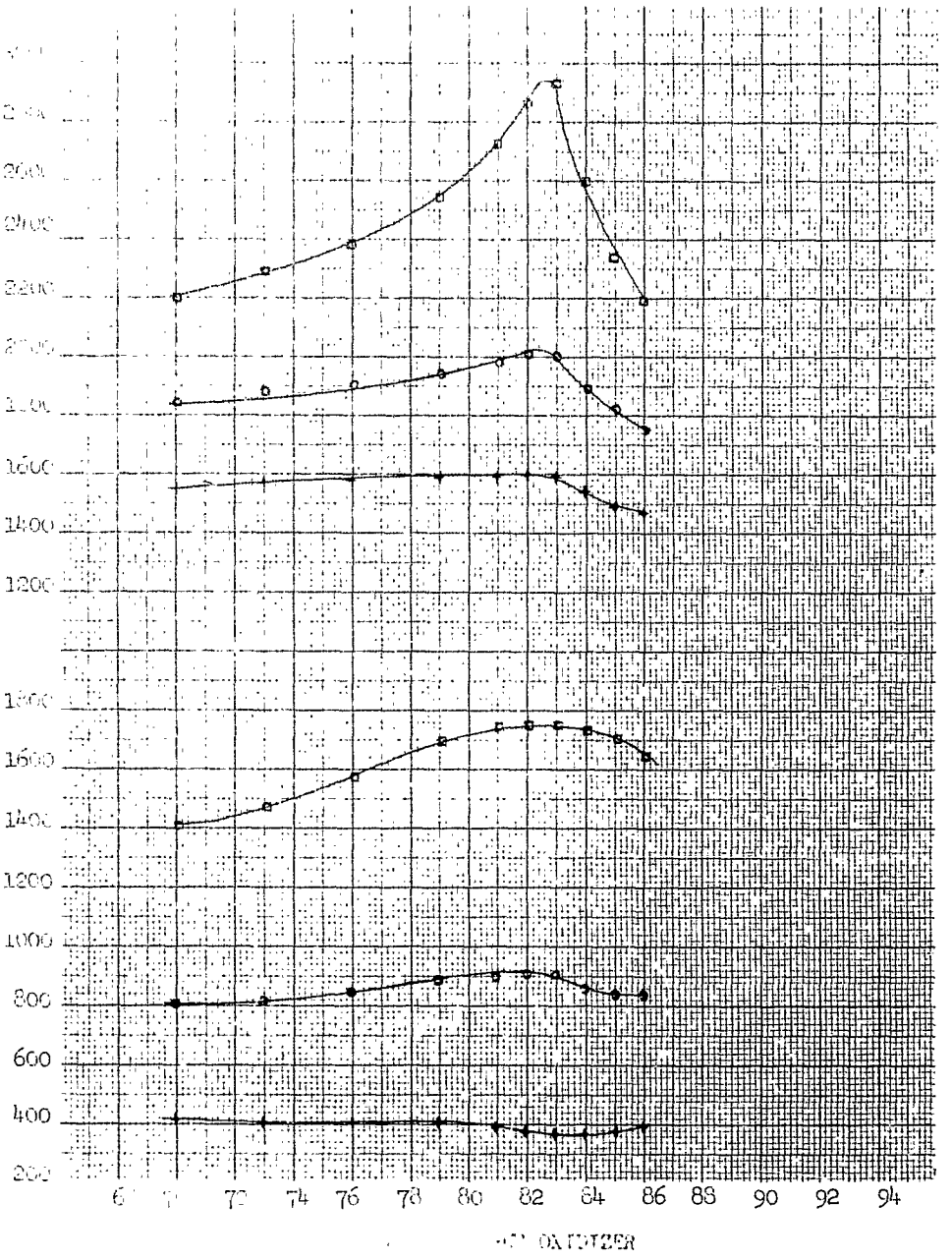
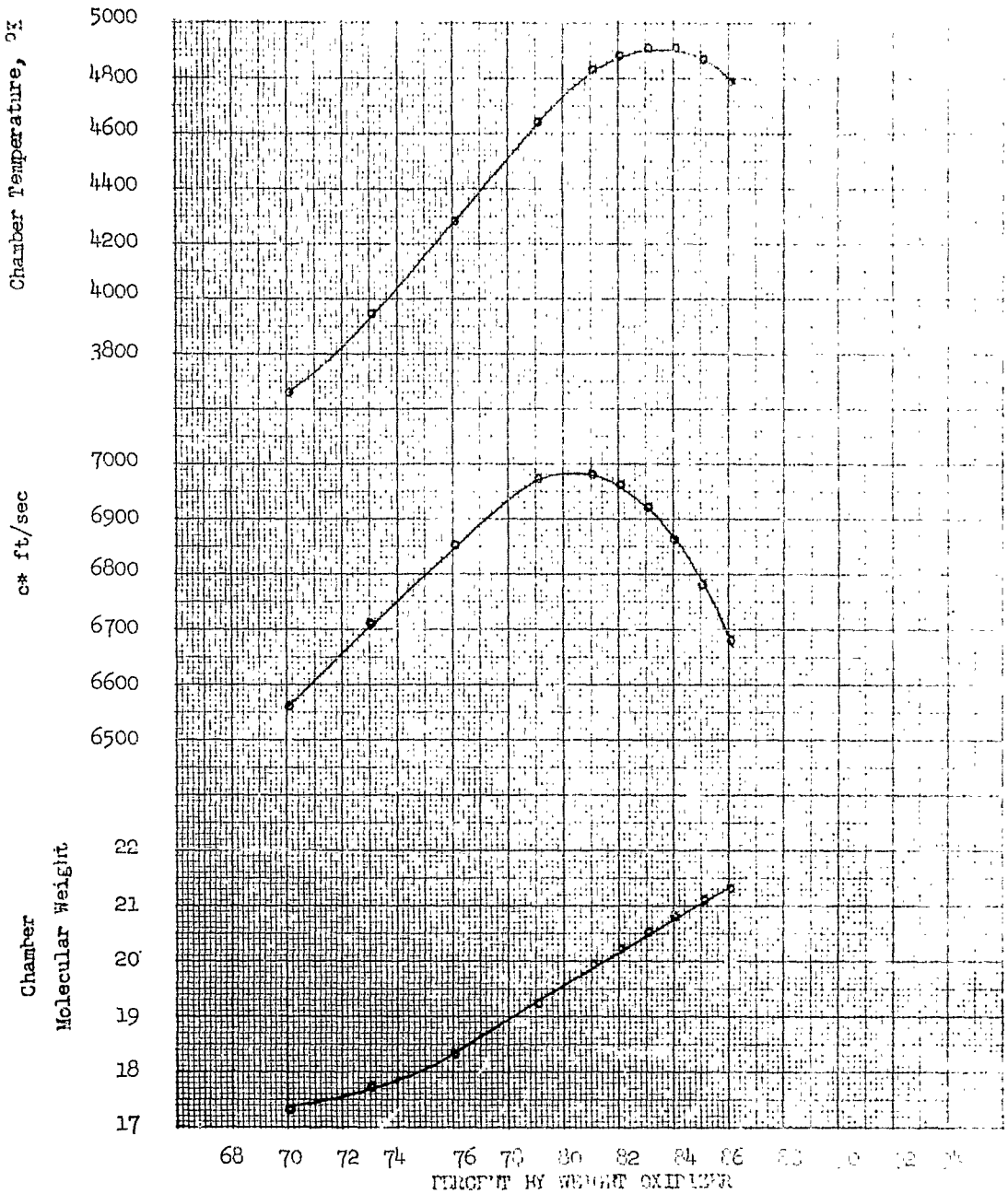

SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
450
440
430
420
410
400
390
380
370
400
390
380
370
360
350
340
330
320
310
66
70
72
74
76
78
80
82
84
86
88
90

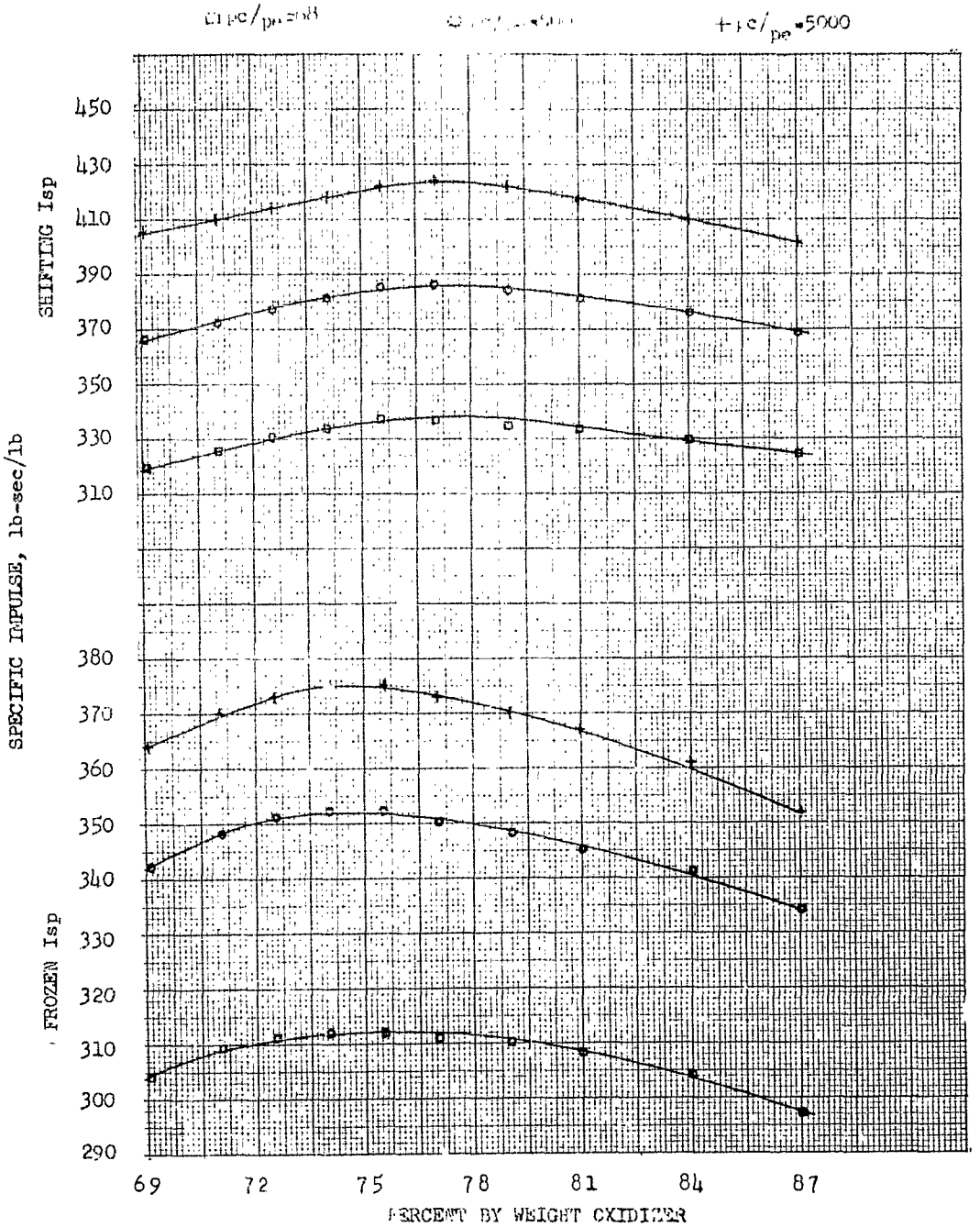
FIGURE 2(5


2400
2200
2000
1800
1600
1400
1200
1600
1400
1200
1000
800
600
400
200
70
72
74
76
78
80
82
84
86
88
90
92
94

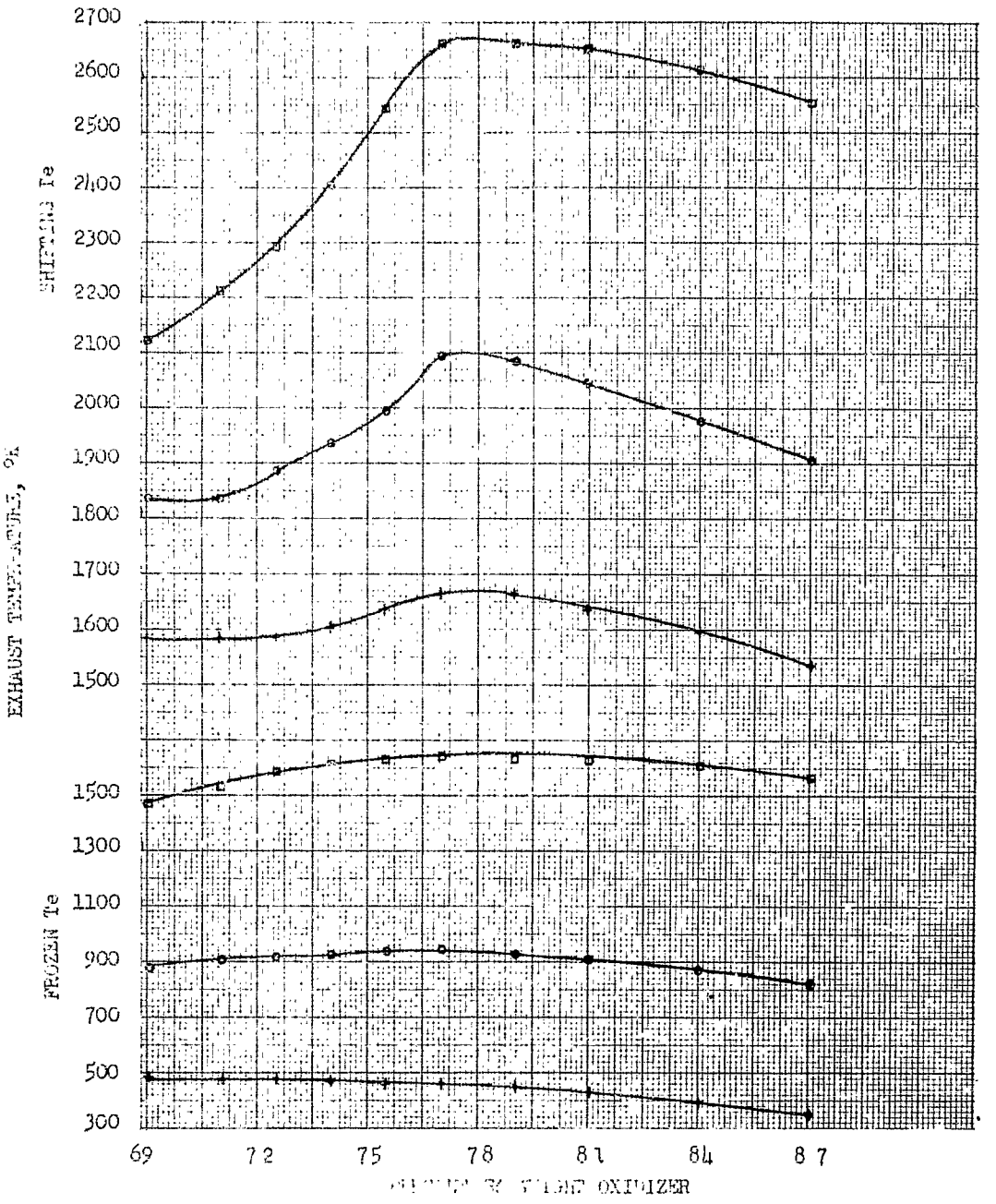
LITHIUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES



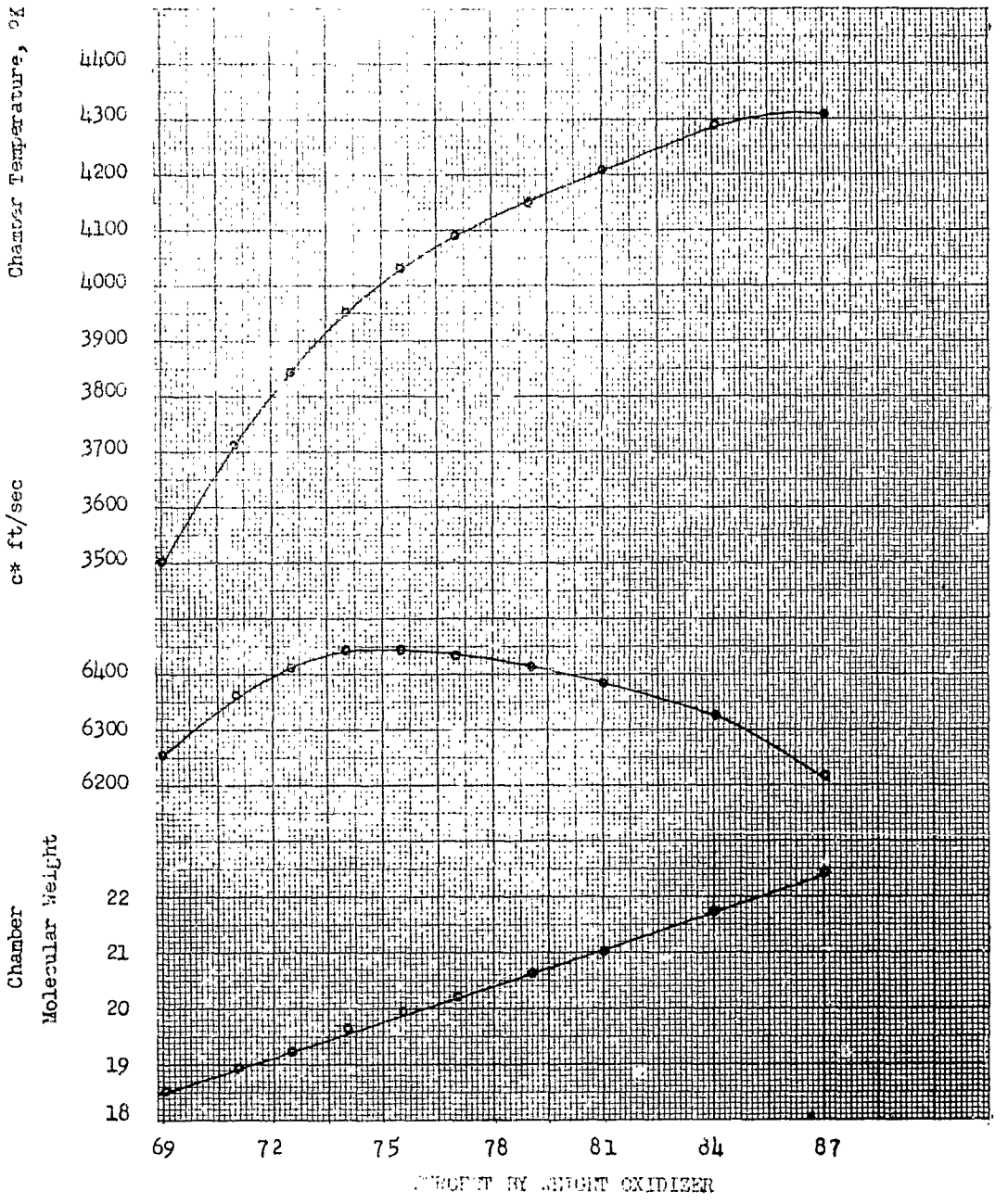
LITHIUM HYDRIDE - [illegible] PERFORMANCE CURVES FIGURE 247

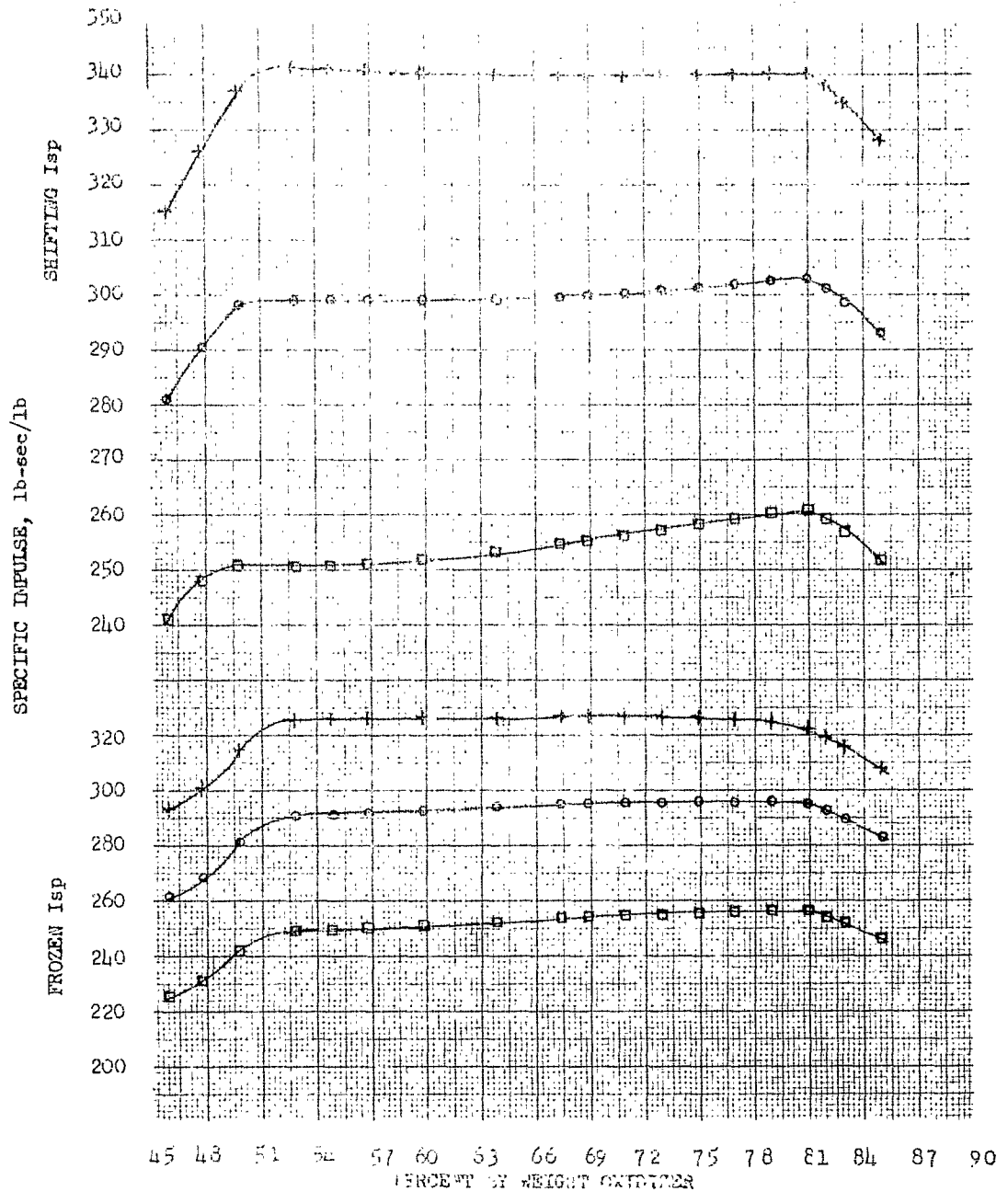


[illegible] - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 248



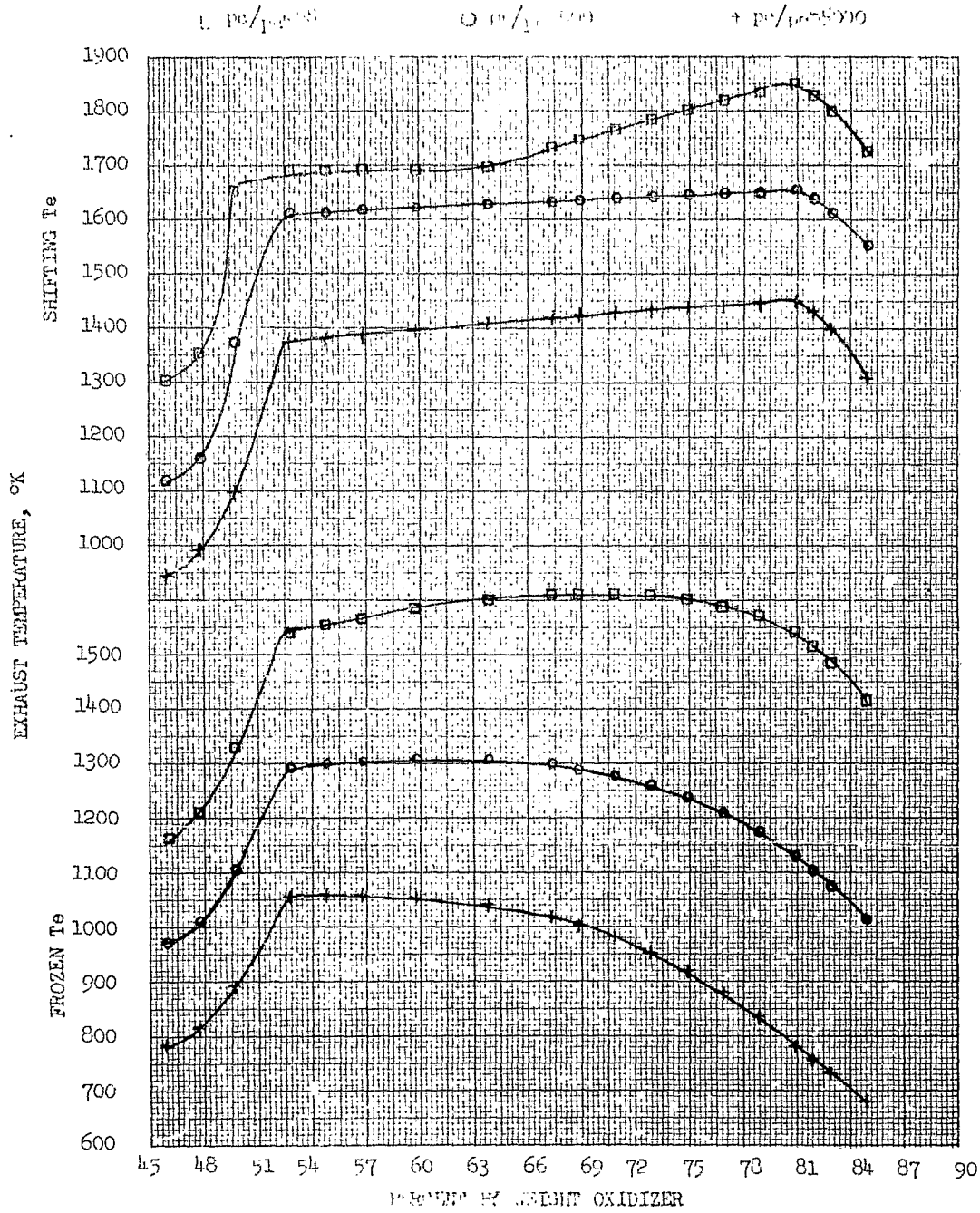
[illegible] - [illegible] DIBORANE PERFORMANCE CURVES FIGURE 249



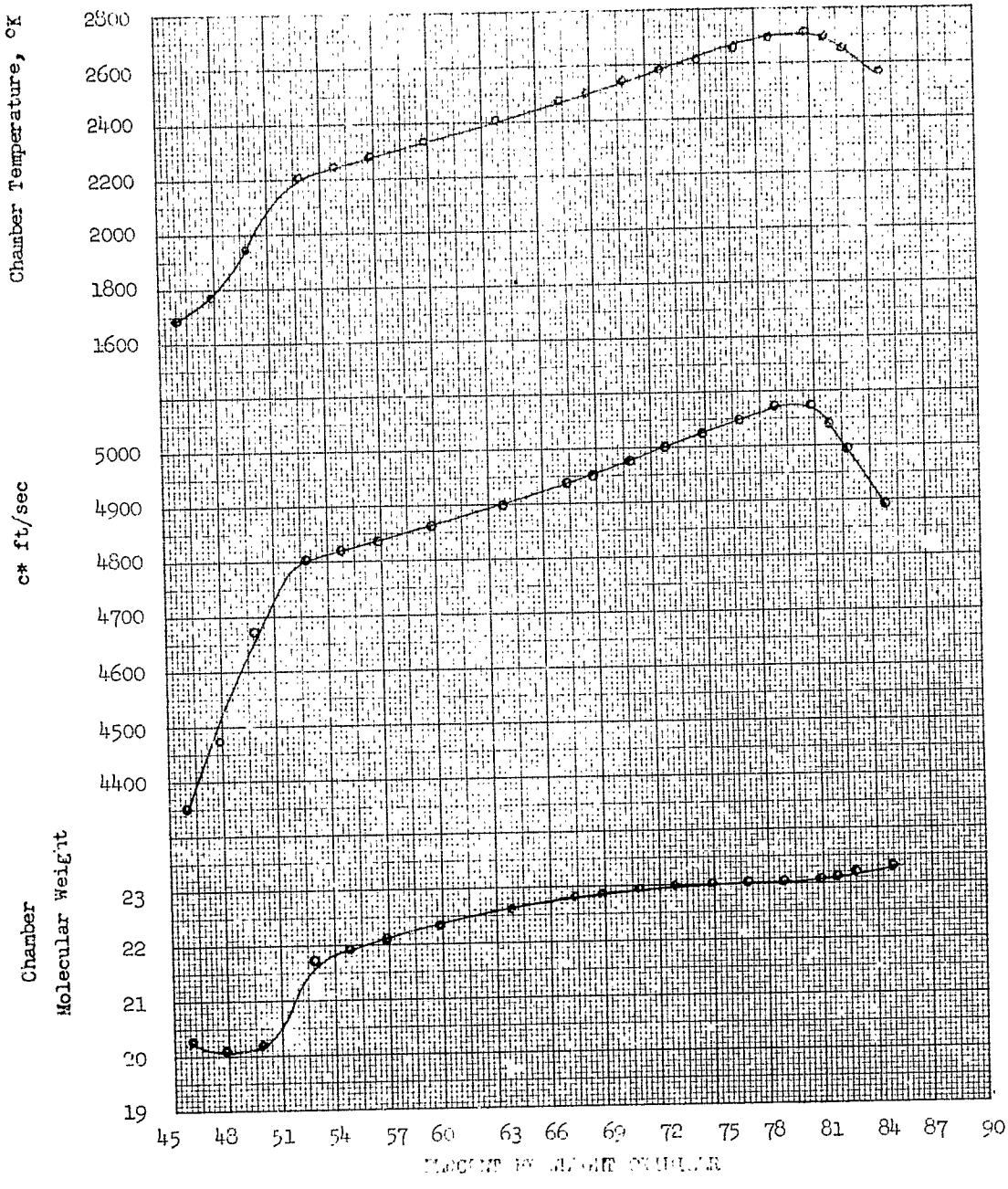

SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
350
340
330
320
310
300
290
280
270
260
250
240
320
300
280
260
240
220
200
45 48 51 54 57 60 63 66 69 72 75 78 81 84 87 90
PERCENT BY WEIGHT OXIDIZER

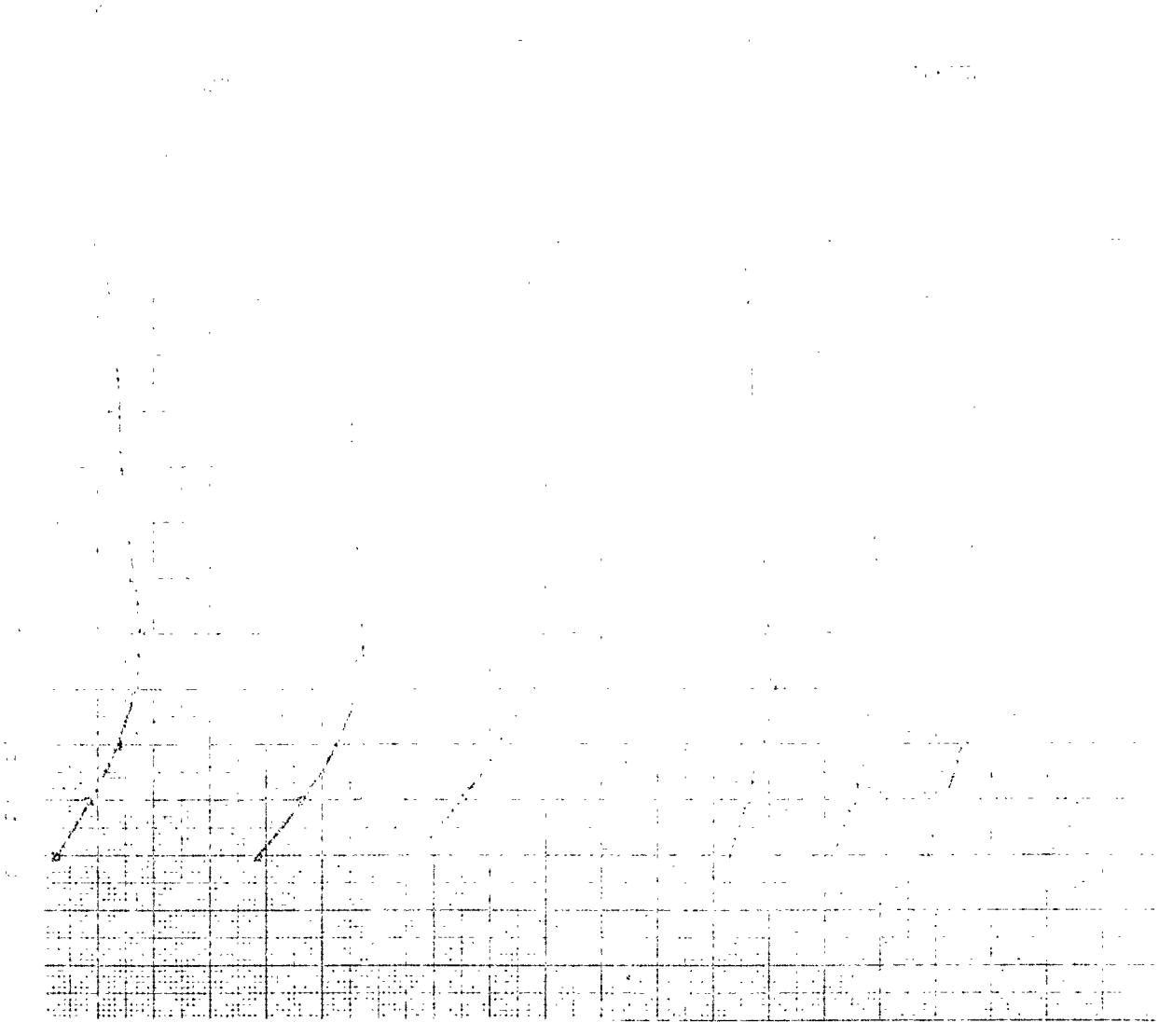
LITHIUM HYDRIDE – [illegible] FIGURE 251

[illegible]

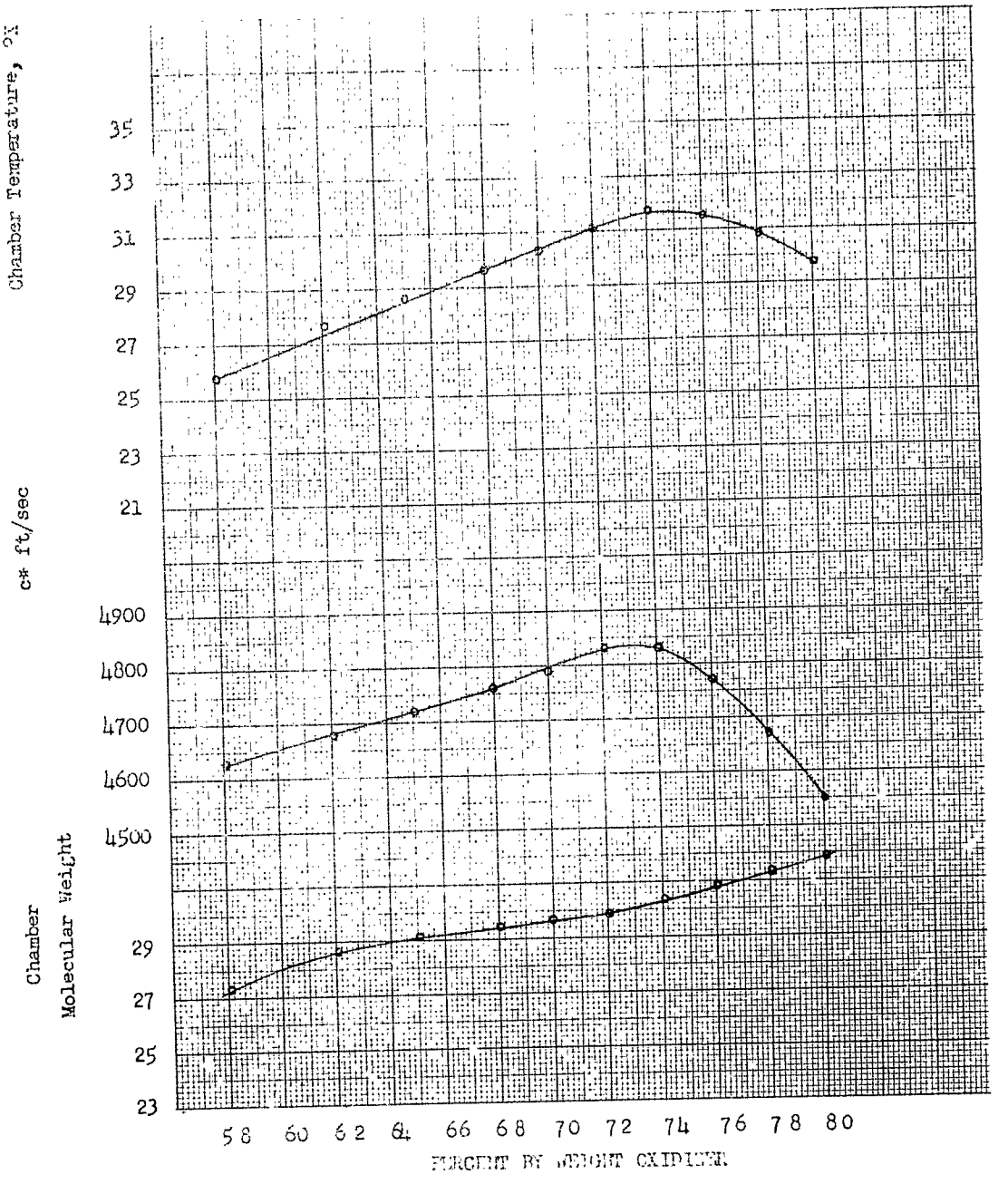


LITHIUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 252

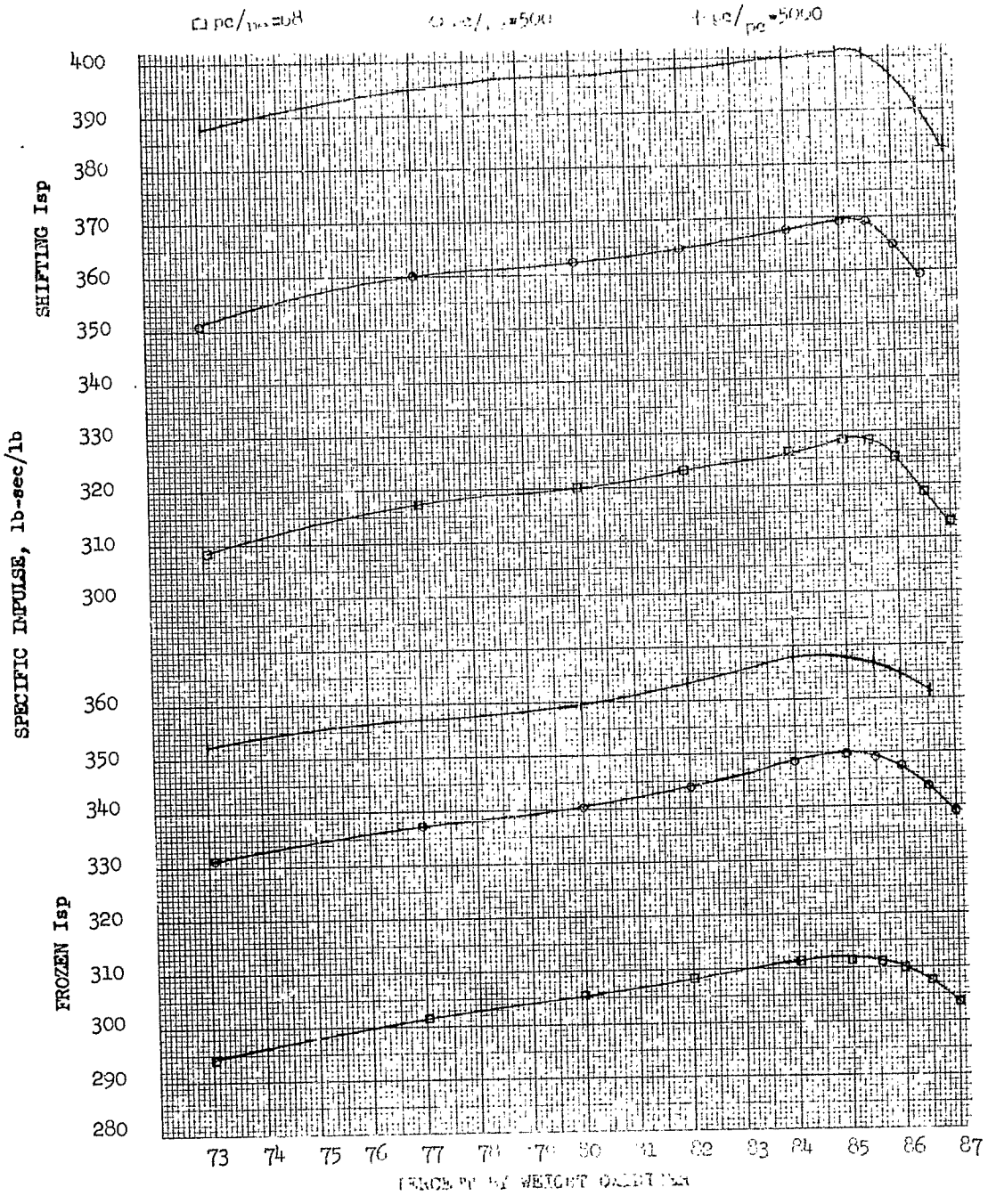


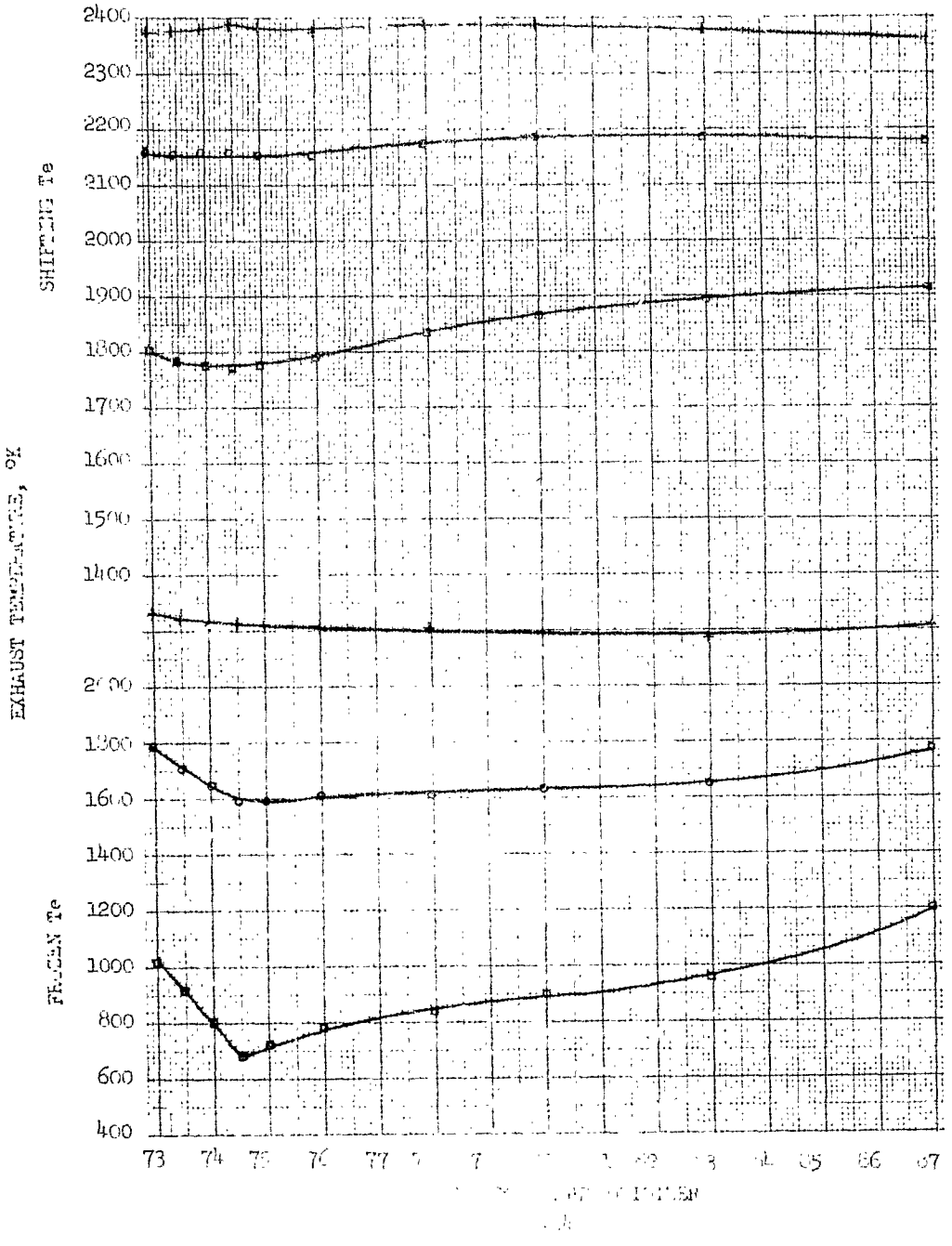


1900
1700
1500
1300
1100
900
700

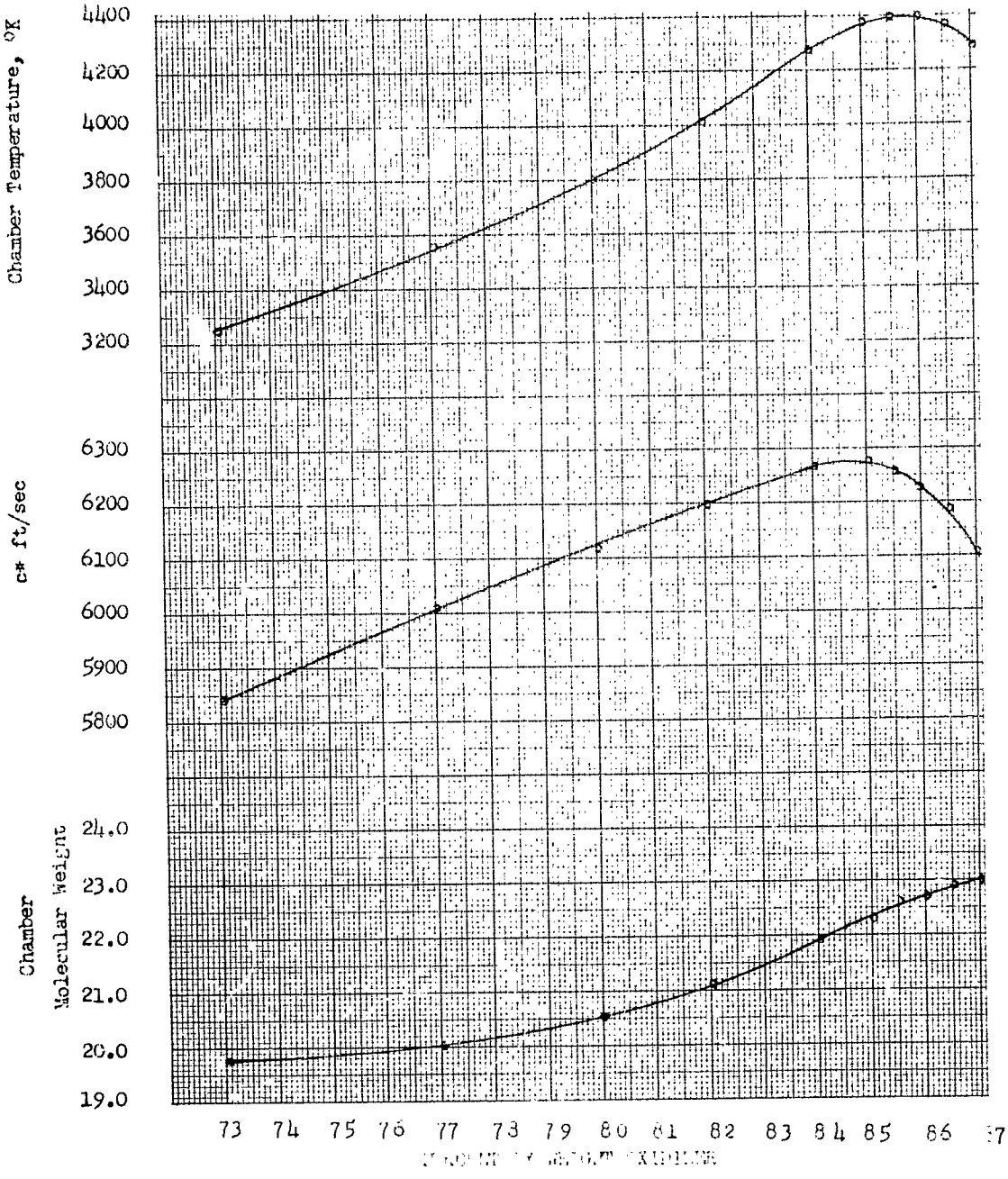

Chamber Temperature, °K
35
33
31
29
27
25
23
21
c* ft/sec
4900
4800
4700
4600
4500
Chamber
Molecular Weight
29
27
25
23
58 60 62 64 66 68 70 72 74 76 78 80
PERCENT BY WEIGHT OXIDIZER

LITHIUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FROZEN

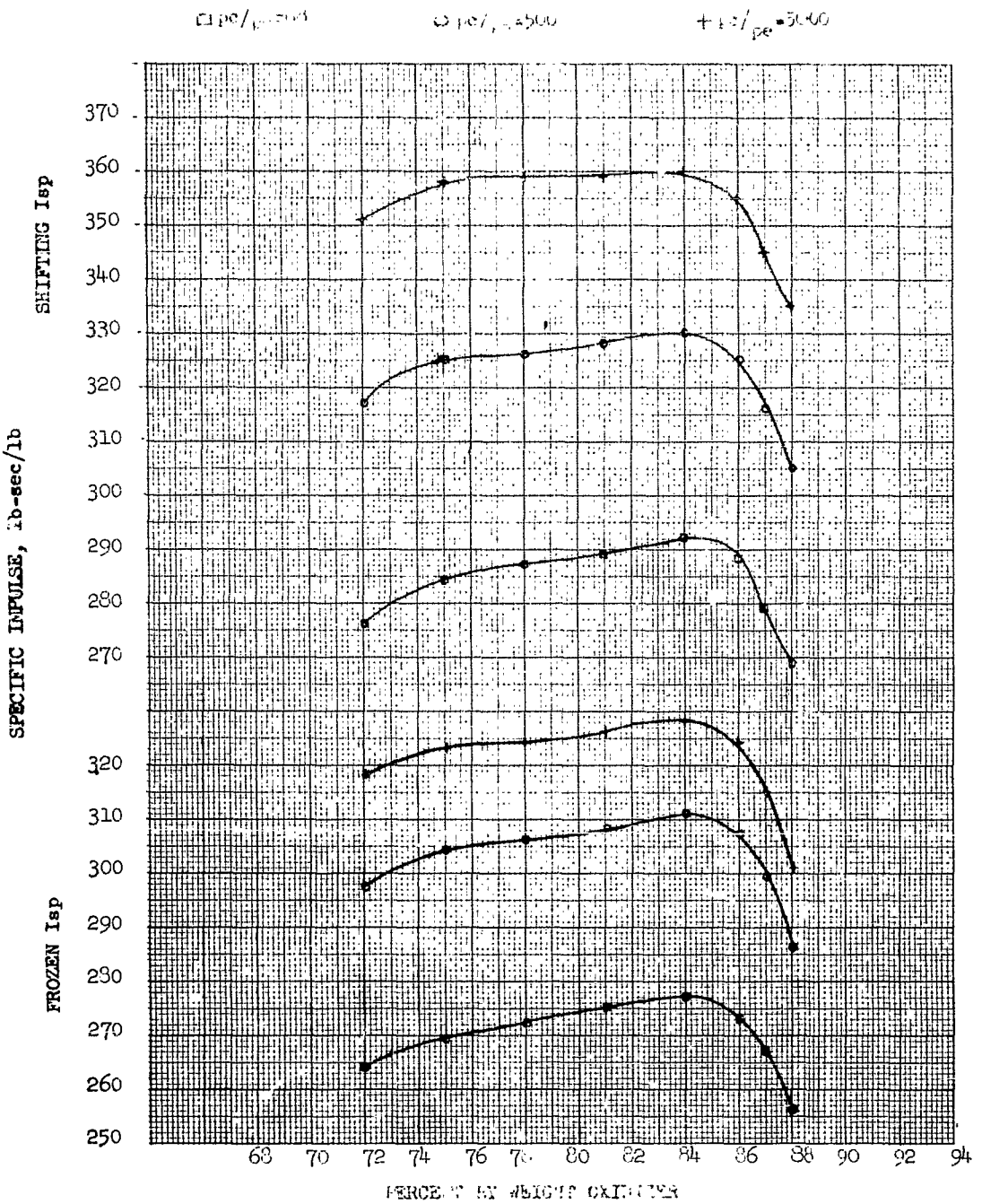



EXHAUST TEMPERATURE, °F
SHIPPING Te
FROZEN Te
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1200
1000
800
600
400
73
74
75
76
77
85
86
87

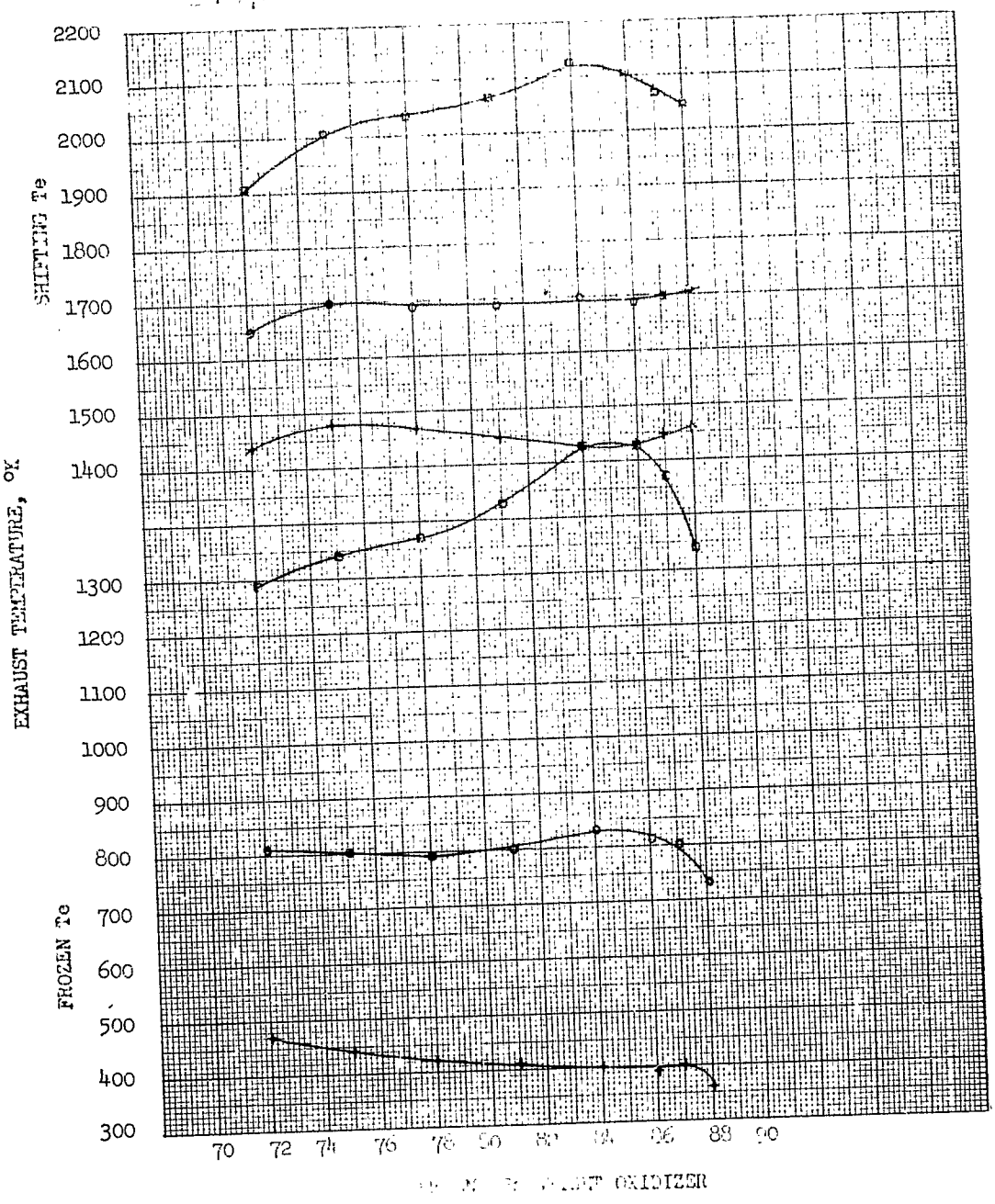
LITHIUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 258



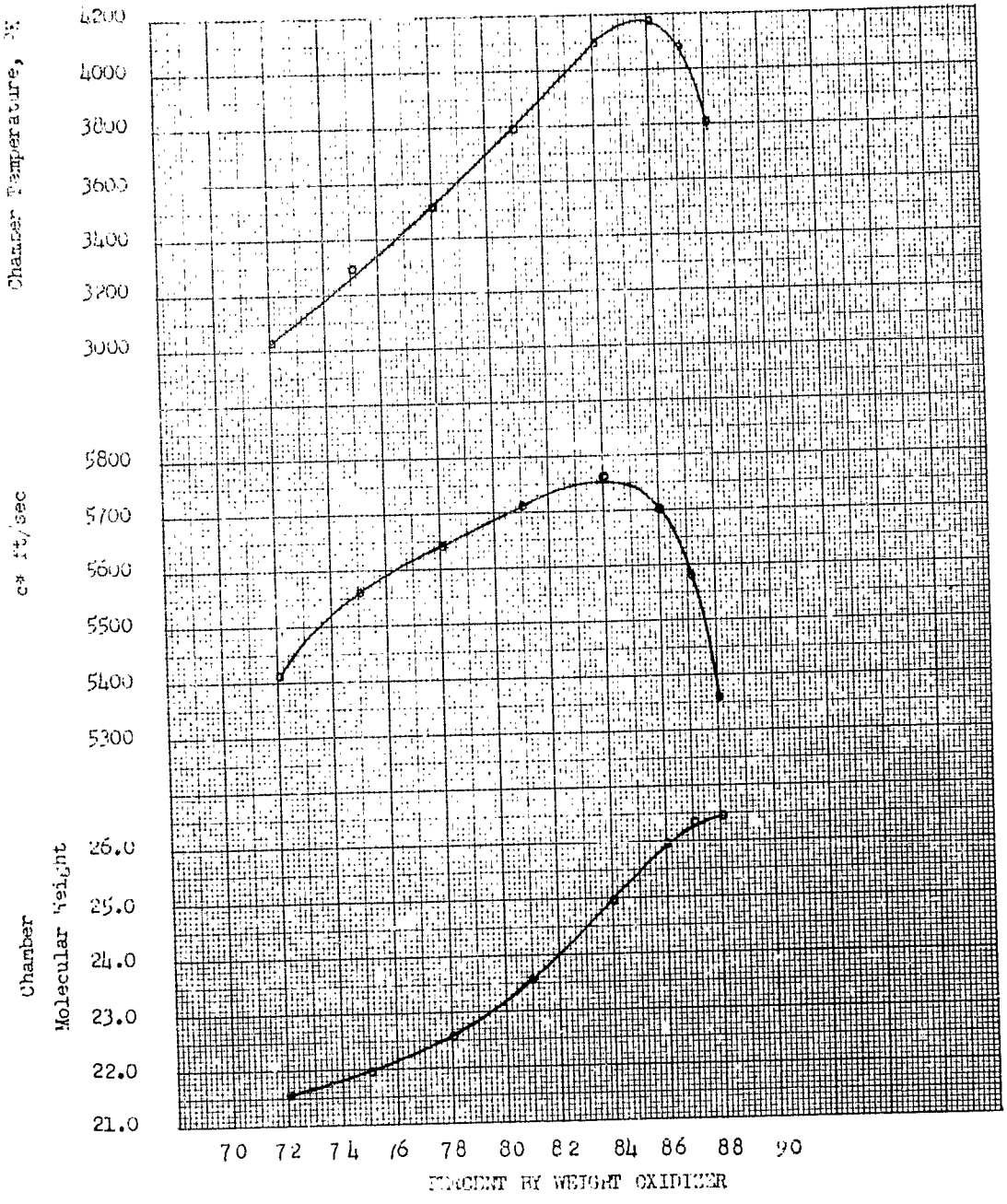
LITHIUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 297



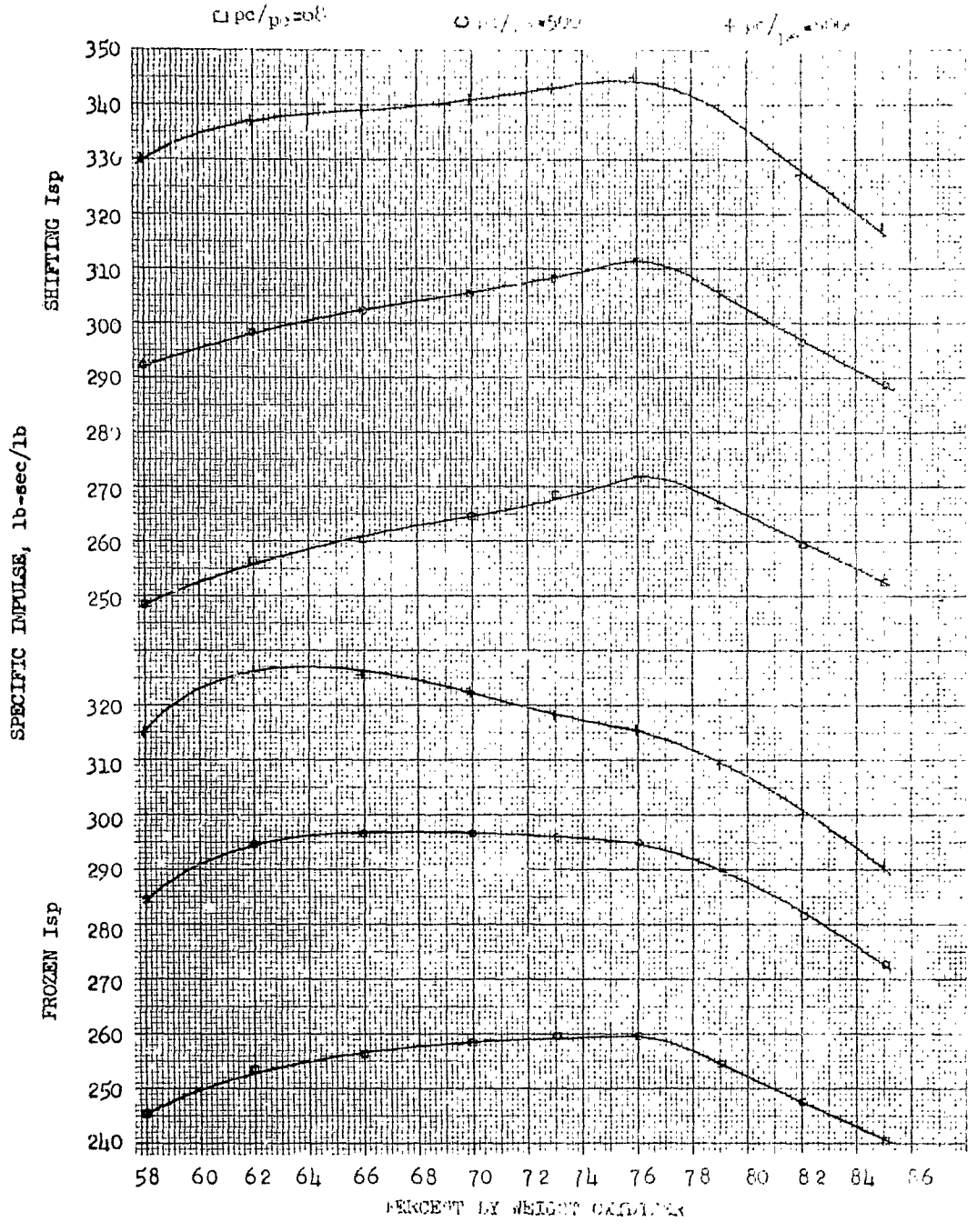
LITHIUM HYDRIDE - [illegible]



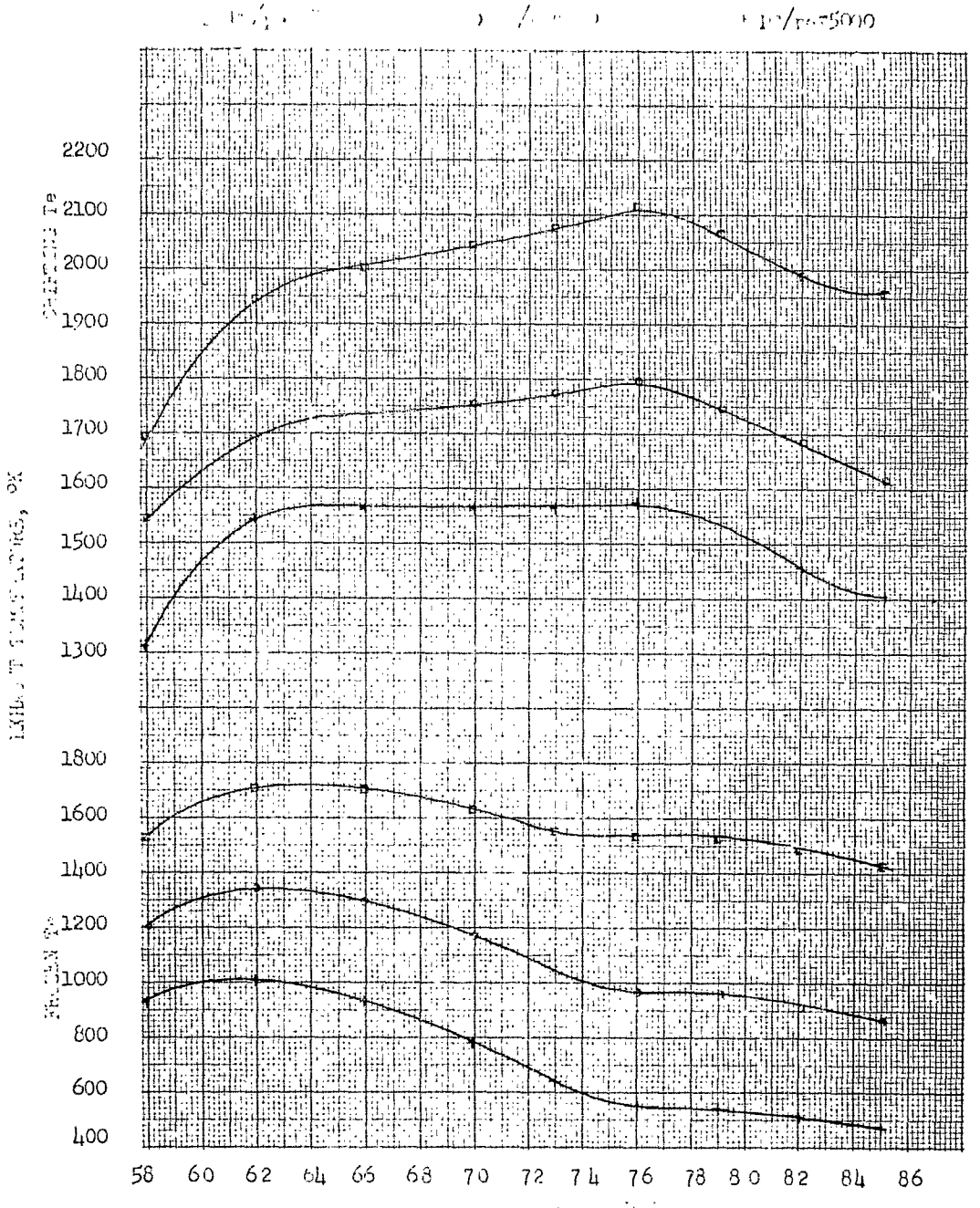
LITHIUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 261



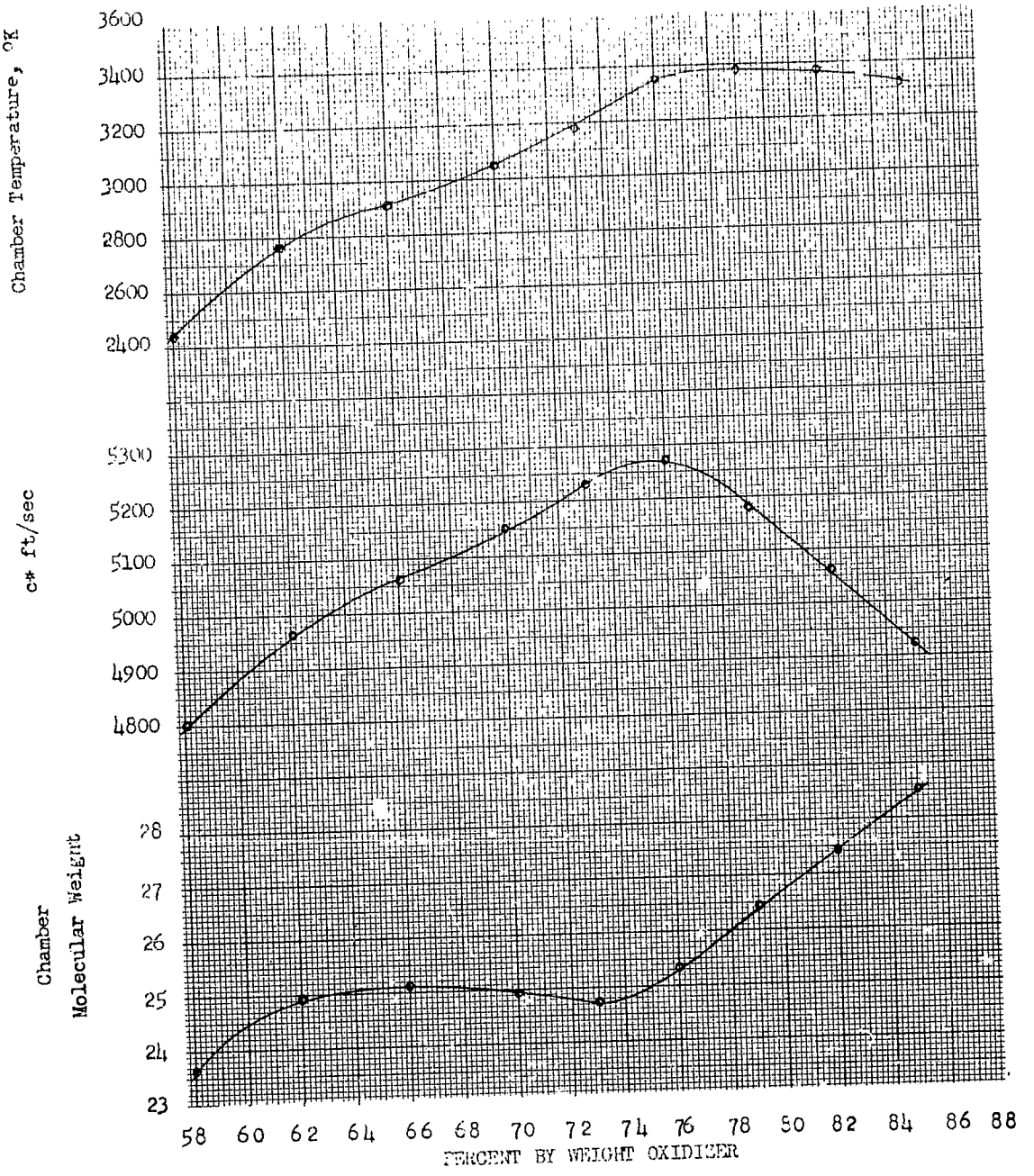
LITHIUM HYDRIDE – PERCHLORYL FLUORIDE PERFORMANCE CURVES



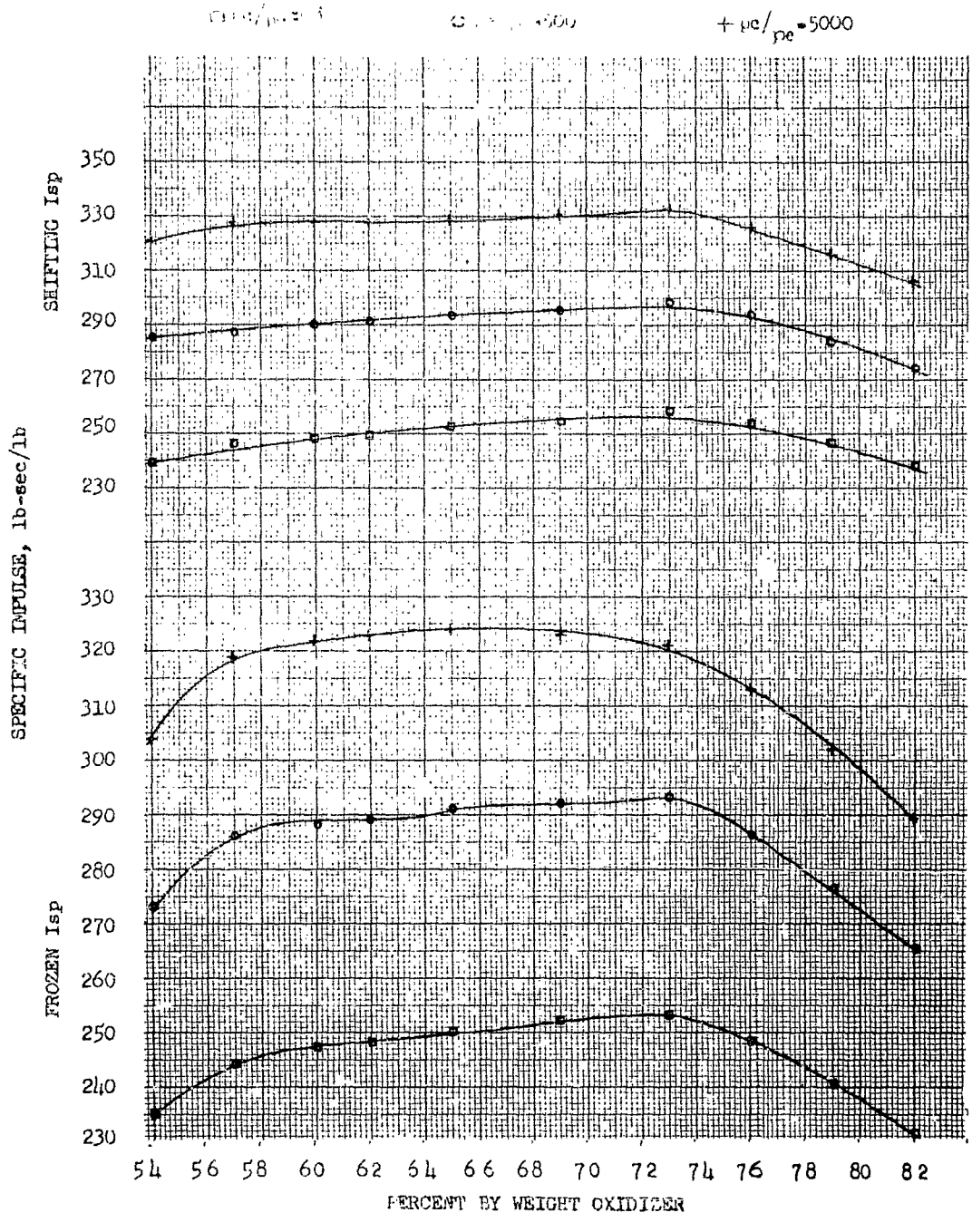
LITHIUM HYDRIDES – PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 263

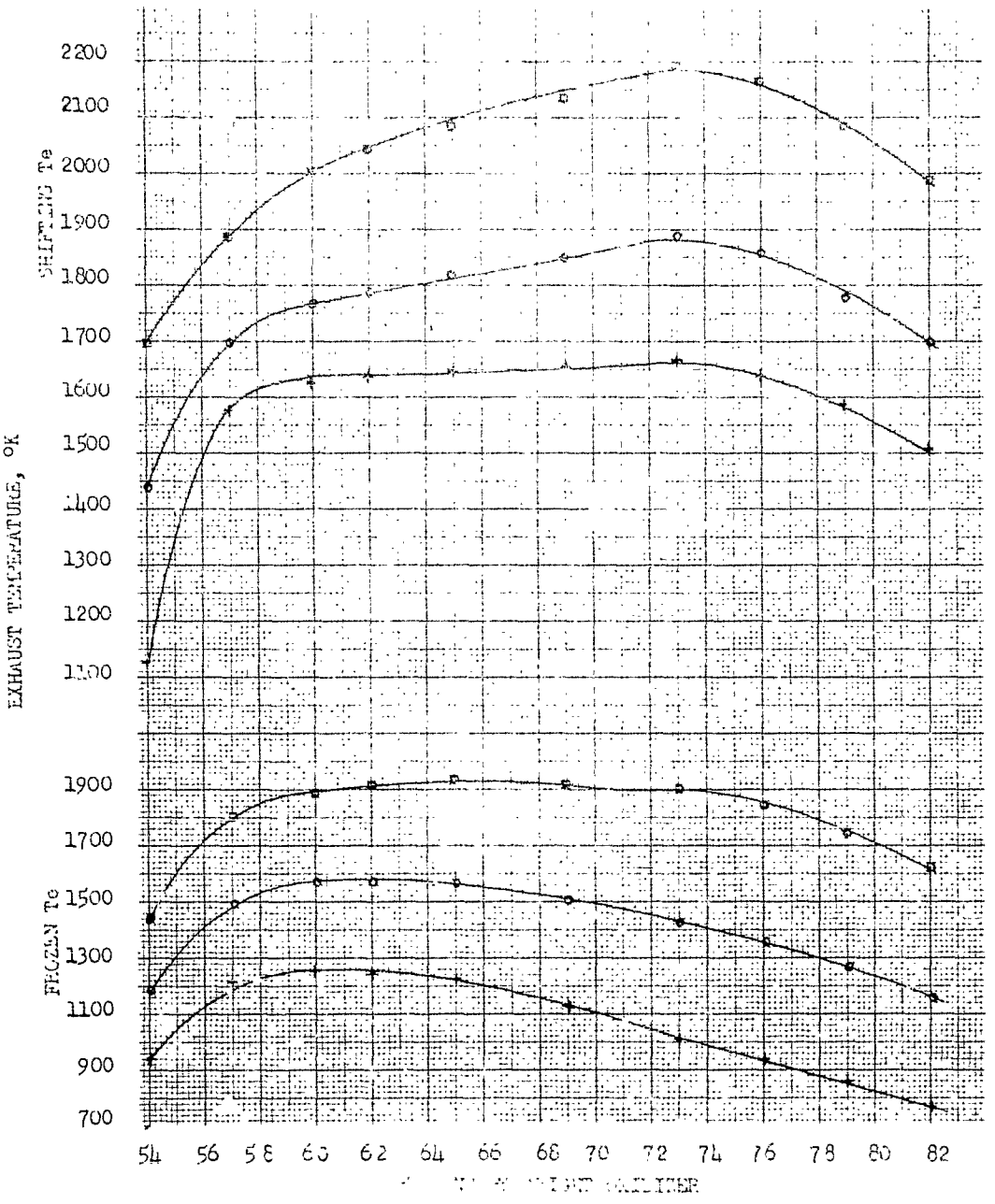


LITHIUM IODIDE - PERCHLORYL FLUORIDE PERFORMANCE CURVES Pc=265

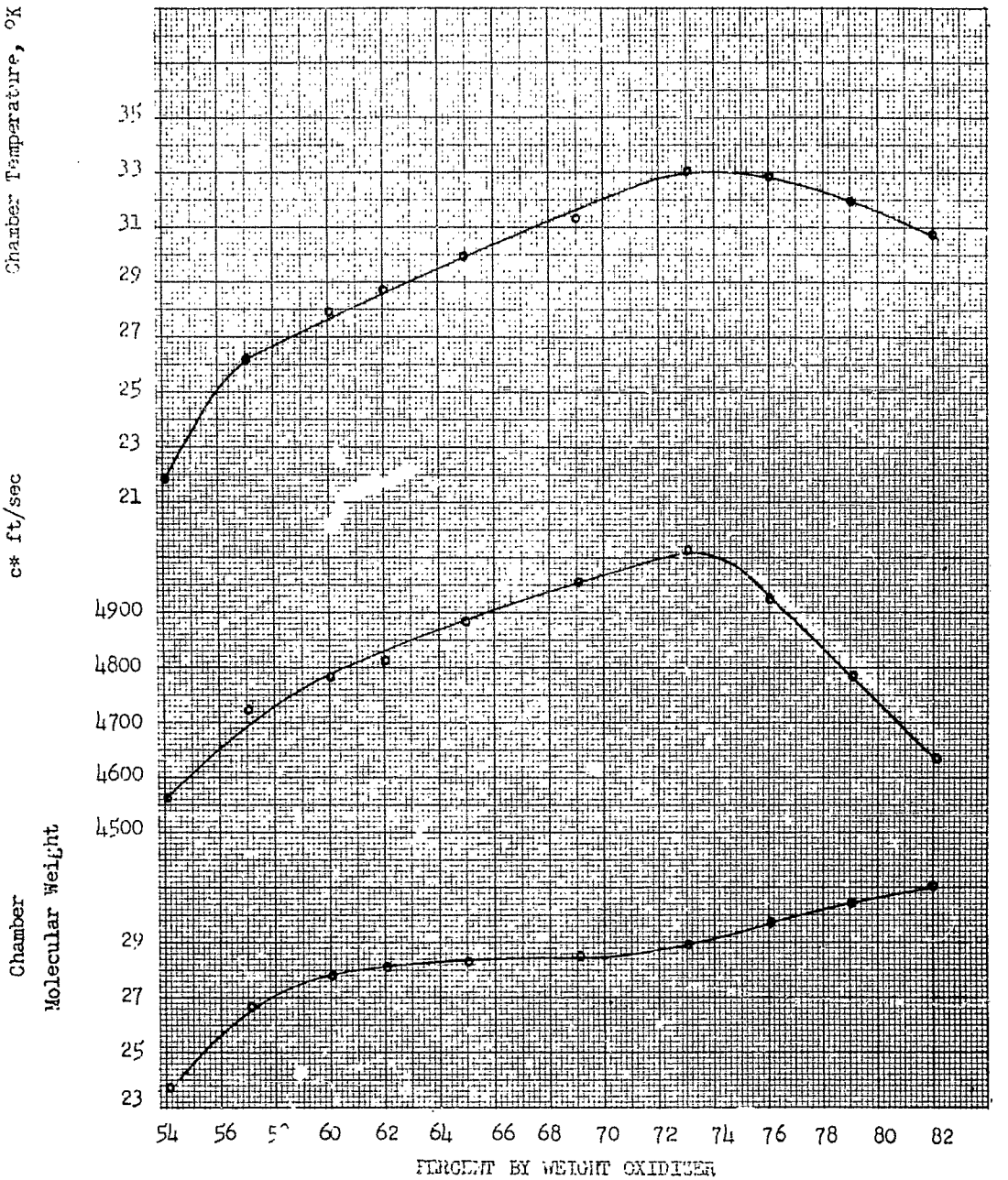


[illegible] PERFORMANCE CURVES FIGURE 265




EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1900
1700
1500
1300
1100
900
700
54
56
58
60
62
64
66
68
70
72
74
76
78
80
82

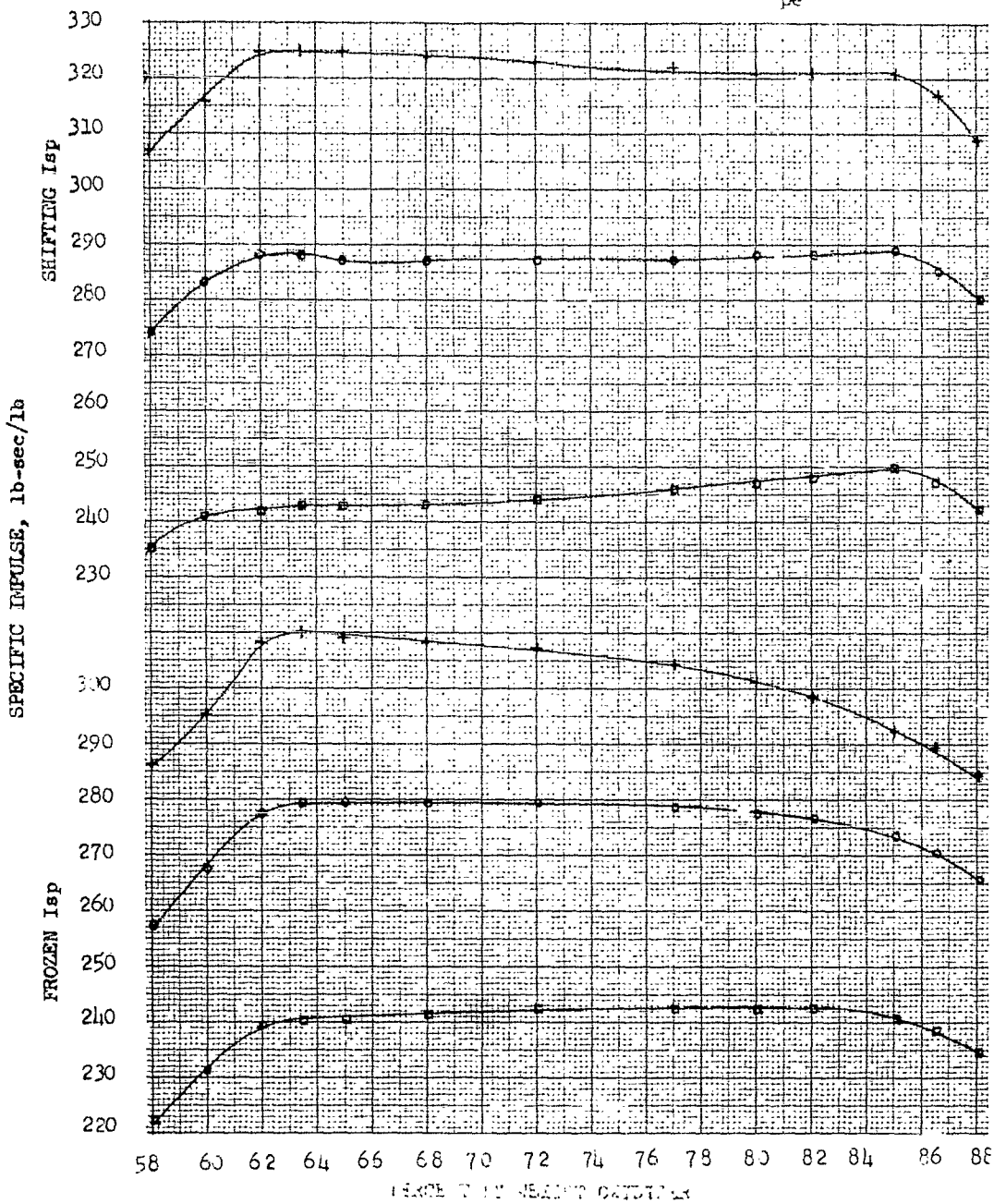
LITHIUM HYDRIDE – AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 267

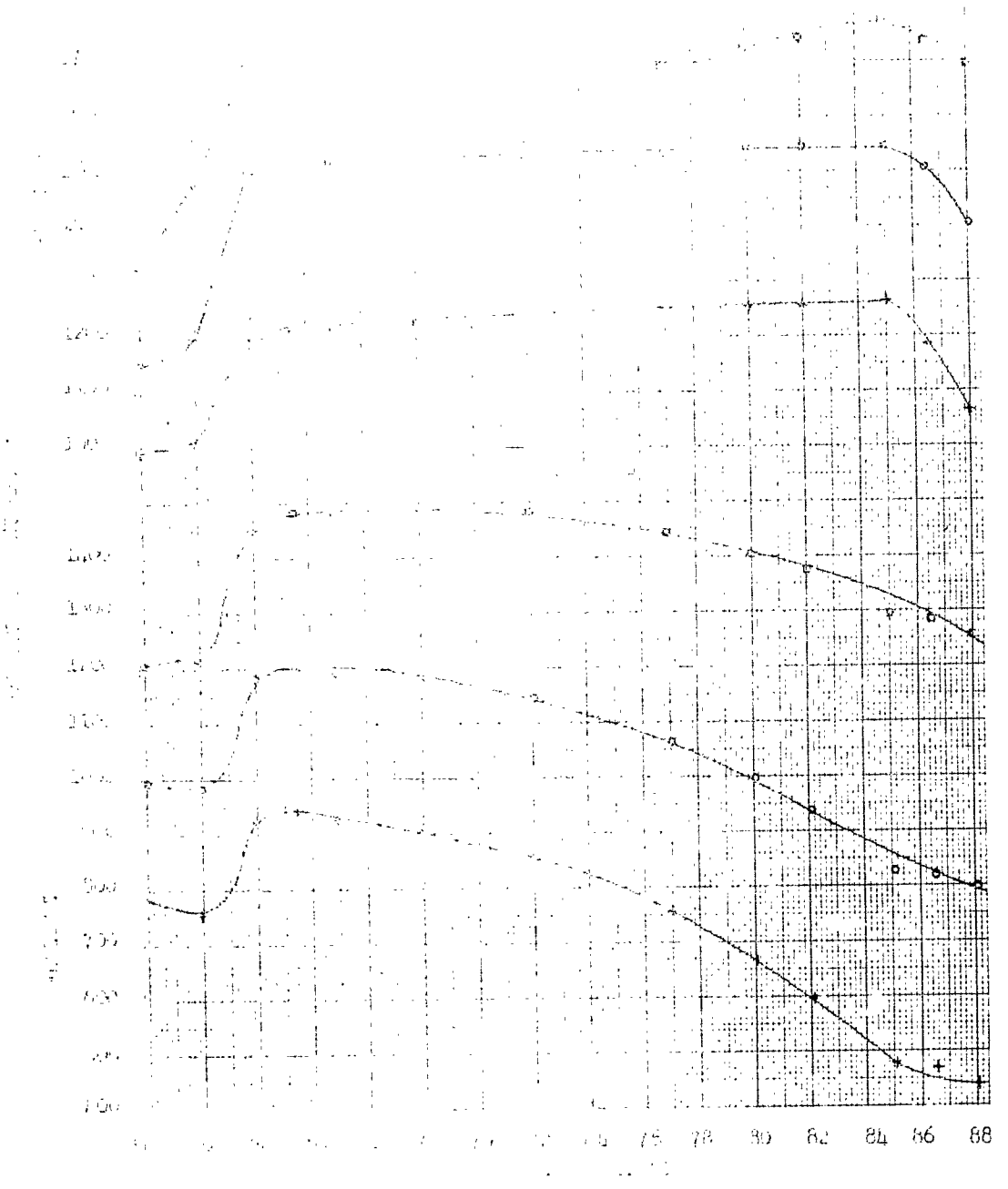


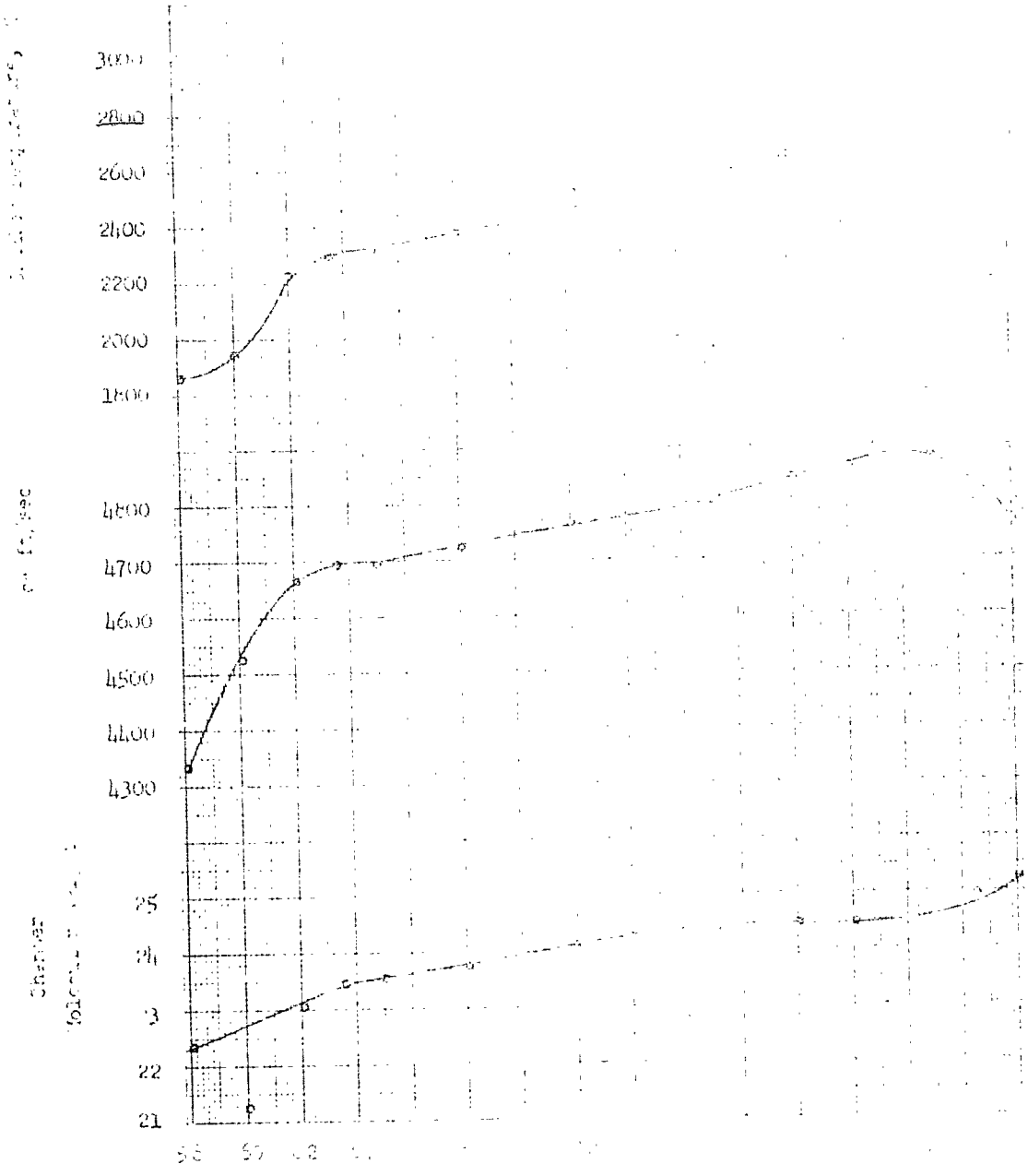
LITHIUM HYDRIDE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 268

P_c = 1000 psi

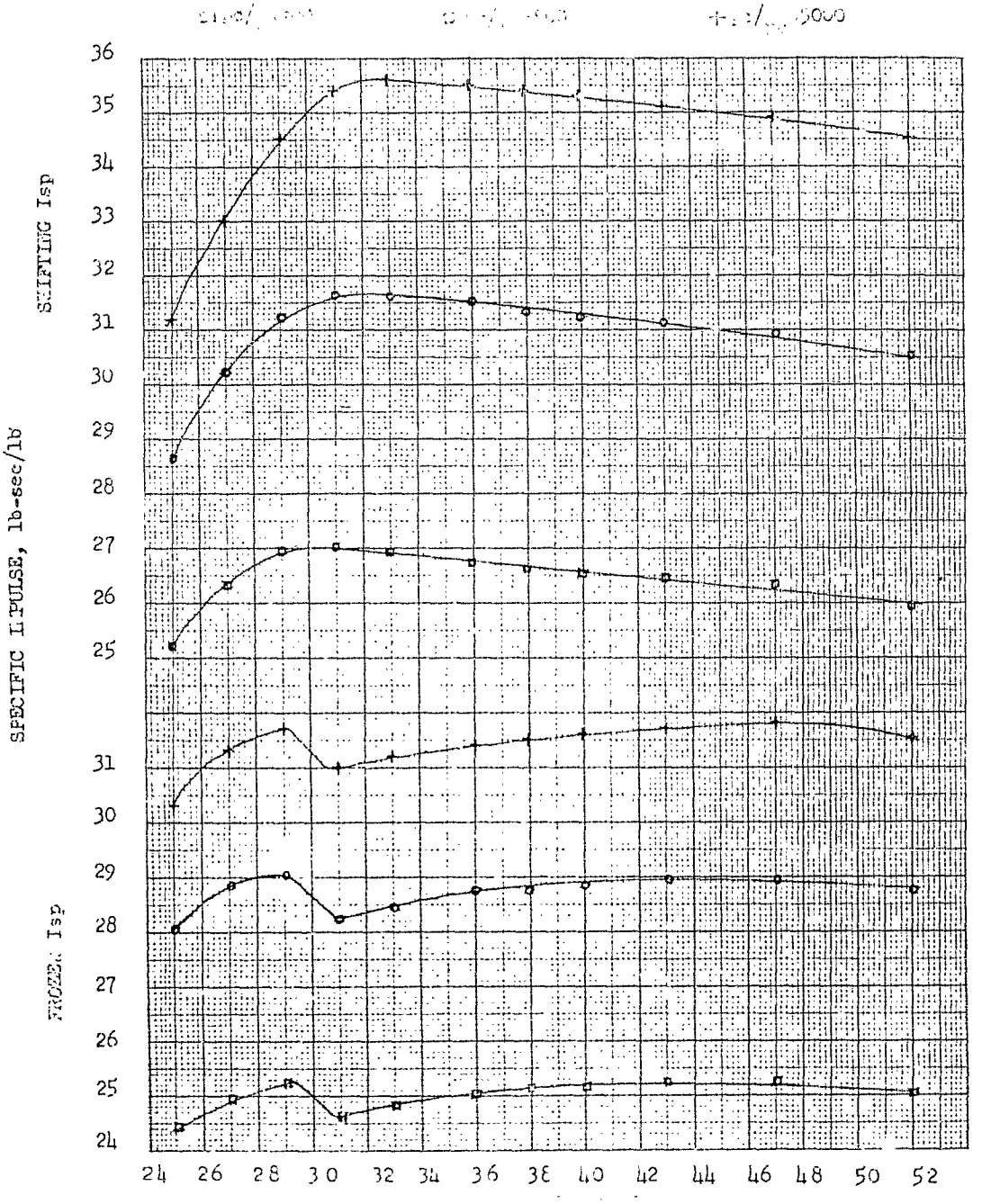
$\Box$ $\mu e/_{pe}$=100 $\quad$ O $\mu e/_{pe}$=500 $\quad$ + $\mu e/_{pe}$=5000



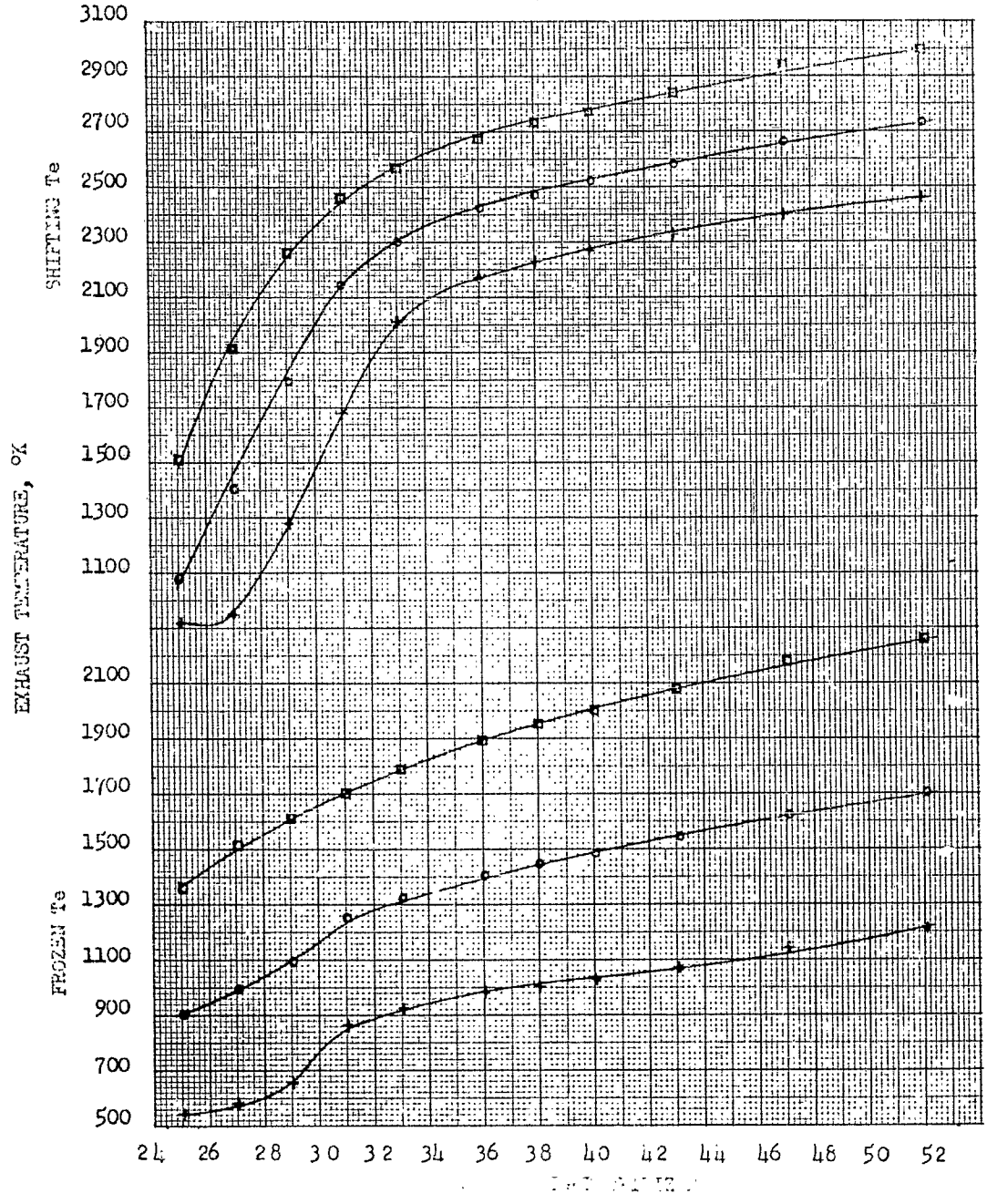

78
80
82
84
86
88

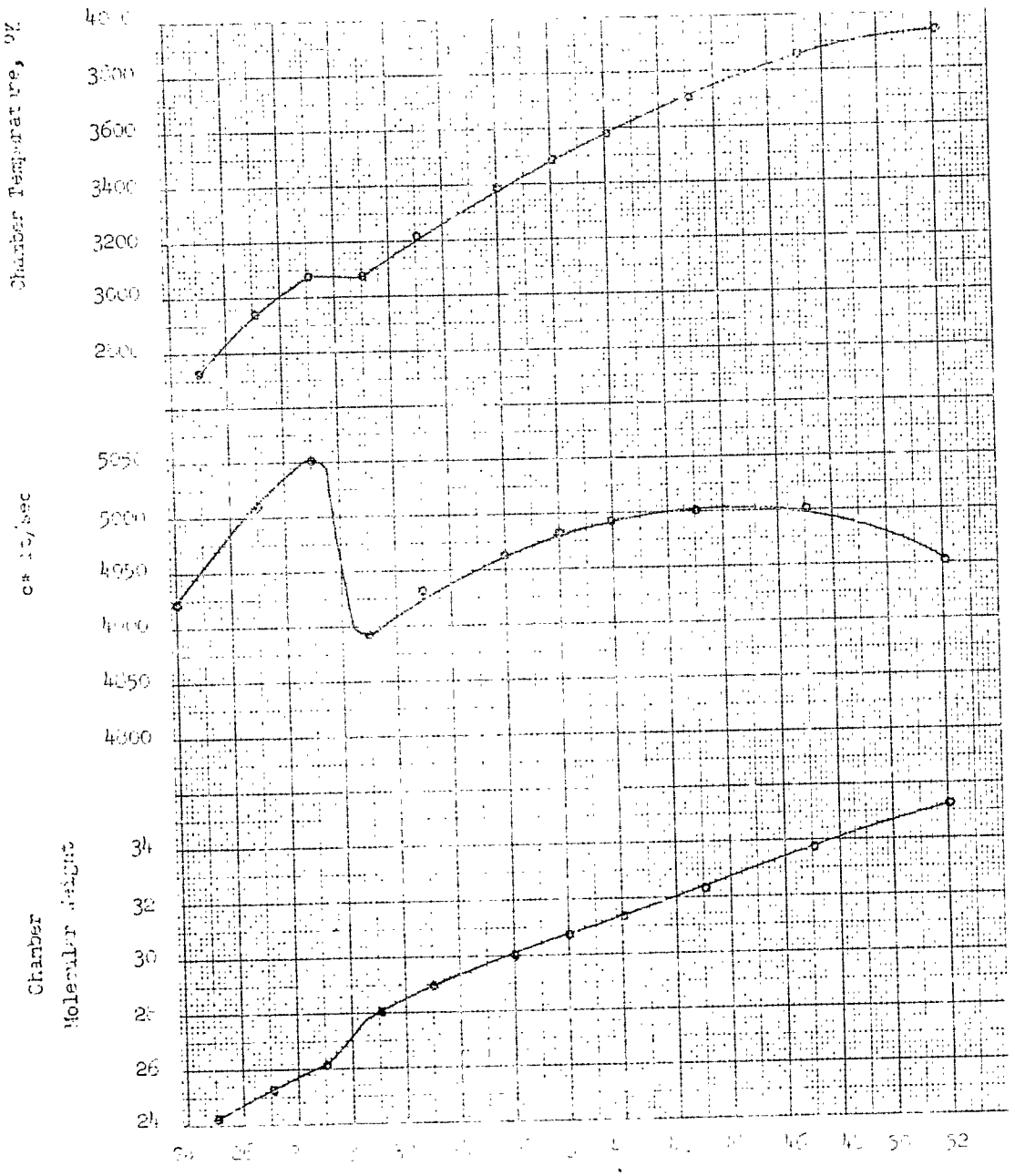

3000
2800
2600
2400
2200
2000
1800
4800
4700
4600
4500
4400
4300
25
24
3
22
21

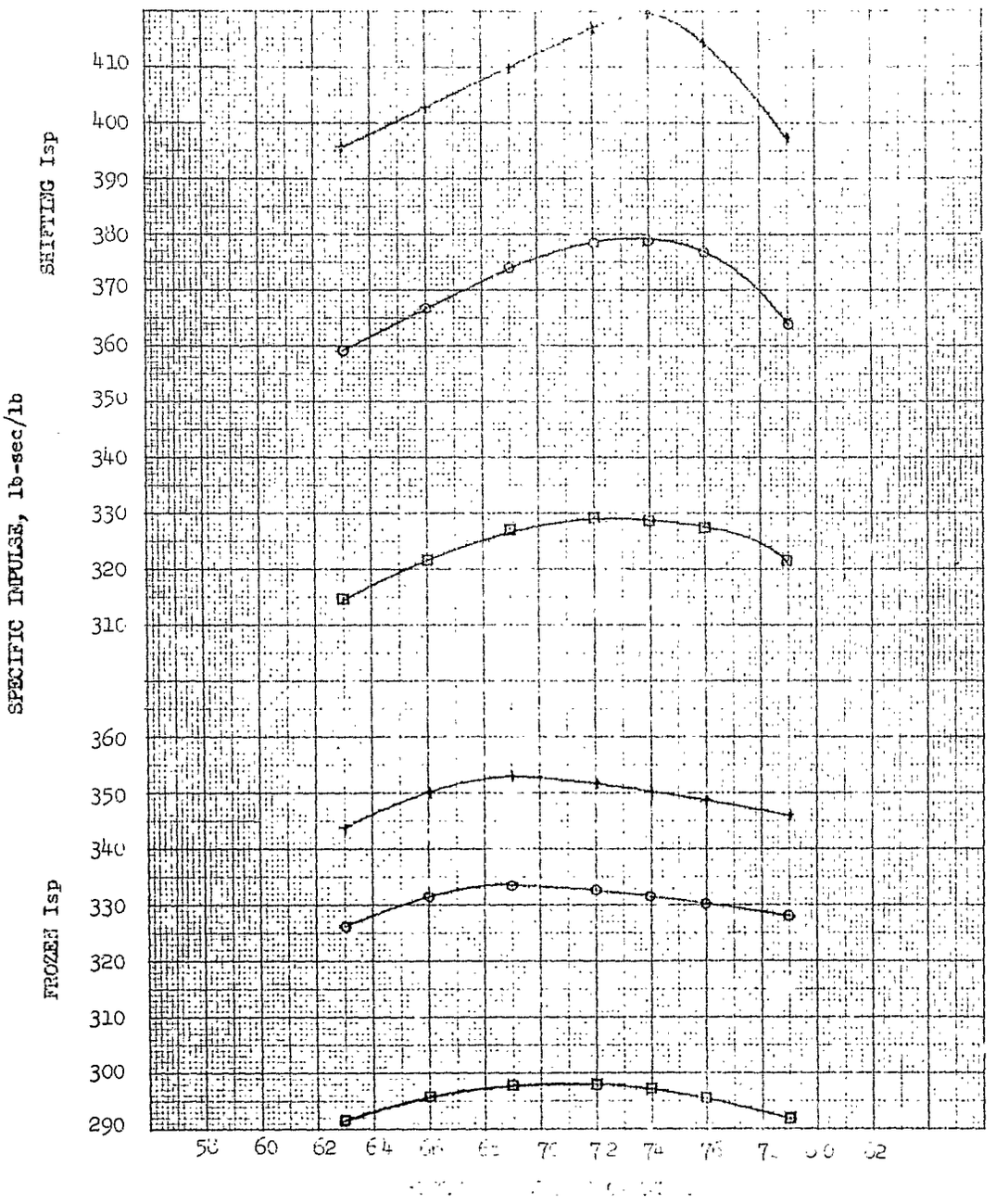
MAGNESIUM HYDRIDE – LIQUID OXYGEN PERFORMANCE CURVES FIGURE 271

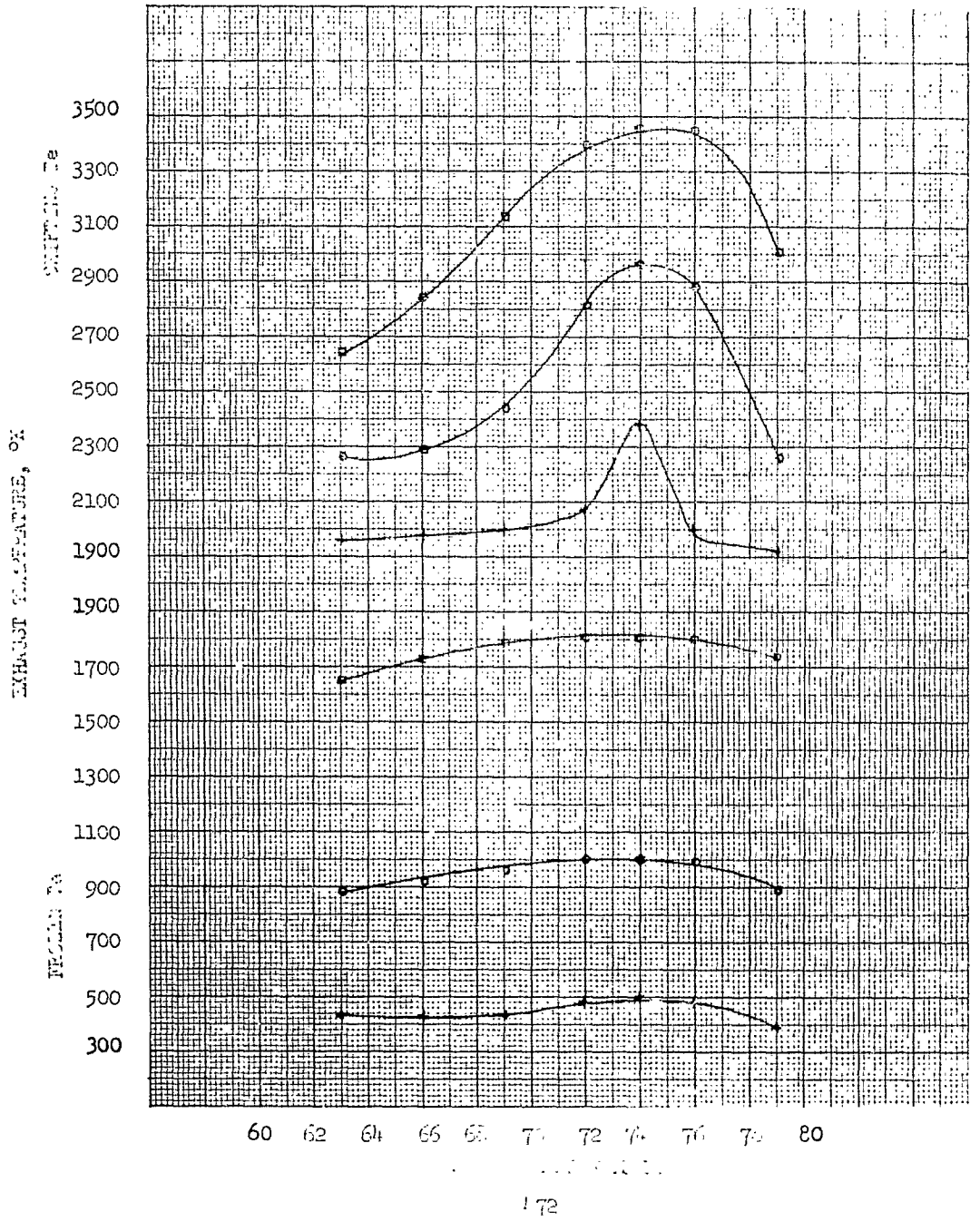


MAGNESIUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 272

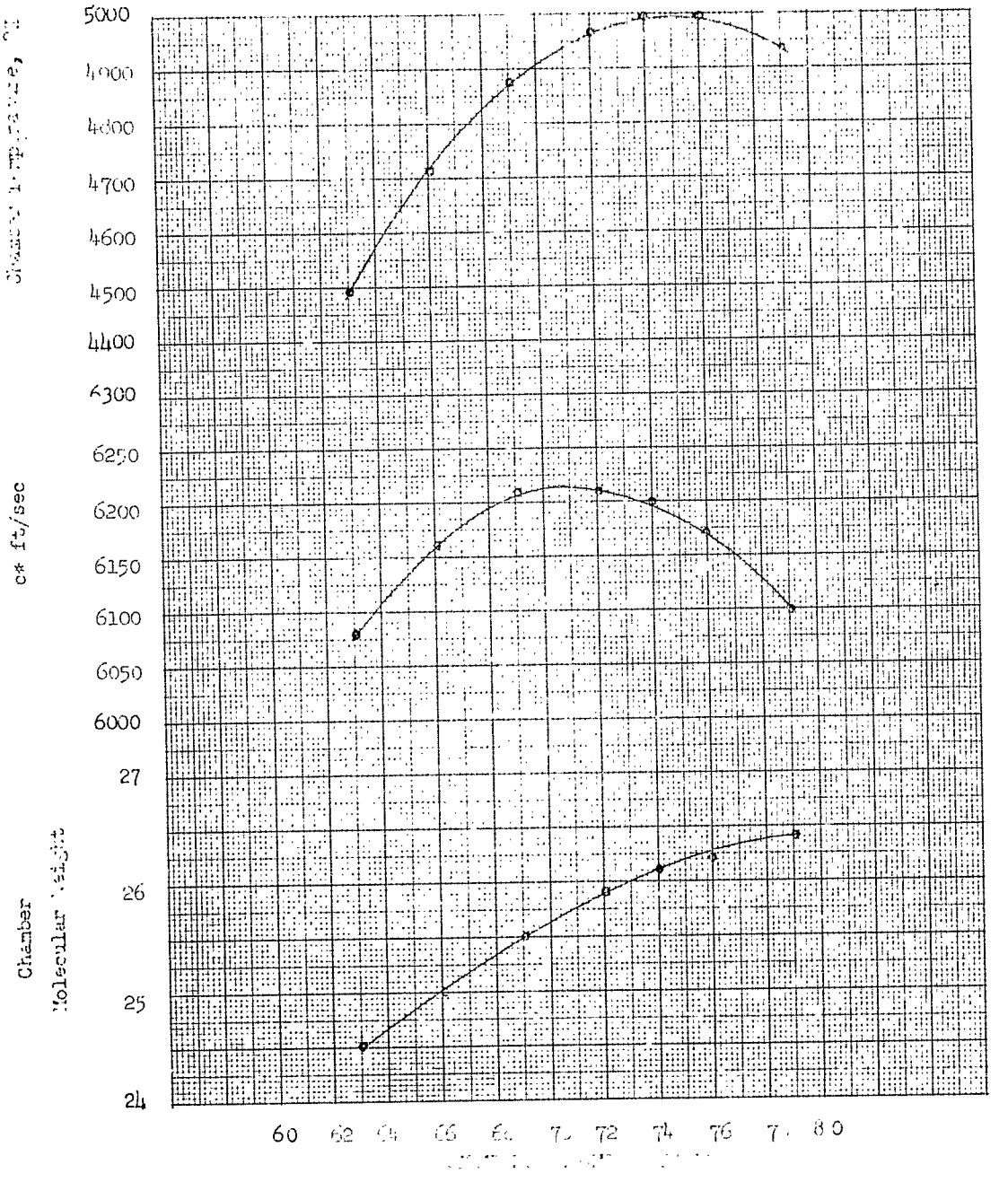



Chamber Temperature, °K
3800
3600
3400
3200
3000
2800
c* ft/sec
5050
5000
4950
4900
4850
4800
Chamber
Molecular Weight
34
32
30
28
26
24

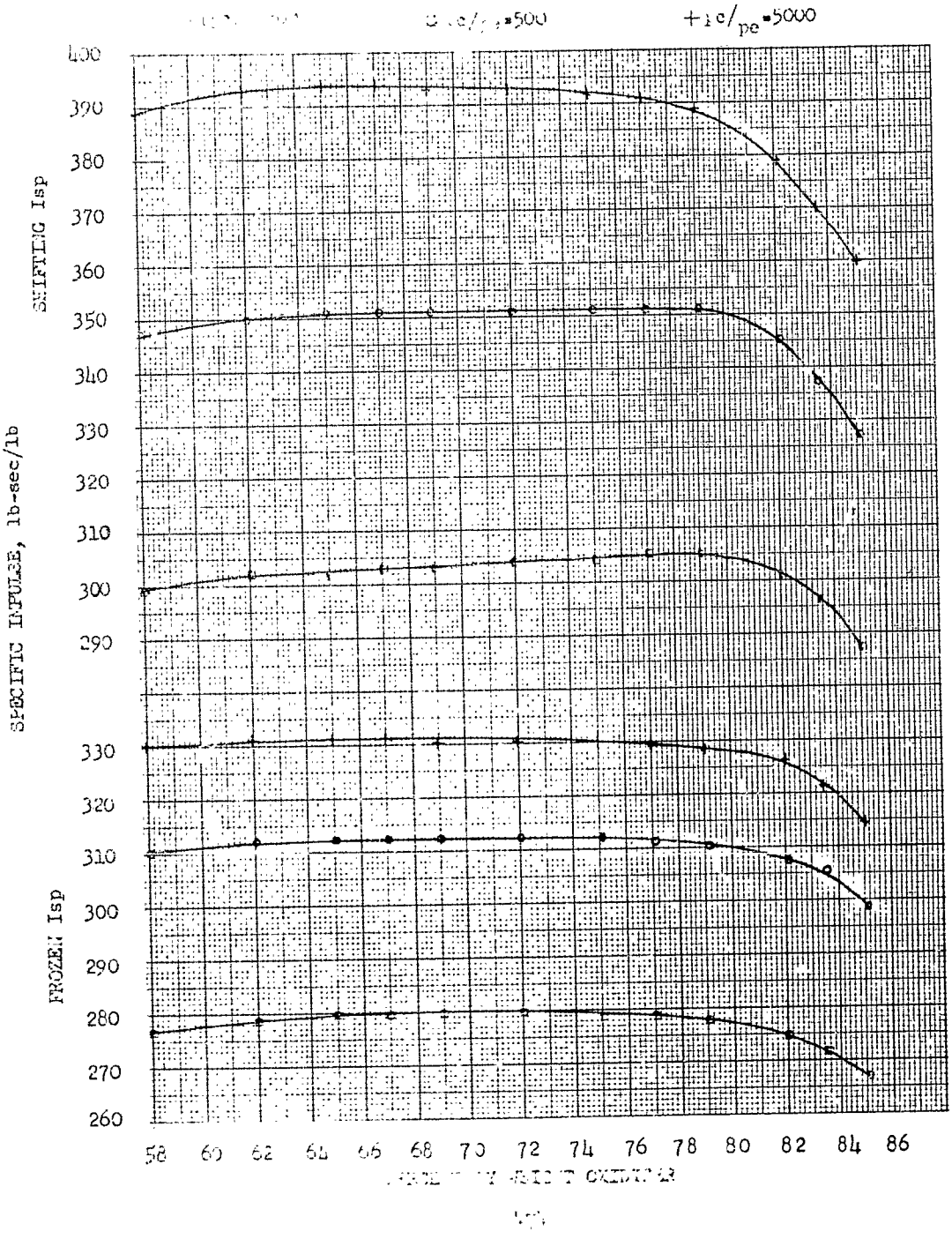

SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
410
400
390
380
370
360
350
340
330
320
310
360
350
340
330
320
310
300
290
58
60
62
64
72
74
76
82


3500
3300
3100
2900
2700
2500
2300
2100
1900
1900
1700
1500
1300
1100
900
700
500
300
60
62
64
66
72
80

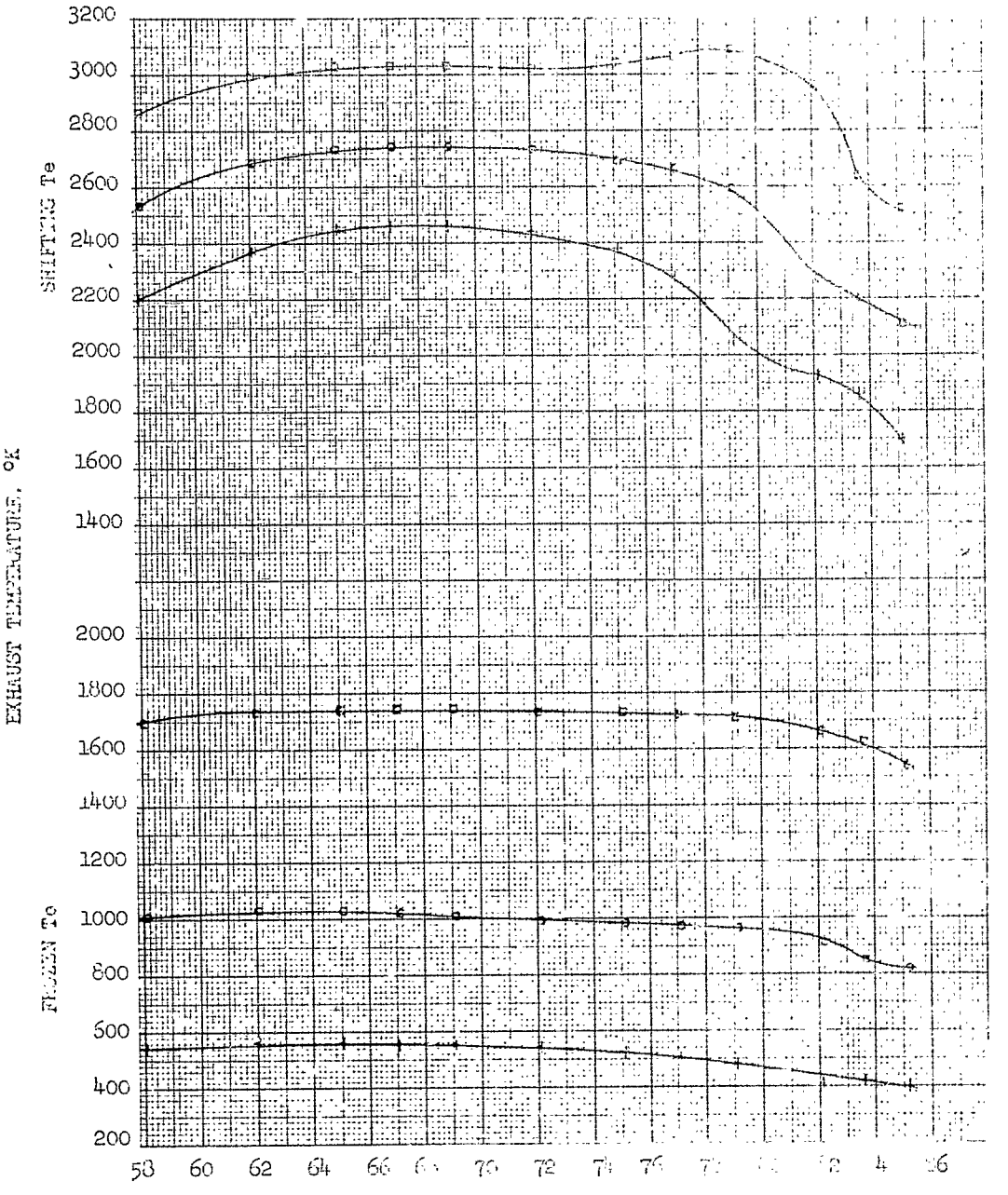
MAGNESIUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 276



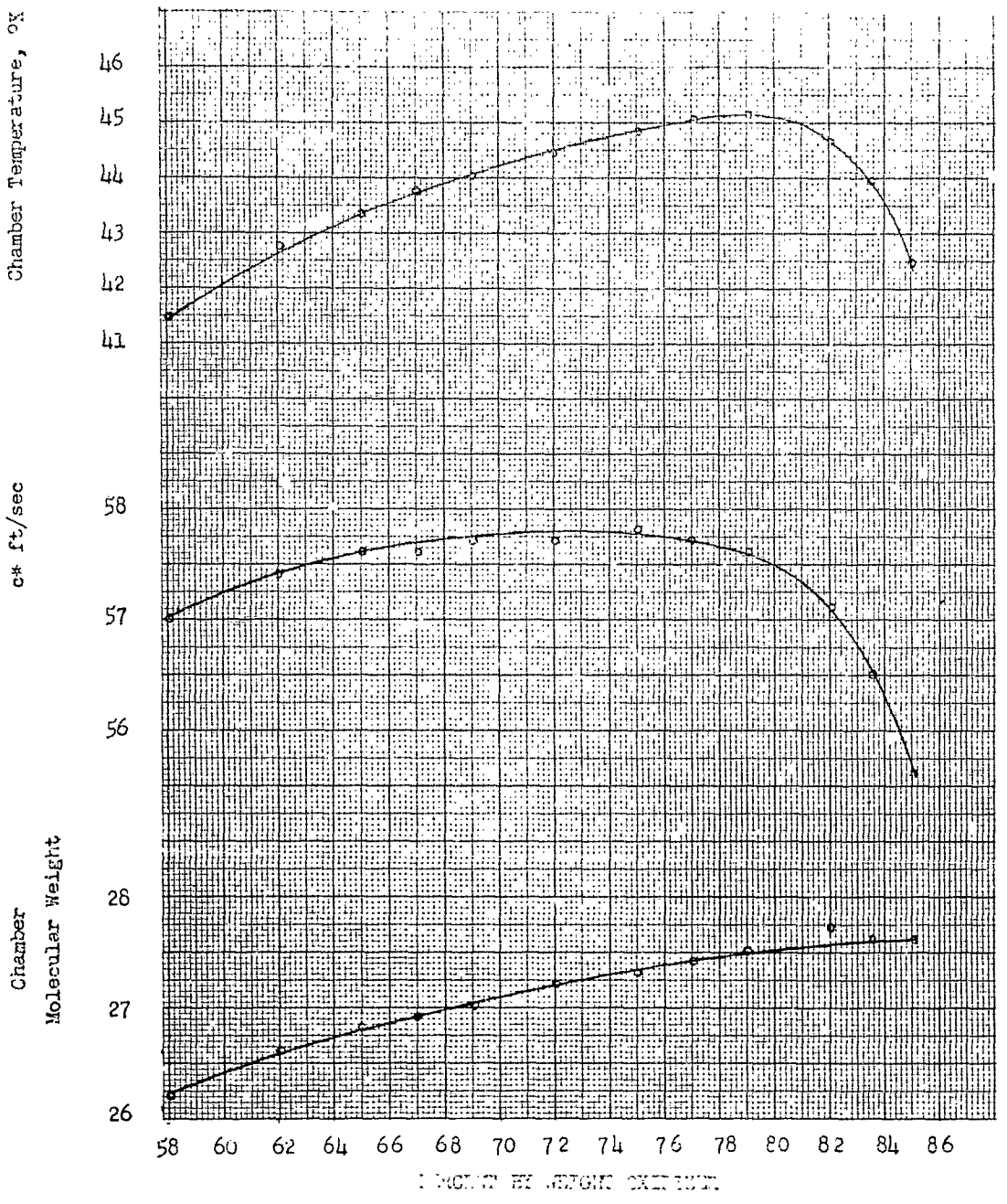
[illegible] - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 277



MAGNESIUM HYDRIDE - OXYGEN DIFLUORIDE PERFORMANCE

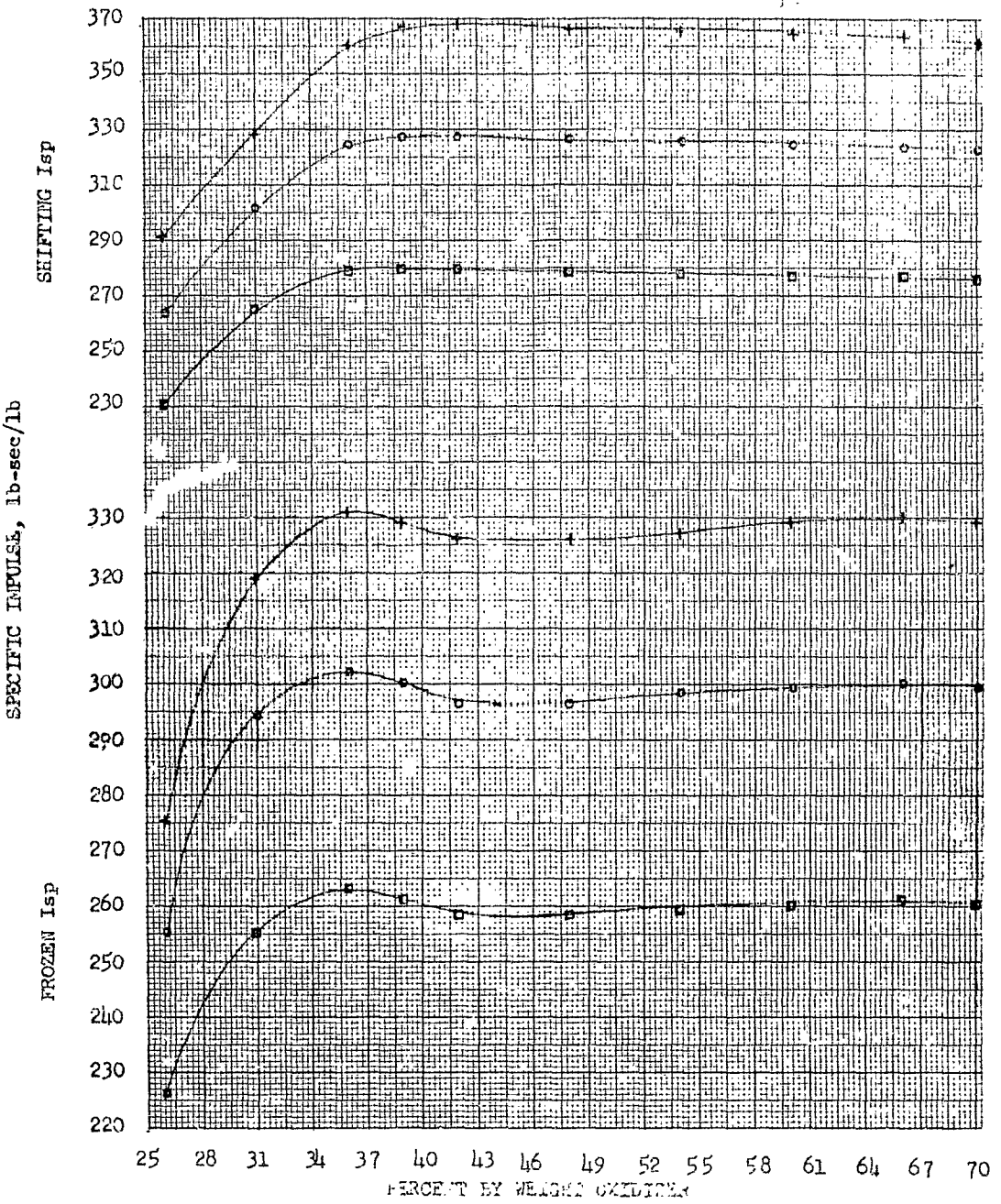


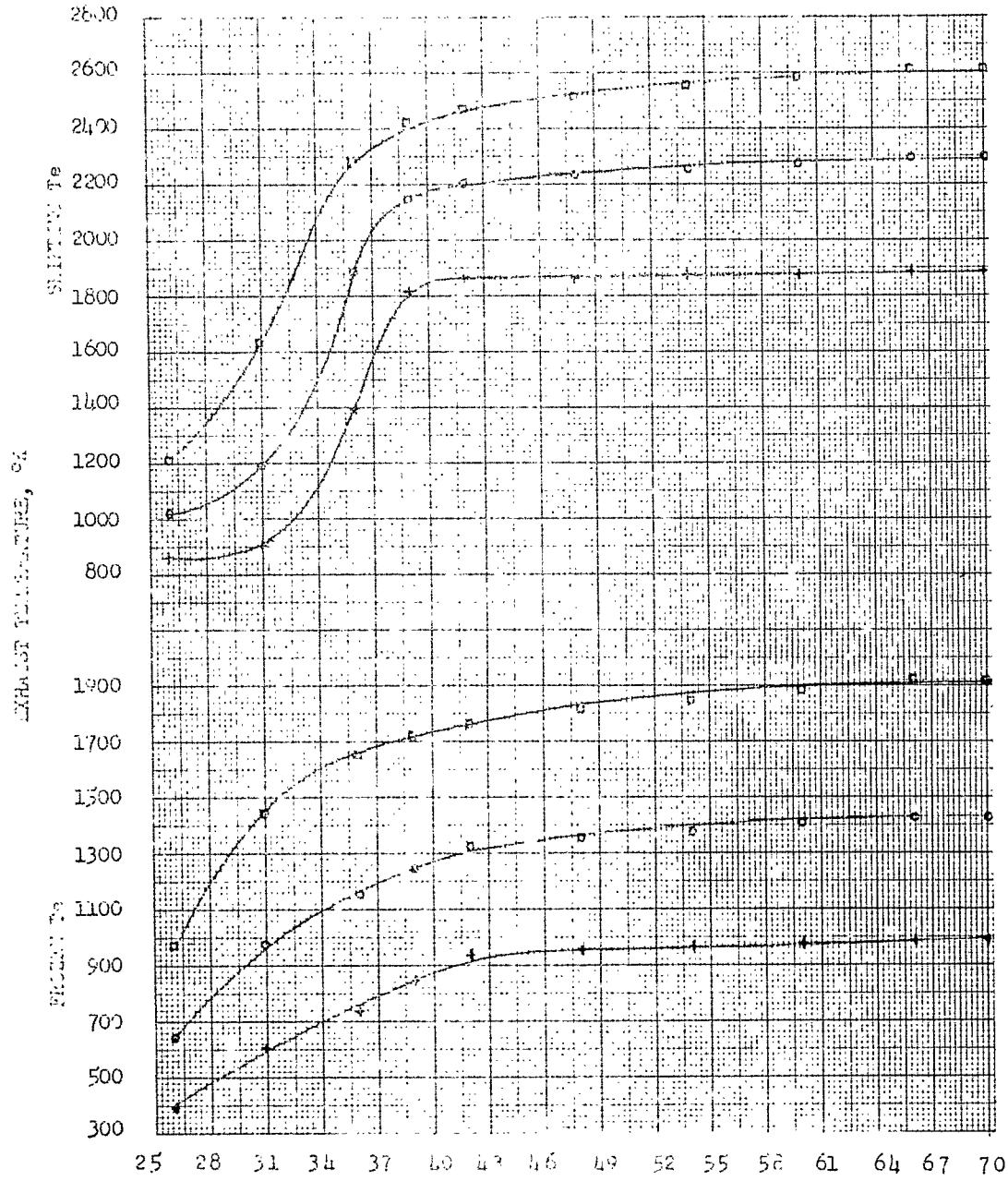
MAGNESIUM HYDRIDE - [illegible] PERFORMANCE PLOTS FIGURE 274

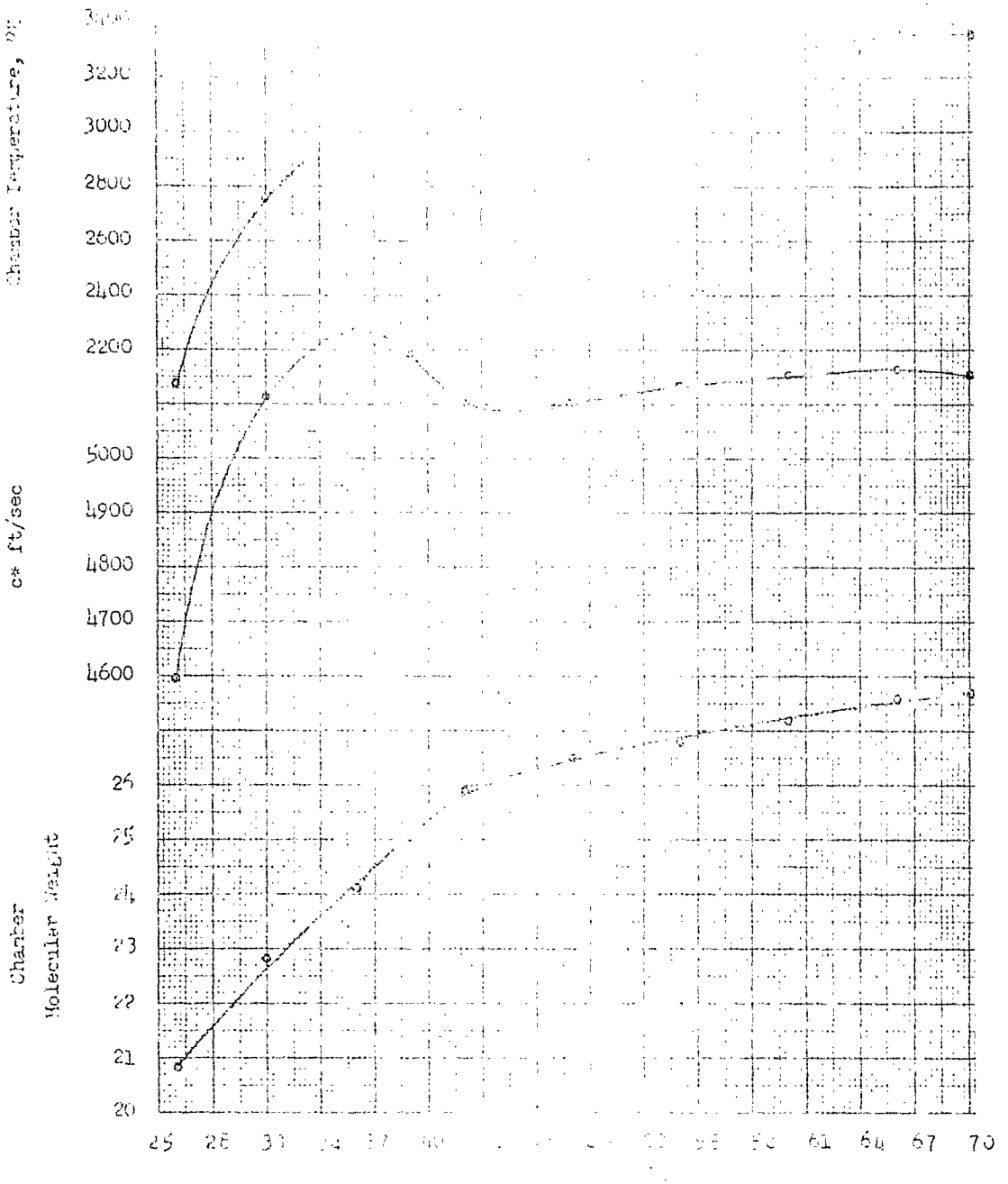


[illegible] IN WEIGHT PERCENT

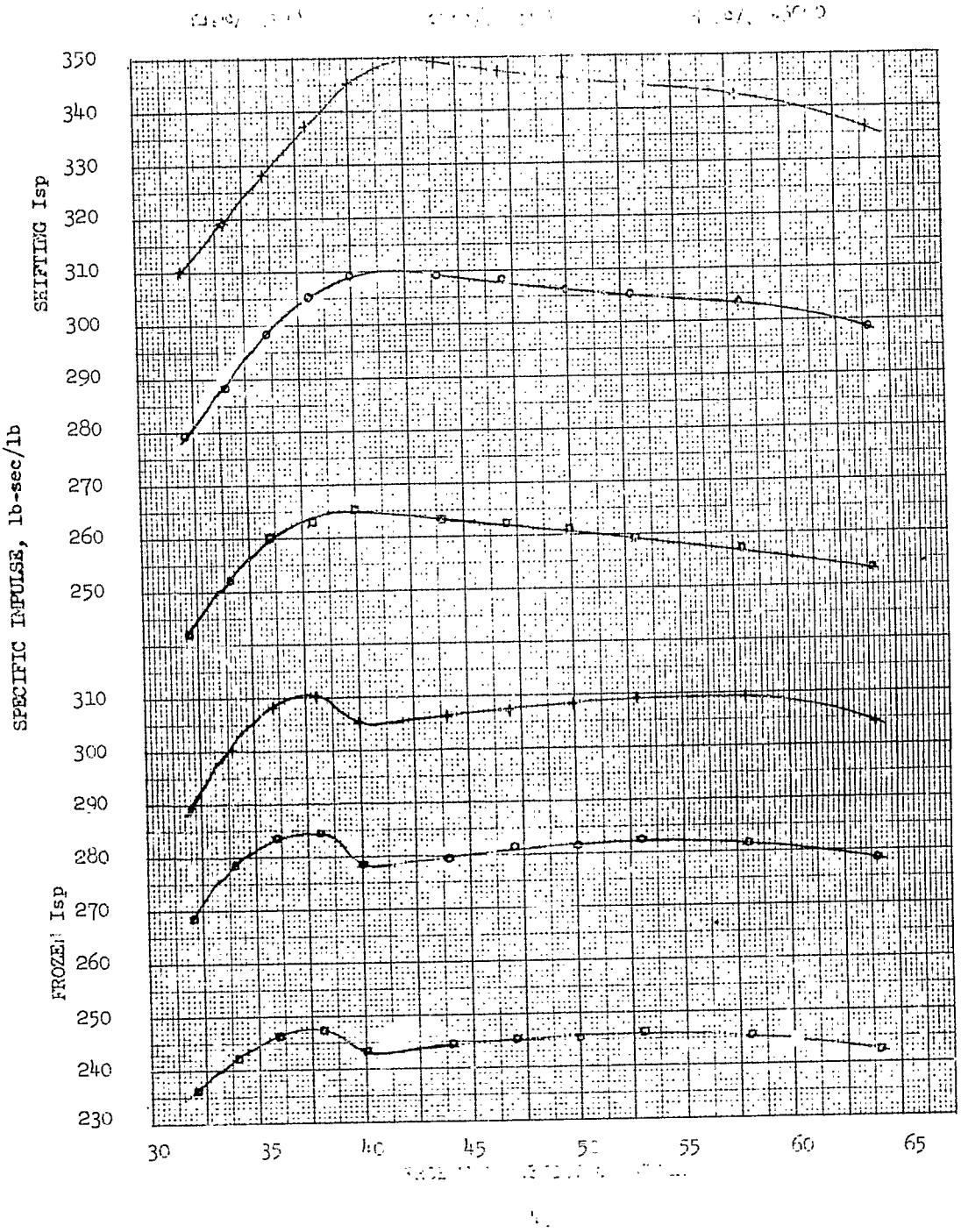
MAGNESIUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 280

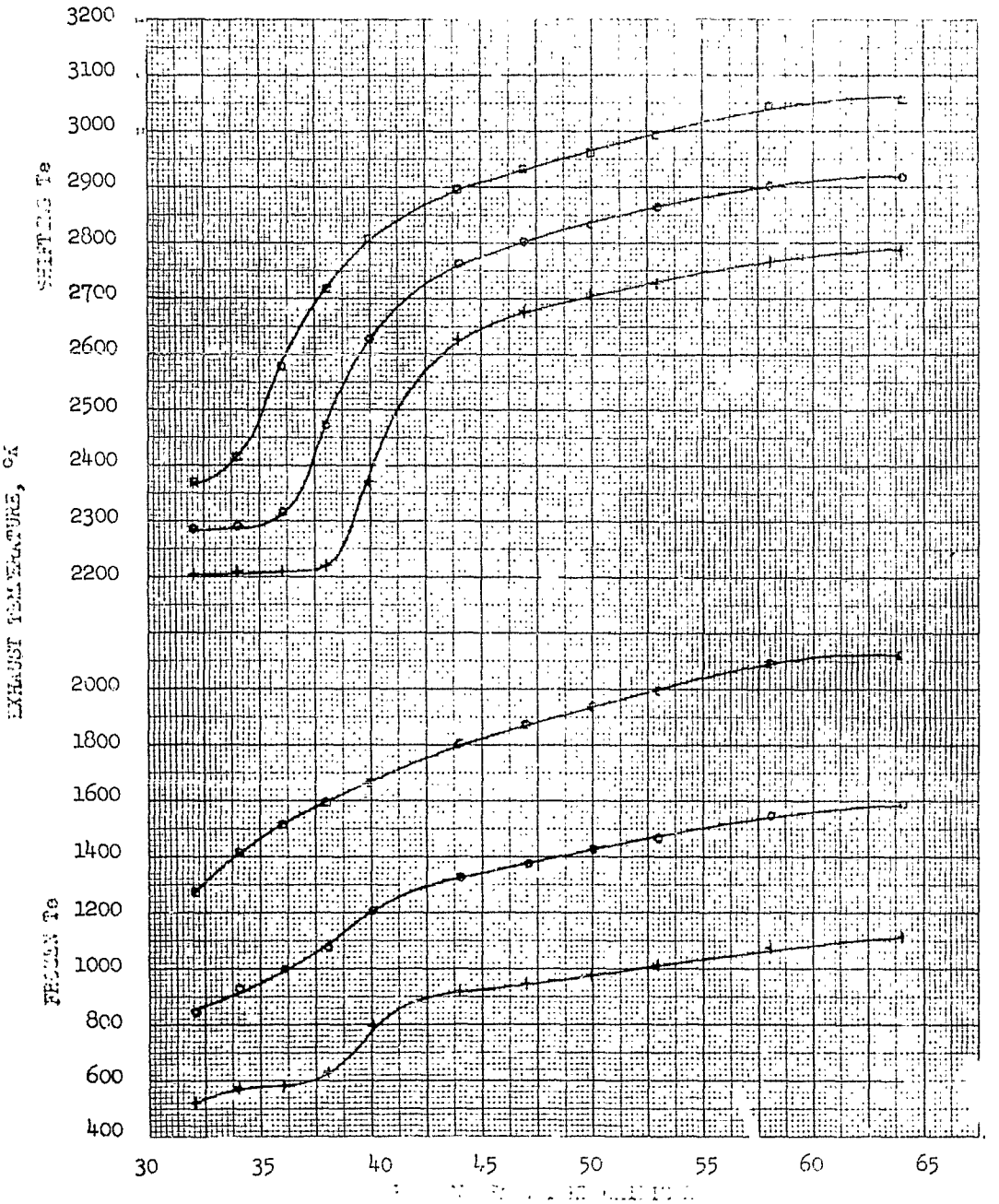


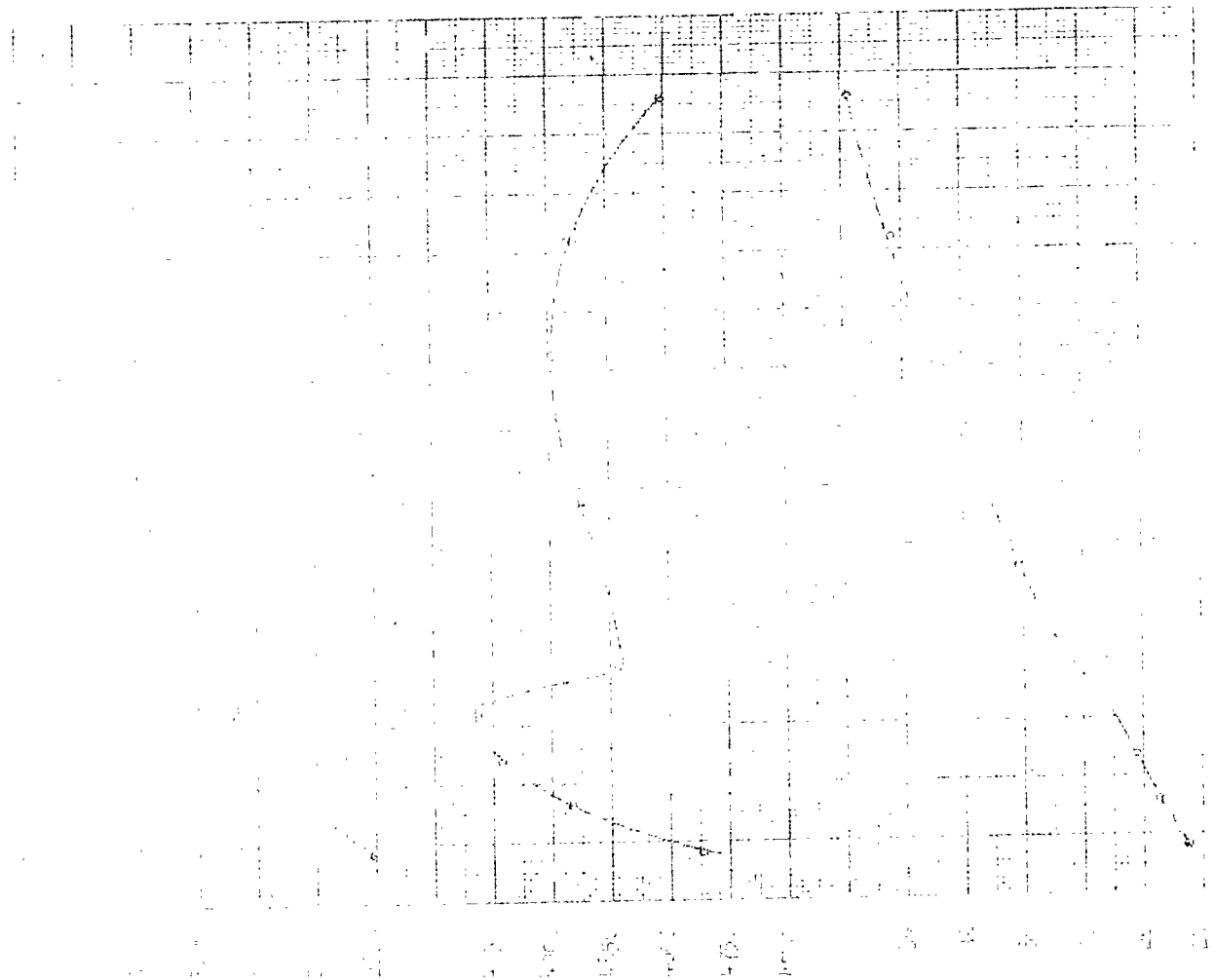

2600
2400
2200
2000
1800
1600
1400
1200
1000
800
1900
1700
1500
1300
1100
900
700
500
300
25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70


Chamber Temperature, °R
3200
3000
2800
2600
2400
2200
c* ft/sec
5000
4900
4800
4700
4600
Chamber
Molecular Weight
26
25
24
23
22
21
20
25
28
31
34
37
40
61
64
67
70

MAGNESIUM HYDRIDE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 2-3

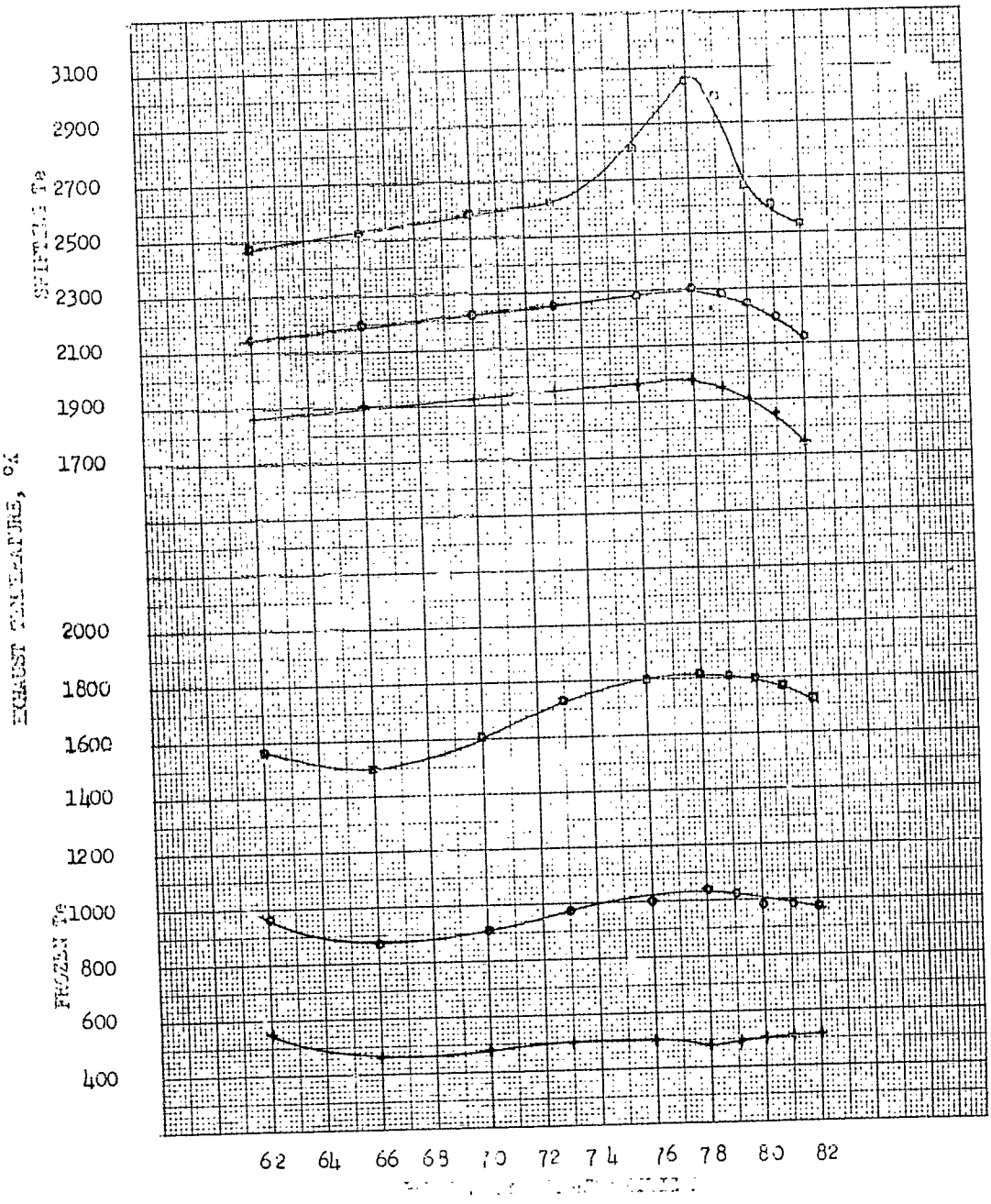



3200
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200
2000
1800
1600
1400
1200
1000
800
600
400
30
35
40
45
50
55
60
65

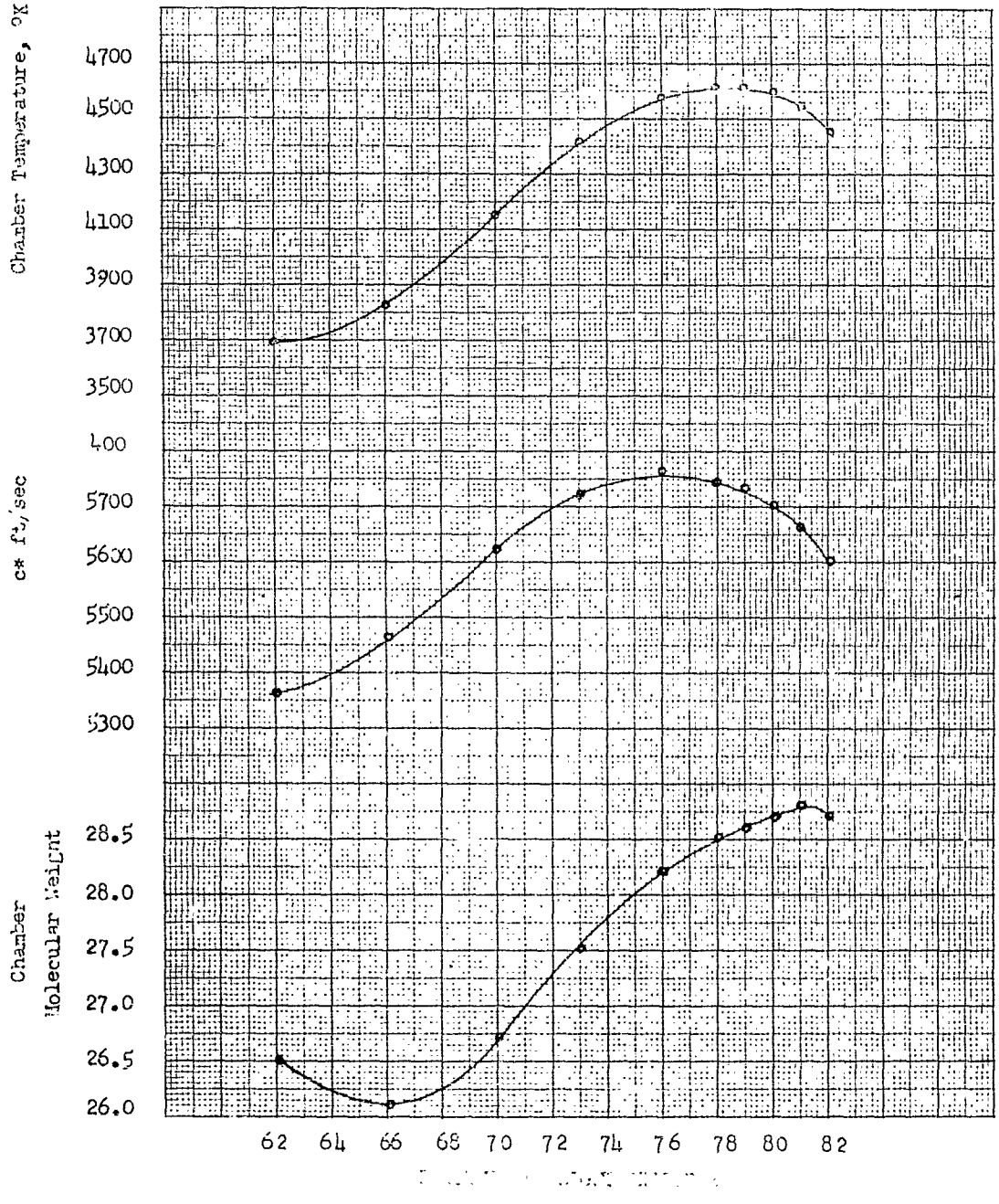


SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
380
370
360
350
340
330
320
310
300
290
280
270
260

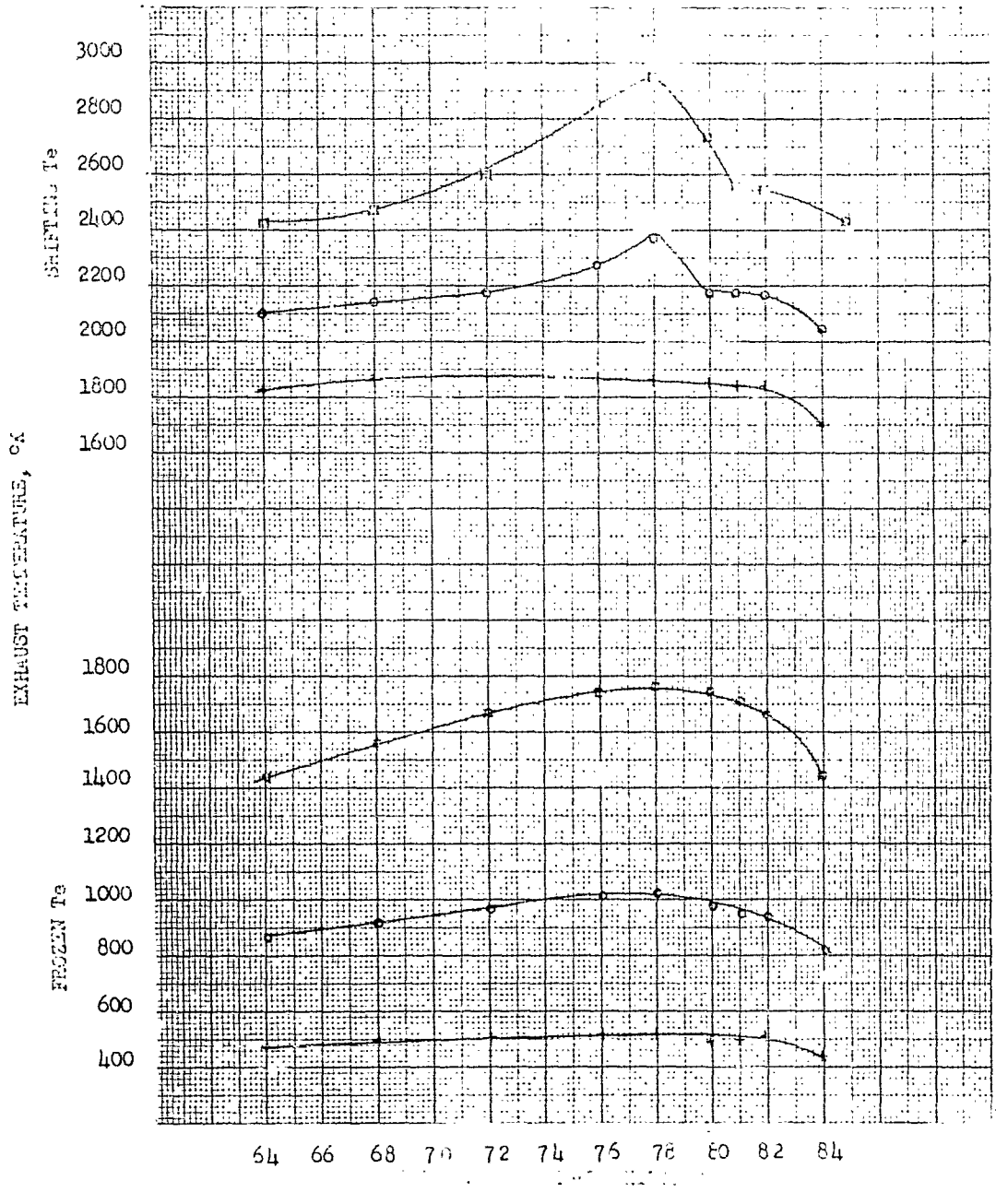
MAGNESIUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 287



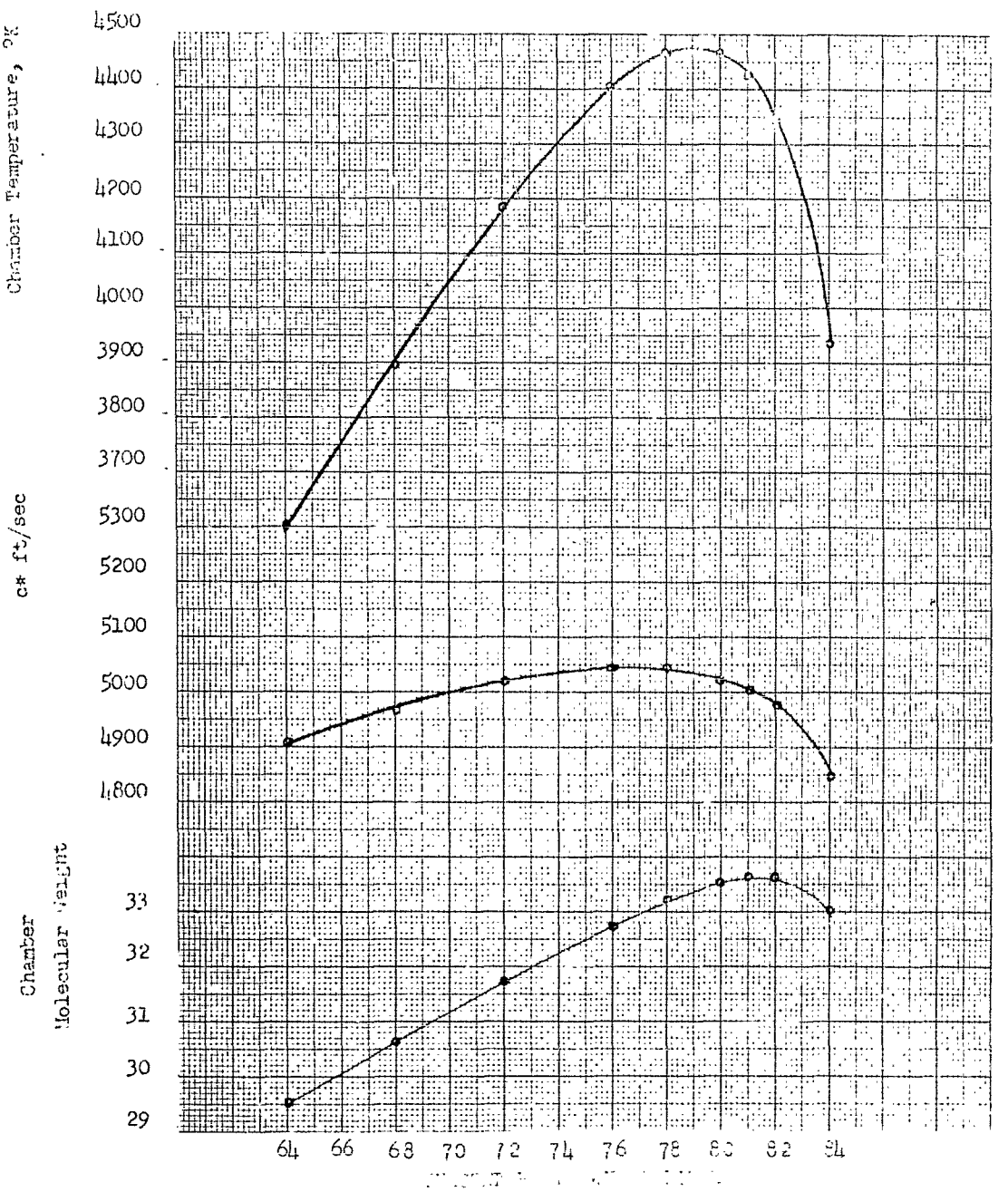
MAGNESIUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 288



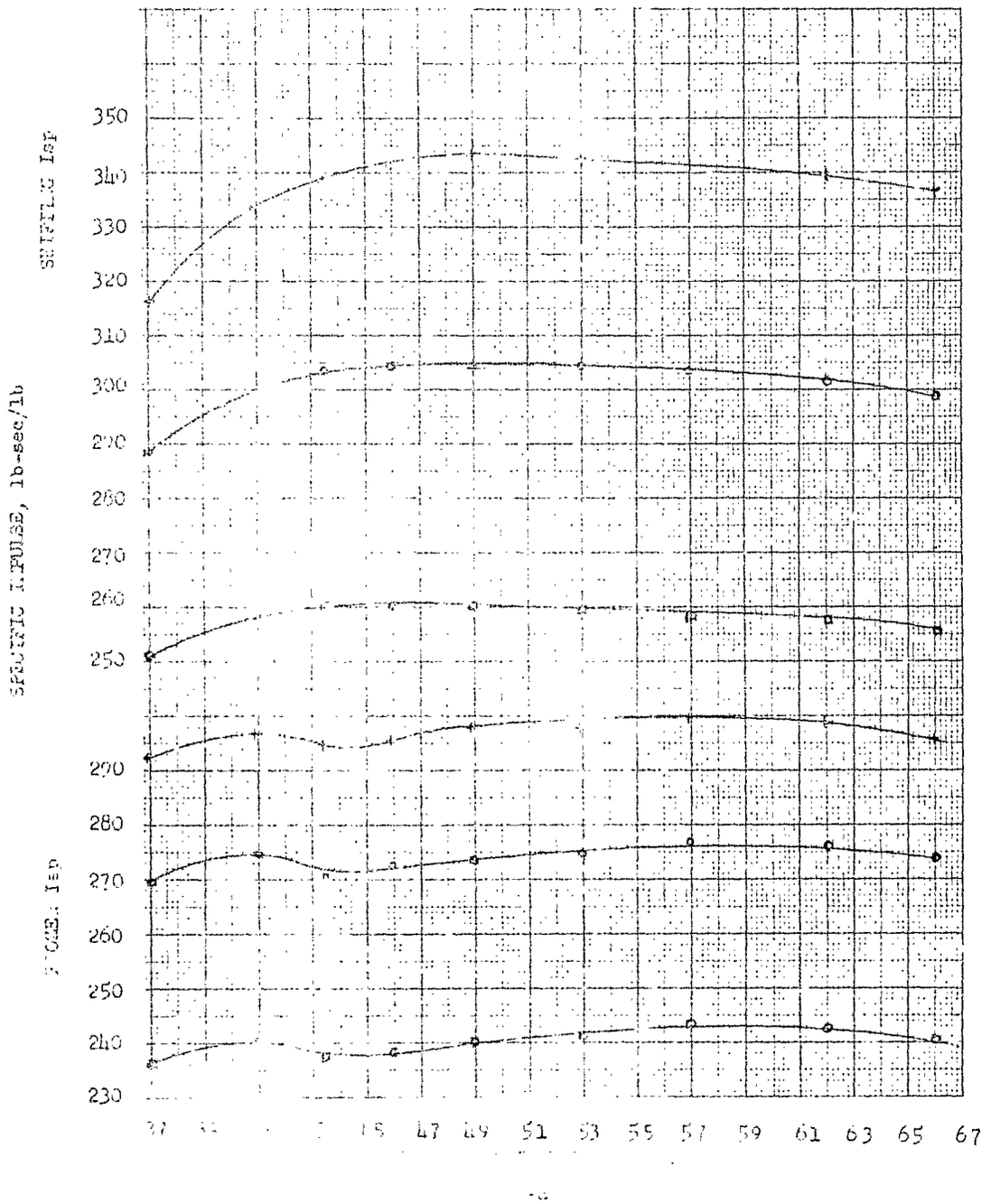
SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
340
330
320
310
300
290
280
270
260
250
310
300
290
280
270
260
250
240
230

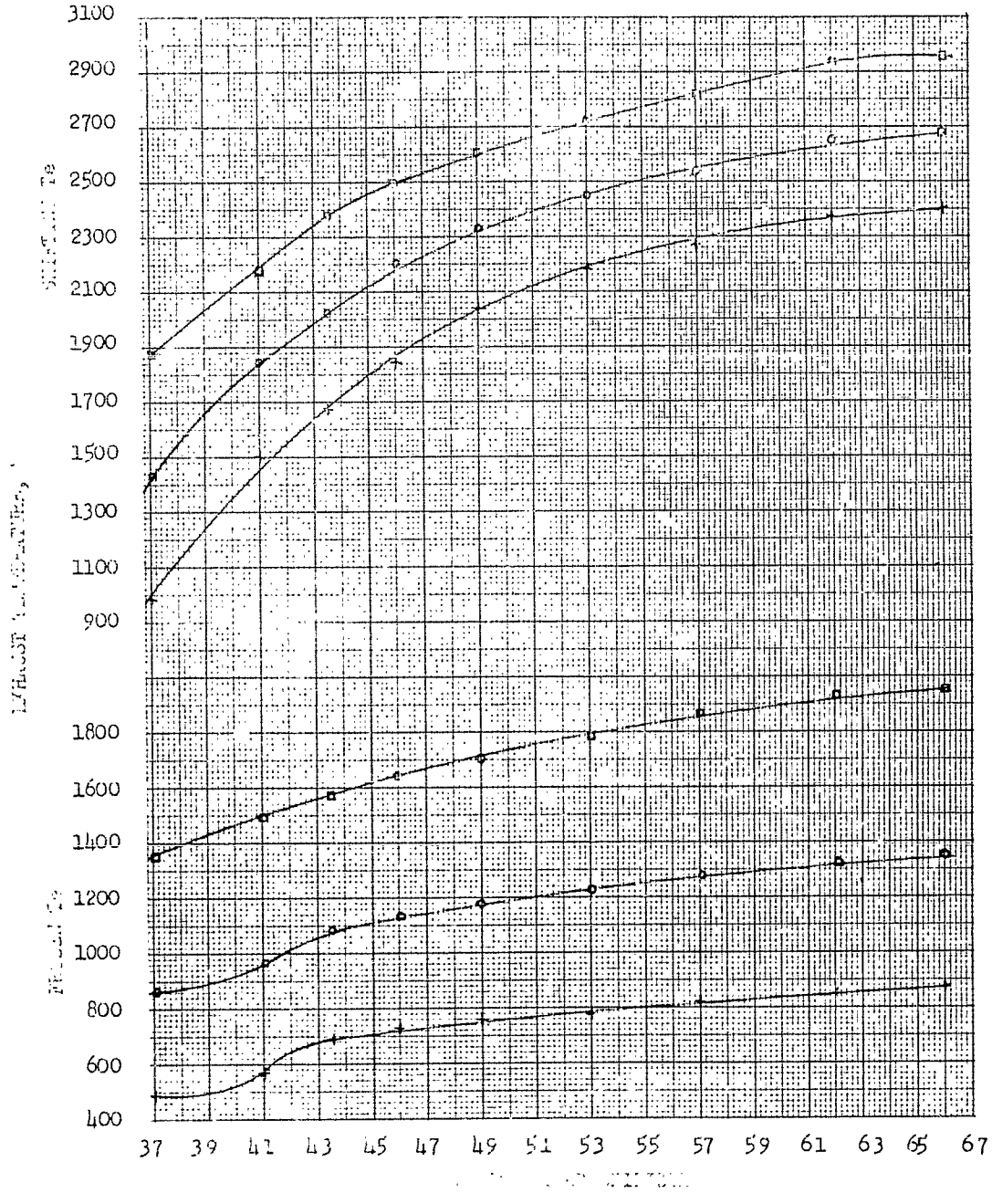

EXHAUST TEMPERATURE, °K
SHIFTING Te
FROZEN Te
3000
2800
2600
2400
2200
2000
1800
1600
1800
1600
1400
1200
1000
800
600
400
64
66
68
70
72
74
76
78
80
82
84

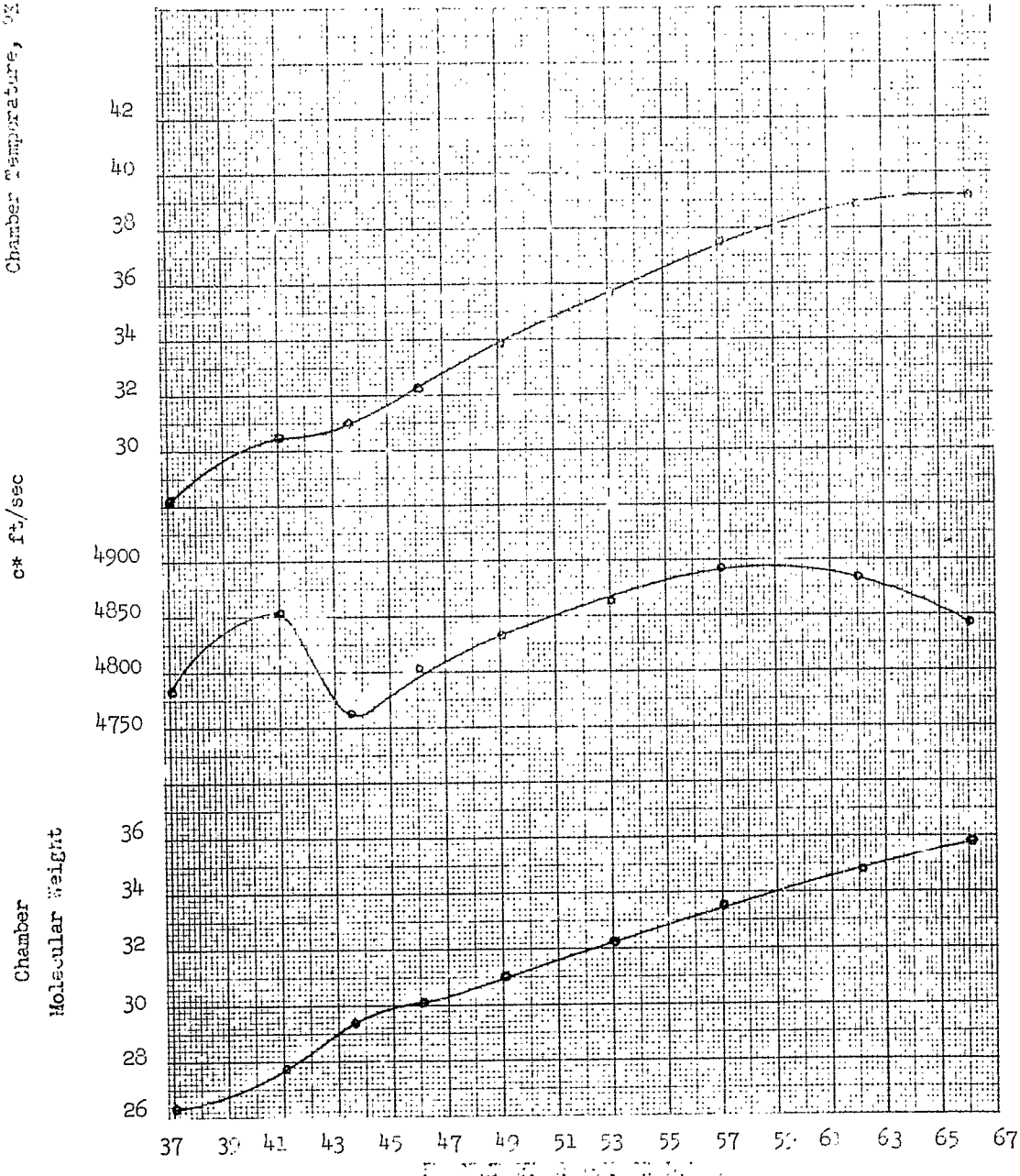
MAGNESIUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 291

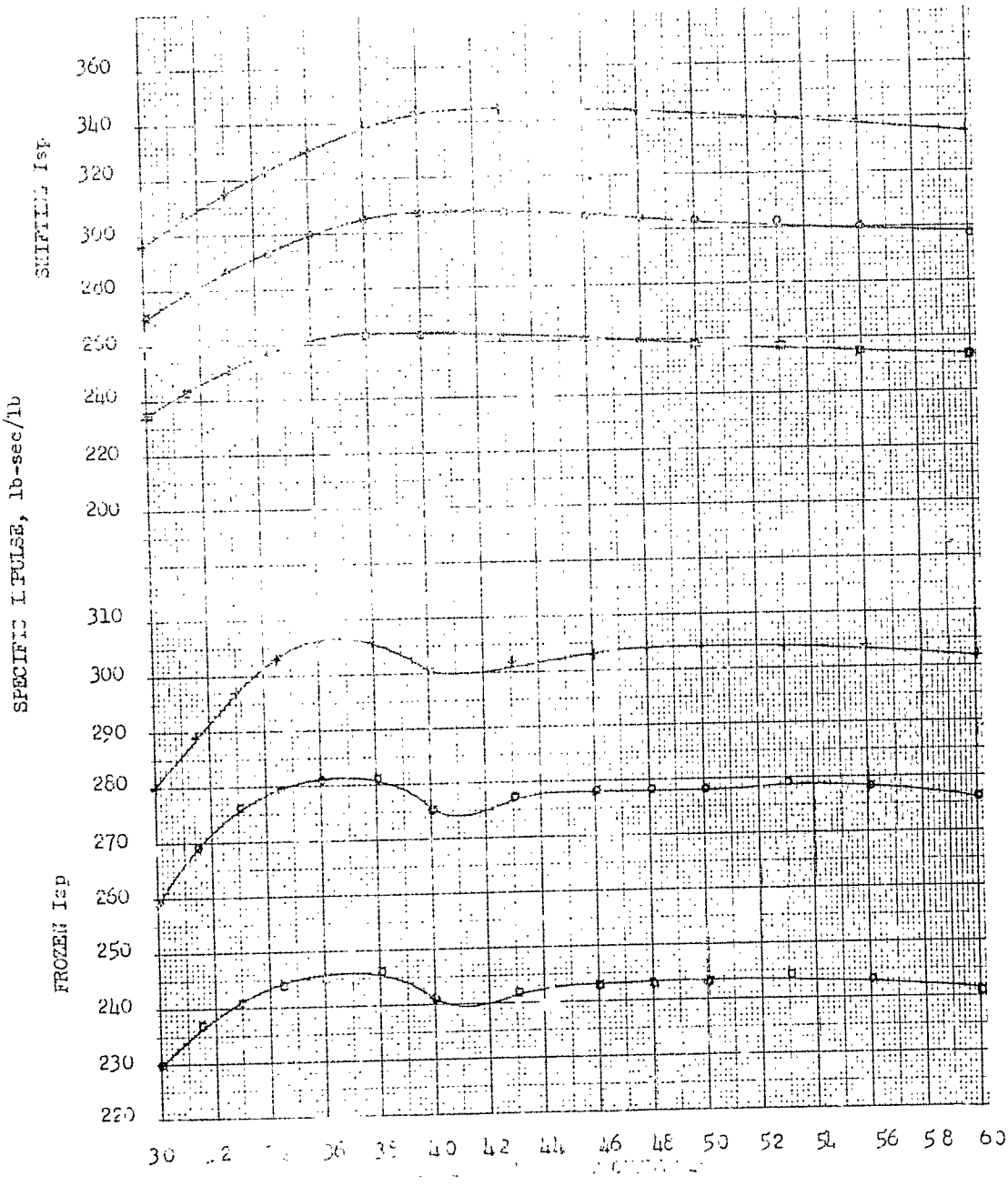


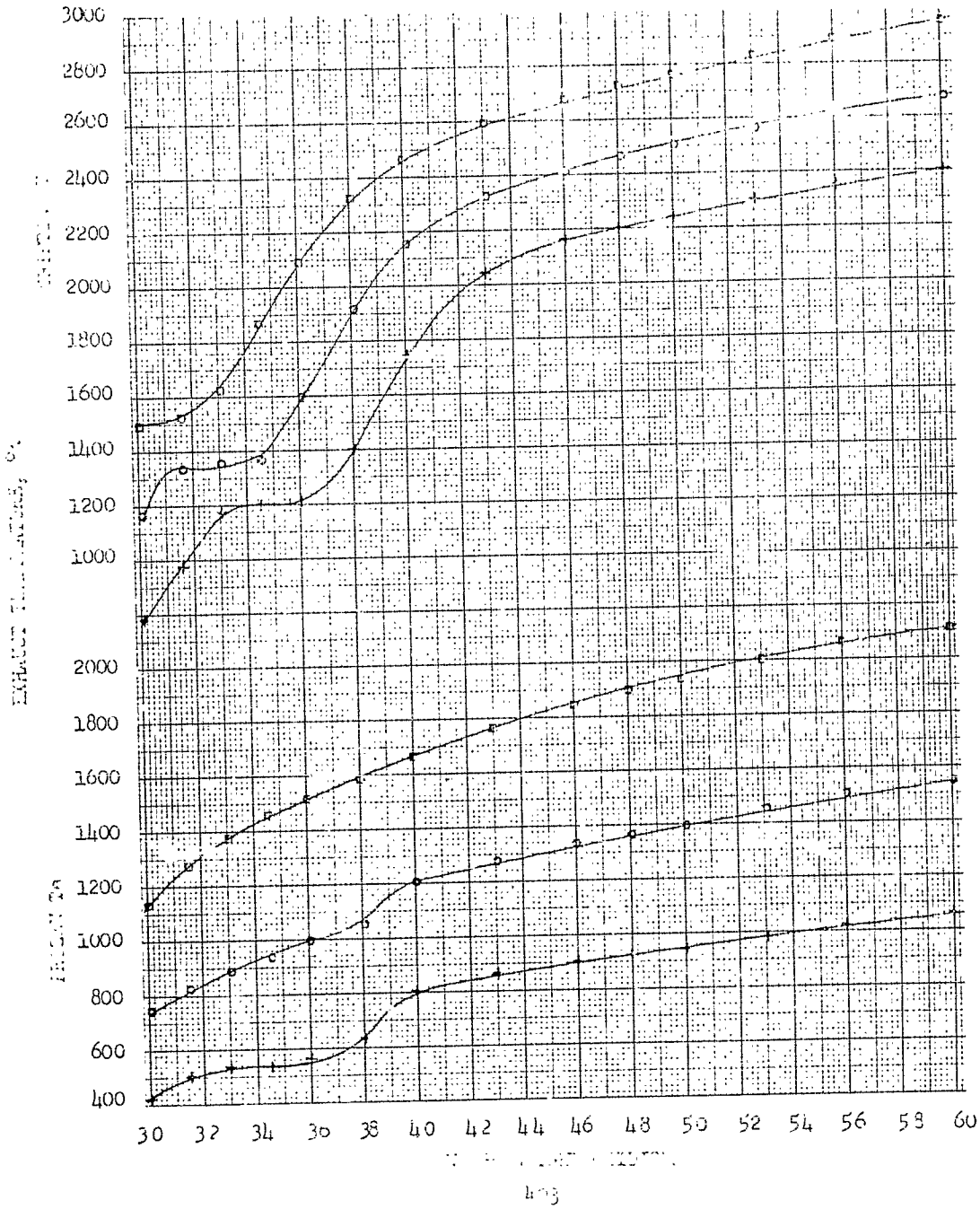
MAGNESIUM [illegible] PERFORMANCE CURVES FIGURE 222

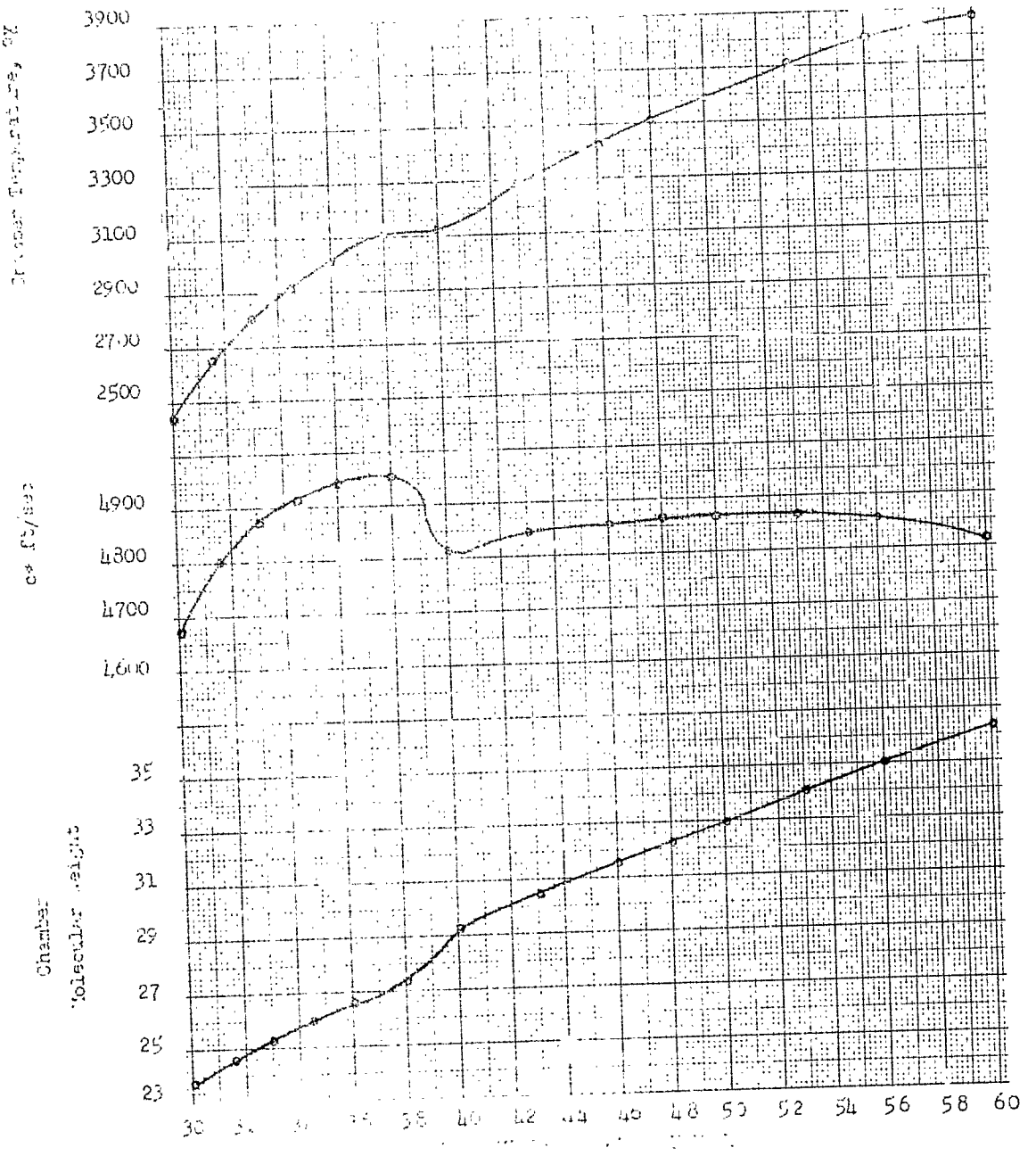



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2900
2700
2500
2300
2100
1900
1700
1500
1300
1100
900
1800
1600
1400
1200
1000
800
600
400
37 39 41 43 45 47 49 51 53 55 57 59 61 63 65 67

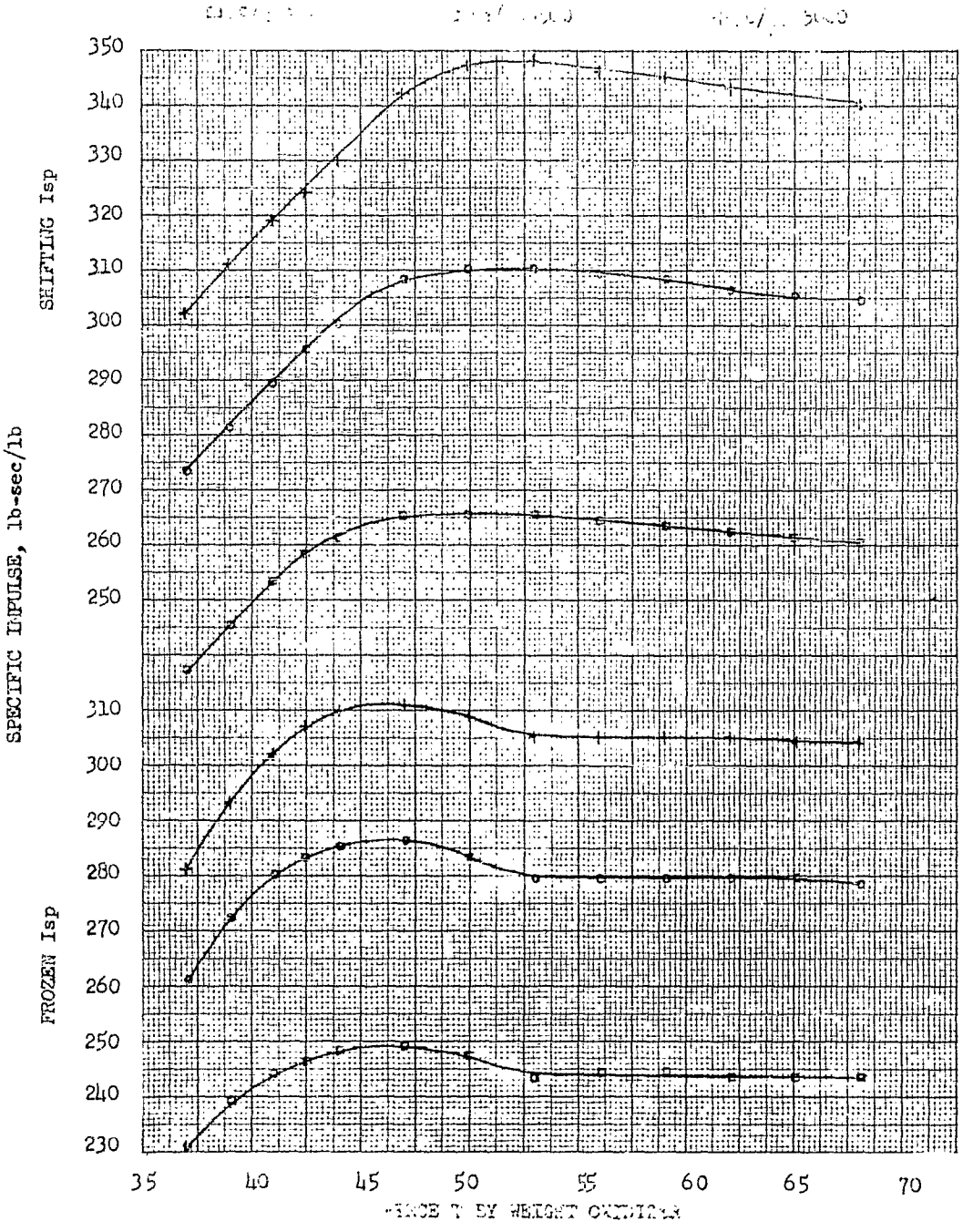

Chamber Temperature, °F
42
40
38
36
34
32
30
c* ft/sec
4900
4850
4800
4750
Chamber
Molecular Weight
36
34
32
30
28
26
37
39
41
43
45
47
49
51
53
55
57
59
61
63
65
67


SPECIFIC IMPULSE, lb-sec/lb
SHIFTING Isp
FROZEN Isp
360
340
320
300
280
260
240
220
200
310
300
290
280
270
260
250
240
230
220
30
36
40
42
44
46
48
50
52
54
56
58
60

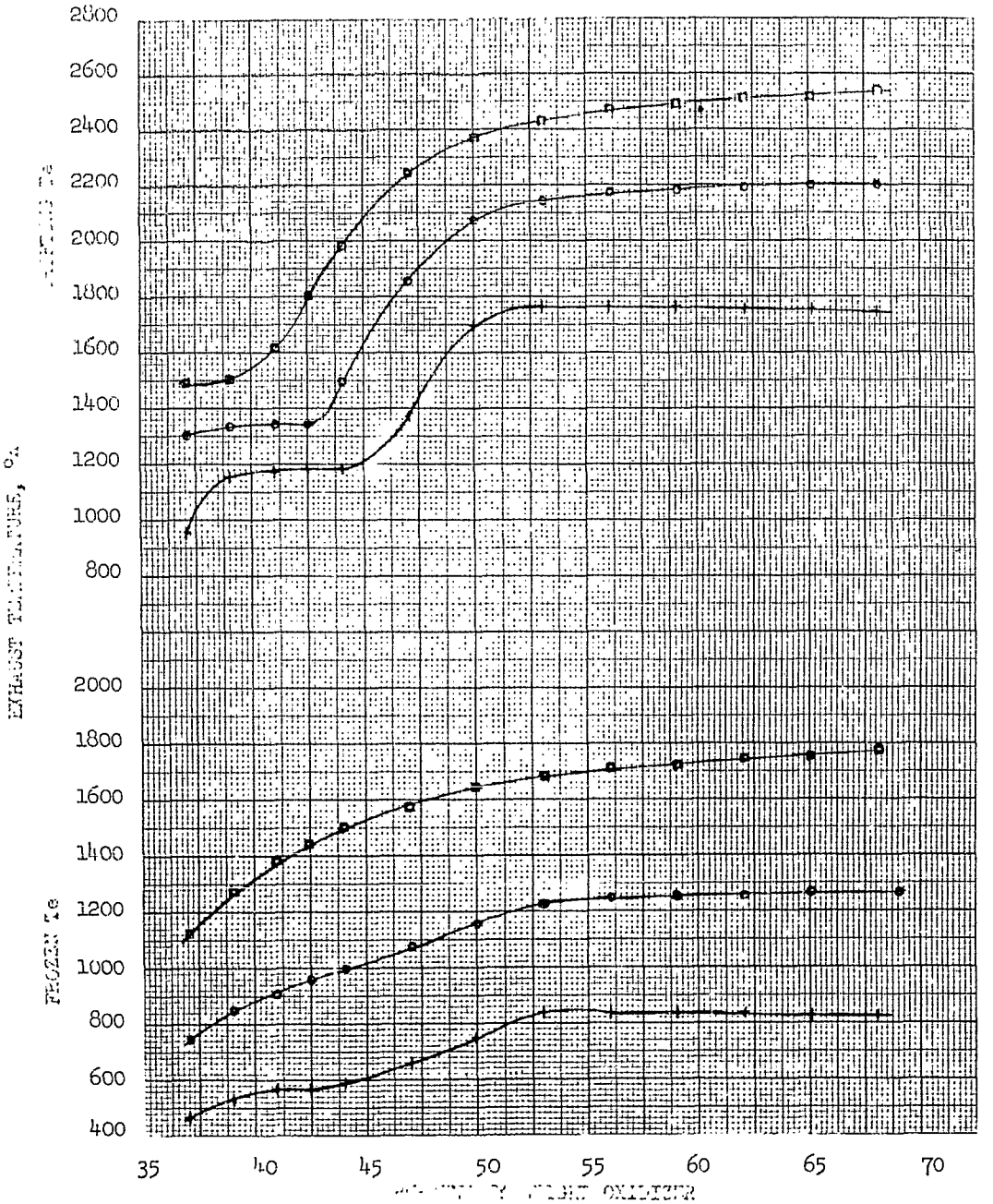

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2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
2000
1800
1600
1400
1200
1000
800
600
400
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32
34
36
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40
42
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58
60

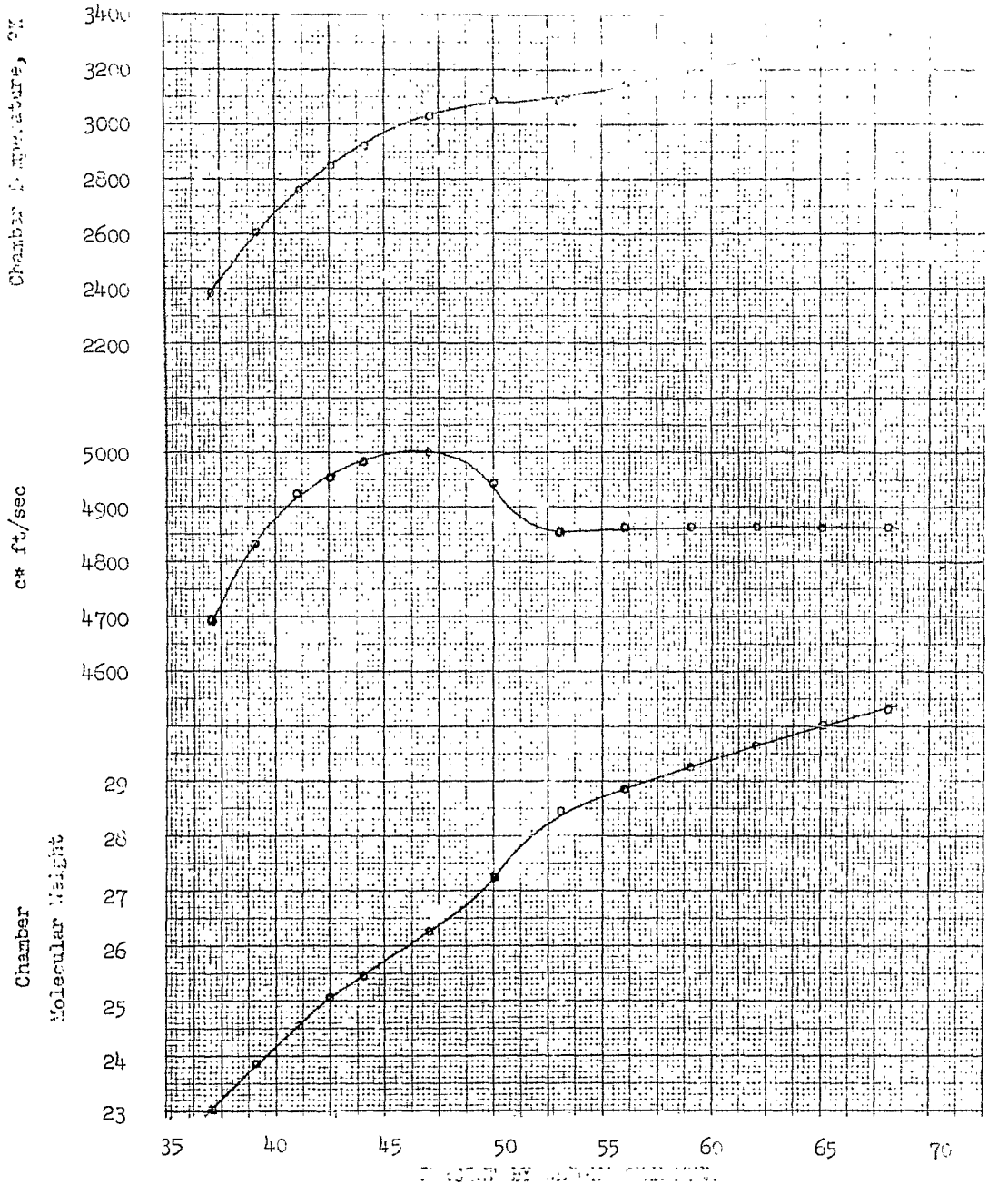

3900
3700
3500
3300
3100
2900
2700
2500
4900
4800
4700
4600
35
33
31
29
27
25
23
30
42
44
46
48
50
52
54
56
58
60

MAGNESIUM HYDRIDE – AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 298



MAGNESIUM MINERS - ALLOWABLE TEMPERATURE CURVES FIGURE 2.1




3400
3200
3000
2800
2600
2400
2200
5000
4900
4800
4700
4600
29
28
27
26
25
24
23
35
40
45
50
55
60
65
70

APPENDIX D

Tables of Complete Thermodynamic Data and Rocket Performance Parameters for Selected Propellant Compositions

CASE						
PROPELLANT COMPOSITION		WEIGHT%	MOLAR			
	O2	76.000				
	H2	24.000				
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.	
	O2	O2	-3.0800	1.142	90.200	
	H2	H2	-1.8870	710.0E-4	20.400	
ATOMIC COMPOSITION(GM AT/100GM)						
	H	23.8095				
	O	4.7500				
PROPELLANT ENTHALPY		-29.779	KCAL/100 GM			
PROPELLANT DENSITY		0.2472	GM/CC	0.009	LB/CU IN	
		CHAMBER	EXHAUST	EXHAUST	EXHAUST	
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000	
SHIFTING EQUILIBRIA						
	ISP (SEC)		389.05	431.02	456.95	
	IVSP(LB-SEC/CU IN)		3.4743	3.8492	4.0807	
	TEMPERATURE (K)	2570.4	1059.1	646.04	352.76	
	CP (CAL/GM-DEG.K)	1.2154	0.99846	0.92090	0.88221	
	MOL. WT.-EFFECTIVE	8.3846	8.4000	8.4000	8.4000	
	CP/CV -EFFECTIVE	1.2422	1.3105	1.3457	1.3664	
	CF -APPROX.		1.5691	1.7384	1.8430	
	PEAE/M (SEC)		28.019	15.427	7.9456	
	AE/AT -APPROX.		7.6896	31.109	160.23	
FROZEN EQUILIBRIA						
	ISP (SEC)		387.75	430.14	454.98	
	TEMPERATURE (K)	2570.4	1046.5	629.56	349.26	
	C* (FT/SEC)	7977.4				
	CF (SEC)		1.5638	1.7348	1.8350	
	PEAE/M (SEC)		27.829	15.092	7.9155	
	AE/AT		7.6373	30.434	159.62	

TABLE 1

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2570.4	1059.1	646.04	352.76
ENTHALPY (KILOCALORIES)	-29.779	-203.73	-243.29	-269.75
ENTROPY (CALORIES/DEG.K)	569.88	569.88	569.88	569.88
HEAT CAPACITY (CAL/K)	121.54	99.846	92.090	88.221
MOLES OF GAS	11.927	11.905	11.905	11.905
MOLECULAR COMPOSITION:				
H	0.0379	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
H2	7.1387	7.1548	7.1548	7.1548
H2O	4.7442	4.7500	4.7500	4.7500
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0058	0.0000	0.0000	0.0000

TABLE 2

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
F2		92.000			
H2		8.0000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
F2	F2		-3.4670	1.510	85.200
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		7.9365			
F		4.6421			
PROPELLANT ENTHALPY		-15.882	KCAL/100 GM		
PROPELLANT DENSITY		0.5760	GM/CC	0.0208	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			407.22	456.56	486.86
IVSP(LB-SEC/CU IN)			8.4751	9.5019	10.132
TEMPERATURE (K)	4462.0		2395.6	1500.7	803.36
CP (CAL/GM-DEG.K)	0.59665		0.53915	0.46985	0.45101
MOL. WT.-EFFECTIVE	14.240		15.592	15.651	15.651
CP/CV -EFFECTIVE	1.3053		1.3096	1.3499	1.3918
CF -APPROX.			1.6533	1.6536	1.9766
PEAE/M (SEC)			32.621	18.158	9.1151
AE/AT -APPROX.			9.0118	36.859	185.03
FROZEN EQUILIBRIA					
ISP (SEC)			377.72	420.67	441.17
TEMPERATURE (K)	4462.0		1540.8	734.49	298.16
C* (FT/SEC)	7924.8				
CF			1.5335	1.7079	1.7911
PEAE/M (SEC)			24.766	10.600	4.1032
AE/AT			6.8418	21.518	83.293

TABLE 3

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4462.0	2395.6	1500.7	803.36
ENTHALPY (KILOCALORIES)	-15.882	-206.46	-255.45	-288.30
ENTROPY (CALORIES/DEG.K)	355.17	355.17	355.17	355.17
HEAT CAPACITY (CAL/K)	59.665	53.915	48.985	45.101
MOLES OF GAS	7.0223	6.4137	6.3894	6.3893
MOLECULAR COMPOSITION:				
H	1.0934	0.0486	0.0002	0.0000
F	0.1726	0.0002	0.0000	0.0000
H2	1.0866	1.5230	1.5471	1.5472
HF	4.6695	4.8419	4.8421	4.8421
F2	0.0000	0.0000	0.0000	0.0000

TABLE 4

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
OF2		85.500			
H2		14.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
OF2	OF2		3.6000	1.530	128.00
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		14.3849			
O		1.5833			
F		3.1667			
PROPELLANT ENTHALPY		-7.8722	KCAL/100 GM		
PROPELLANT DENSITY		0.3844	GM/CC	0.0139	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			410.55	457.02	485.43
IVSP(LB-SEC/CU IN)			5.7027	6.3482	6.7428
TEMPERATURE (K)		3590.6	1663.2	1022.2	553.04
CP (CAL/GM-DEG.K)		0.86195	0.74687	0.67995	0.63908
MOL. WT.-EFFECTIVE		10.995	11.394	11.395	11.395
CP/CV -EFFECTIVE		1.2653	1.3046	1.3450	1.3753
CF -APPROX.			1.6149	1.7976	1.9094
PEAE/M (SEC)			30.738	16.971	8.6441
AE/AT -APPROX.			8.2270	33.376	170.00
FROZEN EQUILIBRIA					
ISP (SEC)			394.25	441.95	466.94
TEMPERATURE (K)		3590.6	1377.8	722.17	318.96
C* (FT/SEC)		8179.7			
CF (SEC)			1.5507	1.7384	1.8367
PEAE/M (SEC)			27.479	12.849	5.3712
AE/AT			7.3548	25.270	105.64

TABLE 5

TABLE 6

CASE
BASIS 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3590.6	1663.2	1022.2	553.04
TEMPERATURE (KELVIN)	-7.6722	-201.58	-247.92	-278.69
ENTHALPY (KILOCALORIES)	460.58	460.58	460.58	460.58
ENTROPY (CALORIES/DEG.K)	86.195	74.687	67.995	63.908
HEAT CAPACITY (CAL/K)	9.0947	8.7761	8.7758	8.7758
MOLES OF GAS				
MOLECULAR COMPOSITION				
H	0.5141	0.0006	0.0000	0.0000
O	0.0077	0.0000	0.0000	0.0000
F	0.0064	0.0000	0.0000	0.0000
H2	3.8318	4.0255	4.0258	4.0258
H2O	1.4735	1.5833	1.5833	1.5833
HF	3.1603	3.1667	3.1667	3.1667
O2	0.0012	0.0000	0.0000	0.0000
OH	0.0993	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
H2O2		89.500			
H2		10.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
H2O2	H2O2		-44.840	1.443	298.16
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		15.6789			
O		5.2622			
PROPELLANT ENTHALPY		-127.81	KCAL/100 GM		
PROPELLANT DENSITY		0.4764	GM/CC	0.0172	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			321.87	359.25	383.22
IVSP(LB-SEC/CU IN)			5.5400	6.1835	6.5960
TEMPERATURE (K)		2567.1	1163.8	743.88	422.73
CP (CAL/GM-DEG.K)		0.88558	0.73100	0.66076	0.61499
MOL. WT.-EFFECTIVE		12.734	12.756	12.756	12.756
CP/CV -EFFECTIVE		1.2139	1.2708	1.3085	1.3393
CF -APPROX.			1.5877	1.7721	1.8903
PEAE/M (SEC)			24.507	14.034	7.4765
AE/AT -APPROX.			8.2258	34.614	184.40
FROZEN EQUILIBRIA					
ISP (SEC)			320.96	358.63	382.21
TEMPERATURE (K)		2567.1	1151.6	728.22	412.15
C* (FT/SEC)		6522.6			
CF (SEC)			1.5832	1.7690	1.8854
PEAE/M (SEC)			24.361	13.786	7.3212
AE/AT			8.1767	34.002	180.57

TABLE 7

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2567.1	1163.8	743.88	422.73
ENTHALPY (KILOCALORIES)	-127.81	-246.87	-276.13	-296.59
ENTROPY (CALORIES/DEG.K)	415.77	415.77	415.77	415.77
HEAT CAPACITY (CAL/K)	88.558	77.600	66.076	61.499
MOLES OF GAS	7.8529	7.8394	7.8394	7.8394
MOLECULAR COMPOSITION:				
H	0.0182	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
H2	2.5725	2.5772	2.5772	2.5772
H2O	5.2536	5.2622	5.2622	5.2622
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0085	0.0000	0.0000	0.0000

TABLE 8

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
N2O4		87.000			
H2		13.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
N2O4	N2O4		-5.4000	1.430	298.16
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		12.8968			
N		1.8910			
O		3.7820			
PROPELLANT ENTHALPY		-17.274	KCAL/100 GM		
PROPELLANT DENSITY		0.4099	GM/CC	0.0148	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			341.22	380.90	406.36
IVSP(LB-SEC/CU IN)			5.0538	5.6415	6.0186
TEMPERATURE (K)	3028.8		1392.1	889.15	503.75
CP (CAL/GM-DEG.K)	0.81011		0.69734	0.62364	0.57343
MOL. WT.-EFFECTIVE	13.394		13.525	13.525	13.529
CP/CV -EFFECTIVE	1.2242		1.2670	1.3082	1.3444
CF -APPROX.			1.5940	1.7794	1.8983
PEAE/M (SEC)			26.080	14.922	7.9221
AE/AT -APPROX.			8.2901	34.855	185.04
FROZEN EQUILIBRIA					
ISP (SEC)			336.65	377.47	402.07
TEMPERATURE (K)	3028.8		1320.1	800.42	426.02
C* (FT/SEC)	6887.3				
CF			1.5726	1.7633	1.8733
PEAE/M (SEC)			25.312	13.688	6.8394
AE/AT			8.0459	31.970	159.75

TABLE 9

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3028.8	1392.1	889.15	503.75
ENTHALPY (KILOCALORIES)	-17.274	-151.08	-184.01	-207.04
ENTROPY (CALORIES/DEG.K)	403.95	403.95	403.95	403.95
HEAT CAPACITY (CAL/K)	81.011	69.734	62.364	57.345
MOLES OF GAS	7.4660	7.3939	7.3938	7.3915
MOLECULAR COMPOSITION:				
H	0.0926	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0010	0.0000	0.0000	0.0000
H2	2.6478	2.6664	2.6663	2.6628
H2O	3.7307	3.7820	3.7820	3.7820
O2	0.0006	0.0000	0.0000	0.0000
OH	0.0462	0.0000	0.0000	0.0000
N2	0.9438	0.9455	0.9454	0.9443
NO	0.0029	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0002	0.0000	0.0001	0.0024

TABLE 10

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NF3		94.500			
H2		5.5000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NF3	NF3		-32.000	1.532	144.00
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.4563			
N		1.3308			
F		3.9925			
PROPELLANT ENTHALPY		-47.735	KCAL/100 GM		
PROPELLANT DENSITY		0.7186	GM/CC	0.0260	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			350.59	389.63	413.16
IVSP(LB-SEC/CU IN)			9.1030	10.117	10.728
TEMPERATURE (K)		4212.3	1969.0	1185.3	627.54
CP (CAL/GM-DEG.K)		0.49527	0.44280	0.39784	0.37821
MOL. WT.-EFFECTIVE		17.603	18.549	18.553	18.554
CP/CV -EFFECTIVE		1.2952	1.3192	1.3684	1.3951
CF -APPROX.			1.6243	1.8052	1.9142
PEAE/M (SEC)			26.177	14.176	7.0778
AE/AT -APPROX.			8.2527	32.840	163.96
FROZEN EQUILIBRIA					
ISP (SEC)			332.18	371.04	390.23
TEMPERATURE (K)		4212.3	1504.8	733.03	298.16
C* (FT/SEC)		6944.4			
CF (SEC)			1.5390	1.7190	1.8080
PEAE/M (SEC)			22.249	9.7032	3.7526
AE/AT			7.0142	22.478	86.932

TABLE 11

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4212.3	1969.0	1185.3	627.54
ENTHALPY (KILOCALORIES)	-47.735	-188.99	-222.21	-243.91
ENTROPY (CALORIES/DEG.K)	301.17	301.17	301.17	301.17
HEAT CAPACITY (CAL/K)	49.527	44.280	39.784	37.821
MOLES OF GAS	5.6807	5.3911	5.3898	5.3898
MOLECULAR COMPOSITION:				
K	0.4796	0.0026	0.0000	0.0000
N	0.0009	0.0000	0.0000	0.0000
F	0.1015	0.0000	0.0000	0.0000
H2	0.5424	0.7306	0.7319	0.7319
HF	3.8910	3.9925	3.9925	3.9925
N2	0.6646	0.6654	0.6654	0.6654
NH	0.0007	0.0000	0.0000	0.0000
NH2	0.0002	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000

TABLE 12

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CLF3		93.500			
H2		6.5000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CLF3	CLF3		-44.400	1.810	298.16
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		6.4484			
F		3.0338			
CL		1.0113			
PROPELLANT ENTHALPY		-50.985	KCAL/100 GM		
PROPELLANT DENSITY		0.6983	GM/CC	0.0252	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			317.88	351.71	371.85
IVSP(LB-SEC/CU IN)			8.0200	8.8735	9.3816
TEMPERATURE (K)		3689.6	1601.4	946.58	494.71
CP (CAL/GM-DEG.R)		0.47511	0.41265	0.37959	0.36714
MOL. WT.-EFFECTIVE		18.364	19.059	19.059	19.059
CP/CV -EFFECTIVE		1.2950	1.3381	1.3787	1.3966
CF -APPROX.			1.6072	1.7782	1.8800
PEAE/M (SEC)			22.853	12.208	6.0350
AE/AT -APPROX.			7.8620	30.862	152.56
FROZEN EQUILIBRIA					
ISP (SEC)			304.20	339.22	355.36
TEMPERATURE (K)		3689.6	1307.4	643.78	298.16
C* (FT/SEC)		6363.8			
CF (SEC)			1.5380	1.7150	1.7966
PEAE/M (SEC)			20.234	8.9349	3.9502
AE/AT			6.9611	22.587	99.858

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3689.6	1601.4	946.58	494.71
ENTHALPY (KILOCALORIES)	-50.985	-167.12	-193.15	-209.90
ENTROPY (CALORIES/DEG.K)	282.07	282.07	282.07	282.07
HEAT CAPACITY (CAL/K)	47.511	41.265	37.959	36.714
MOLES OF GAS	5.4455	5.2469	5.2468	5.2468
MOLECULAR COMPOSITION:				
H	0.2664	0.0001	0.0000	0.0000
F	0.0120	0.0000	0.0000	0.0000
CL	0.1191	0.0001	0.0000	0.0000
H2	1.1344	1.2016	1.2016	1.2016
HCL	0.8914	1.0112	1.0113	1.0113
HF	3.0218	3.0338	3.0338	3.0338
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0004	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000

TABLE 11

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CL03F		89.000			
H2		11.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CL03F	CL03F		-10.100	1.430	298.16
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		10.9127			
O		2.6060			
F		0.6686			
CL		0.6686			
PROPELLANT ENTHALPY		-19.070	KCAL/100 GM		
PROPELLANT DENSITY		0.4605	GM/CC	0.0166	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			341.25	382.42	408.53
IVSP(LB-SEC/CU IN)			5.6774	6.3623	6.7967
TEMPERATURE (K)		3368.7	1655.8	1070.6	605.83
CP (CAL/GM-DEG.K)		0.67736	0.59400	0.53582	0.48799
MOL. WT.-EFFECTIVE		15.355	15.810	15.810	15.810
CP/CV -EFFECTIVE		1.2362	1.2684	1.3065	1.3469
CF -APPROX.			1.6193	1.8147	1.9385
PEAE/M (SEC)			26.536	15.309	8.1094
AE/AT -APPROX.			8.5680	36.322	192.40
FROZEN EQUILIBRIA					
ISP (SEC)			330.17	372.75	396.22
TEMPERATURE (K)		3388.7	1426.8	816.32	397.45
C* (FT/SEC)		6780.4			
CF (SEC)			1.5667	1.7688	1.8801
PEAE/M (SEC)			24.332	12.331	5.6482
AE/AT			7.8567	29.257	134.01

TABLE 15

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3388.7	1655.8	1070.6	605.83
ENTHALPY (KILOCALORIES)	-19.070	-152.90	-187.14	-210.88
ENTROPY (CALORIES/DEG.K)	358.00	358.00	358.00	358.00
HEAT CAPACITY (CAL/K)	67.736	59.400	53.582	48.799
MOLES OF GAS	6.5127	6.3252	6.3250	6.3250
MOLECULAR COMPOSITION:				
H	0.1971	0.0003	0.0000	0.0000
O	0.0064	0.0000	0.0000	0.0000
F	0.0010	0.0000	0.0000	0.0000
CL	0.0466	0.0001	0.0000	0.0000
H2	1.9756	1.9816	1.9817	1.9817
H2O	2.4818	2.6059	2.6060	2.6060
HCL	0.8218	0.8686	0.8686	0.8686
HF	0.8677	0.8686	0.8686	0.8686
O2	0.0032	0.0000	0.0000	0.0000
OH	0.1112	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0001	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000

TABLE 16

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NO2CLO4		91.000			
H2		9.0000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NO2CLO4	NO2CLO4		8.0000	2.220	298.16
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		8.9286			
N		0.6256			
O		3.7535			
CL		0.6256			
PROPELLANT ENTHALPY		-3.4195	KCAL/100 GM		
PROPELLANT DENSITY		0.5961	GM/CC	0.0215	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			333.45	380.36	413.84
IVSP(LB-SEC/CU IN)			7.1818	8.1922	8.9132
TEMPERATURE (K)		3540.9	2238.1	1585.9	1009.1
CP (CAL/GM-DEG.K)		0.61913	0.57642	0.53427	0.47112
MOL. WT.-EFFECTIVE		18.188	19.578	19.646	19.647
CP/CV -EFFECTIVE		1.2143	1.2137	1.2335	1.2734
CF -APPROX.			1.6740	1.9094	2.0775
PEAE/M (SEC)			29.640	18.349	10.731
AE/AT -APPROX.			10.125	46.057	269.34
FROZEN EQUILIBRIA					
ISP (SEC)			314.84	358.57	385.28
TEMPERATURE (K)		3540.9	1609.8	973.73	465.44
C* (FT/SEC)		6409.1			
CF (SEC)			1.5805	1.8000	1.9341
PEAE/M (SEC)			24.305	12.909	5.7426
AE/AT			8.3025	32.402	144.14

TABLE 17

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3540.9	2238.1	1585.9	1009.1
ENTHALPY (KILOCALORIES)	-3.4195	-131.21	-169.69	-200.24
ENTROPY (CALORIES/DEG.K)	327.42	327.42	327.42	327.42
HEAT CAPACITY (CAL/K)	61.913	57.642	53.427	47.112
MOLES OF GAS	5.4982	5.1076	5.0901	5.0899
MOLECULAR COMPOSITION:				
H	0.1572	0.0100	0.0002	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0412	0.0002	0.0000	0.0000
CL	0.0677	0.0086	0.0002	0.0000
H2	0.7362	0.4070	0.3980	0.3980
H2O	3.2026	3.7368	3.7534	3.7535
HCL	0.5574	0.6169	0.6254	0.6256
O2	0.0714	0.0009	0.0000	0.0000
OH	0.3358	0.0140	0.0001	0.0000
N2	0.2973	0.3125	0.3128	0.3128
NO	0.0307	0.0006	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CL2	0.0002	0.0000	0.0000	0.0000
CLO	0.0001	0.0000	0.0000	0.0000

TABLE 18

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NH4CLO4		95.500			
H2		4.5000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NH4CLO4	NH4CLO4		-69.420	1.960	298.16
H2	H2		-1.8870	710.0E-4	20.400
ATOMIC COMPOSITION(GM AT/100GM)					
H		7.7154			
N		0.8128			
O		3.2511			
CL		0.8128			
PROPELLANT ENTHALPY		-60.636	KCAL/100 GM		
PROPELLANT DENSITY		0.8920	GM/CC	0.0322	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		280.50	316.55	340.08
IVSP(LB-SEC/CU IN)		9.0402	10.202	10.960
TEMPERATURE (K)	3040.3	1571.8	1061.9	628.91
CP (CAL/GM-DEG.K)	0.54774	0.48449	0.43419	0.38647
MOL. WT.-EFFECTIVE	20.926	21.411	21.411	21.411
CP/CV -EFFECTIVE	1.2097	1.2370	1.2719	1.3161
CF -APPROX.		1.6278	1.8370	1.9736
PEAE/M (SEC)		22.627	13.546	7.4675
AE/AT -APPROX.		8.9351	39.305	216.68
FROZEN EQUILIBRIA				
ISP (SEC)		272.58	310.03	330.94
TEMPERATURE (K)	3040.3	1392.9	854.26	463.13
C* (FT/SEC)	5544.1			
CF (SEC)		1.5818	1.7992	1.9206
PEAE/M (SEC)		21.112	11.384	5.7818
AE/AT		8.3371	33.033	167.77

TABLE 19

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3040.3	1571.8	1061.9	626.91
ENTHALPY (KILOCALORIES)	-60.636	-151.06	-175.79	-193.55
ENTROPY (CALORIES/DEG.K)	283.66	283.66	283.66	283.66
HEAT CAPACITY (CAL/K)	54.774	48.449	43.419	38.647
MOLES OF GAS	4.7787	4.6706	4.6705	4.6705
MOLECULAR COMPOSITION:				
H	0.0261	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0048	0.0000	0.0000	0.0000
CL	0.0374	0.0001	0.0000	0.0000
H2	0.3076	0.2002	0.2002	0.2002
H2O	3.1030	3.2511	3.2511	3.2511
HCL	0.7748	0.8127	0.8128	0.8128
O2	0.0194	0.0000	0.0000	0.0000
OH	0.0932	0.0000	0.0000	0.0000
N2	0.4007	0.4064	0.4064	0.4064
NO	0.0113	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CL2	0.0003	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000

TABLE 20

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
O2		53.000			
N2H4		47.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
O2	O2		-3.0800	1.142	90.200
N2H4	N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.8662			
N		2.9331			
O		3.3125			
PROPELLANT ENTHALPY		12.571	KCAL/100 GM		
PROPELLANT DENSITY		1.073	GM/CC	0.0388	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			304.29	345.47	374.32
IVSP(LB-SEC/CU IN)			11.793	13.389	14.507
TEMPERATURE (K)		3398.2	2007.3	1393.8	860.49
CP (CAL/GM-DEG.K)		0.53617	0.49750	0.46526	0.40448
MOL. WT.-EFFECTIVE		20.632	21.757	21.789	21.790
CP/CV -EFFECTIVE		1.2190	1.2249	1.2438	1.2911
CF -APPROX.			1.6630	1.6881	2.0458
PEAE/M (SEC)			26.214	16.009	9.1213
AE/AT -APPROX.			9.7491	43.747	249.26
FROZEN EQUILIBRIA					
ISP (SEC)			288.83	328.82	352.59
TEMPERATURE (K)		3398.2	1529.0	908.35	434.01
C* (FT/SEC)		5886.8			
CF (SEC)			1.5786	1.7971	1.9271
PEAE/M (SEC)			22.183	11.576	5.1580
AE/AT			8.2497	31.633	140.95

TABLE 21

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3398.2	2007.3	1393.8	860.49
ENTHALPY (KILOCALORIES)	12.571	-93.840	-124.59	-148.46
ENTROPY (CALORIES/DEG.K)	294.26	294.26	294.26	294.26
HEAT CAPACITY (CAL/K)	53.617	49.750	46.526	40.448
MOLES OF GAS	4.8468	4.5963	4.5894	4.5894
MOLECULAR COMPOSITION:				
H	0.0602	0.0002	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0428	0.0006	0.0000	0.0000
H2	0.2368	0.0046	0.0000	0.0000
H2O	2.5213	2.9201	2.9329	2.9331
O2	0.1822	0.1823	0.1891	0.1897
OH	0.2896	0.0166	0.0004	0.0000
N2	1.4193	1.4613	1.4661	1.4665
NO	0.0943	0.0104	0.0010	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000

TABLE 22

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
F2		55.000			
N2H4		45.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
F2	F2		-3.4670	1.510	85.200
N2H4	N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.6166			
N		2.8083			
F		2.8947			
PROPELLANT ENTHALPY		11.902	KCAL/100 GM		
PROPELLANT DENSITY		1.231	GM/CC	0.0445	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			343.91	381.30	403.83
IVSP(LB-SEC/CU IN)			15.294	16.957	17.958
TEMPERATURE (K)		3959.2	1769.3	1057.7	559.37
CP (CAL/GM-DEG.K)		0.51650	0.46135	0.42172	0.39781
MOL. WT.-EFFECTIVE		16.933	17.667	17.668	17.670
CP/CV -EFFECTIVE		1.2940	1.3224	1.3637	1.3941
CF -APPROX.			1.6114	1.7866	1.8921
PEAE/M (SEC)			25.176	13.573	6.7776
AE/AT -APPROX.			8.0268	31.798	158.78
FROZEN EQUILIBRIA					
ISP (SEC)			328.74	366.76	385.87
TEMPERATURE (K)		3959.2	1425.3	708.16	299.42
C* (FT/SEC)		6866.8			
CF (SEC)			1.5403	1.7184	1.8080
PEAE/M (SEC)			22.138	9.8587	3.9620
AE/AT			7.0580	23.096	92.819

TABLE 23

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3959.2	1769.3	1057.7	559.37
ENTHALPY (KILOCALORIES)	11.902	-124.03	-155.19	-175.52
ENTROPY (CALORIES/DEG.K)	311.73	311.73	311.73	311.73
HEAT CAPACITY (CAL/K)	51.650	46.135	42.172	39.781
MOLES OF GAS	5.9057	5.6602	5.6598	5.6594
MOLECULAR COMPOSITION:				
H	0.4648	0.0008	0.0000	0.0000
N	0.0005	0.0000	0.0000	0.0000
F	0.0268	0.0000	0.0000	0.0000
H2	1.1411	1.3605	1.3609	1.3603
HF	2.8679	2.8947	2.8947	2.8947
N2	1.4033	1.4041	1.4041	1.4039
NH	0.0008	0.0000	0.0000	0.0000
NH2	0.0004	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0004
F2	0.0000	0.0000	0.0000	0.0000

TABLE 24

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
N2H4		40.000			
OF2		60.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
N2H4	N2H4		12.050	1.004	298.16
OF2	OF2		3.6000	1.530	128.00
ATOMIC COMPOSITION (GM AT/100GM)					
H		4.9925			
N		2.4962			
O		1.1111			
F		2.2222			
PROPELLANT ENTHALPY		19.040	KCAL/100 GM		
PROPELLANT DENSITY		1.265	GM/CC	0.0457	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			344.98	390.58	420.39
IVSP(LB-SEC/CU IN)			15.766	17.850	19.212
TEMPERATURE (K)	4036.6		2415.0	1666.3	926.54
CP (CAL/GM-DEG.K)	0.49250		0.45908	0.42928	0.38273
MOL. WT.-EFFECTIVE	18.718		20.509	20.595	20.595
CP/CV -EFFECTIVE	1.2748		1.2675	1.2900	1.3371
CF -APPROX.			1.6742	1.6955	2.0402
PEAE/M (SEC)			29.510	17.265	9.2522
AE/AT -APPROX.			9.7454	41.895	224.51
FROZEN EQUILIBRIA					
ISP (SEC)			319.38	358.13	379.95
TEMPERATURE (K)	4036.6		1540.7	806.38	315.81
C* (FT/SEC)	6629.5				
CF (SEC)			1.6500	1.7380	1.8439
PEAE/M (SEC)			22.281	10.400	3.8391
AE/AT			7.3581	25.236	93.159

TABLE 25

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4036.6	2415.0	1606.3	926.54
ENTHALPY (KILOCALORIES)	19.040	-117.74	-156.28	-184.07
ENTROPY (CALORIES/DEG.K)	302.01	302.01	302.01	302.01
HEAT CAPACITY (CAL/K)	49.250	45.908	42.928	38.273
MOLES OF GAS	5.3424	4.8759	4.8556	4.8555
MOLECULAR COMPOSITION:				
H	0.3364	0.0196	0.0002	0.0000
N	0.0006	0.0000	0.0000	0.0000
O	0.0937	0.0007	0.0000	0.0000
F	0.0363	0.0003	0.0000	0.0000
H2	0.5042	0.2768	0.2740	0.2740
H2O	0.6044	1.0911	1.1111	1.1111
HF	2.1860	2.2220	2.2222	2.2222
O2	0.0445	0.0012	0.0000	0.0000
OH	0.2530	0.0150	0.0000	0.0000
N2	1.2123	1.2472	1.2481	1.2481
NO	0.0710	0.0019	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000

TABLE 26

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
H2O2		67.000			
N2H4		33.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
H2O2	H2O2		-44.840	1.443	298.16
N2H4	N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		8.0581			
N		2.0594			
O		3.9393			
PROPELLANT ENTHALPY		-75.912	KCAL/100 GM		
PROPELLANT DENSITY		1.261	GM/CC	0.0456	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		286.01	323.20	347.52
IVSP(LB-SEC/CU IN)		13.031	14.725	15.833
TEMPERATURE (K)	2923.2	1517.3	1030.7	616.20
CP (CAL/GM-DEG.K)	0.60702	0.53716	0.47937	0.42536
MOL. WT.-EFFECTIVE	19.398	19.768	19.768	19.768
CP/CV -EFFECTIVE	1.2030	1.2302	1.2654	1.3095
CF -APPROX.		1.6265	1.6380	1.9763
PEAE/M (SEC)		23.203	13.949	7.7552
AE/AT -APPROX.		8.9788	39.662	220.51
FROZEN EQUILIBRIA				
ISP (SEC)		278.84	317.40	339.00
TEMPERATURE (K)	2923.2	1368.3	854.42	480.43
C* (FT/SEC)	5657.6			
CF (SEC)		1.5857	1.8050	1.9278
PEAE/M (SEC)		21.872	11.998	6.3164
AE/AT		8.4637	34.114	179.60

TABLE 27

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2923.2	1517.3	1030.7	616.20
ENTHALPY (KILOCALORIES)	-75.912	-169.92	-195.96	-214.71
ENTROPY (CALORIES/DEG.K)	306.23	306.23	306.23	306.23
HEAT CAPACITY (CAL/K)	60.702	53.716	47.937	42.536
MOLES OF GAS	5.1550	5.0588	5.0588	5.0588
MOLECULAR COMPOSITION:				
H	0.0156	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0041	0.0000	0.0000	0.0000
H2	0.2098	0.0898	0.0897	0.0897
H2O	3.7664	3.9393	3.9393	3.9393
O2	0.0298	0.0000	0.0000	0.0000
OH	0.0900	0.0000	0.0000	0.0000
N2	1.0200	1.0297	1.0297	1.0297
NO	0.0193	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000

TABLE 28

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
N2O4		57.000			
N2H4		43.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
N2O4	N2O4		-5.4000	1.430	298.16
N2H4	N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.3669			
N		3.9224			
O		2.4778			
PROPELLANT ENTHALPY		12.823	KCAL/100 GM		
PROPELLANT DENSITY		1.209	GM/CC	0.0437	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			291.41	320.26	352.33
IVSP(LB-SEC/CU IN)			12.733	14.343	15.394
TEMPERATURE (K)		3256.9	1704.4	1135.4	667.66
CP (CAL/GM-DEG.K)		0.51812	0.47299	0.42557	0.37794
MOL. WT.-EFFECTIVE		20.846	21.529	21.530	21.530
CP/CV -EFFECTIVE		1.2255	1.2425	1.2770	1.3231
CF -APPROX.			1.6384	1.6456	1.9809
PEAF/M (SEC)			23.487	13.889	7.6096
AE/AT -APPROX.			8.9856	39.045	213.92
FROZEN EQUILIBRIA					
ISP (SEC)			280.14	310.08	338.46
TEMPERATURE (K)		3256.9	1437.8	839.49	435.98
C* (FT/SEC)		5722.6			
CF (SEC)			1.5751	1.7883	1.9029
PEAF/M (SEC)			21.285	10.946	5.3424
AE/AT			8.1433	30.770	150.18

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3256.9	1704.4	1135.4	667.66
ENTHALPY (KILOCALORIES)	12.823	-84.774	-111.02	-129.84
ENTROPY (CALORIES/DEG.K)	284.35	284.35	284.35	284.35
HEAT CAPACITY (CAL/K)	51.812	47.299	42.557	37.794
MOLES OF GAS	4.7970	4.6448	4.6447	4.6447
MOLECULAR COMPOSITION:				
H	0.0515	0.0001	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0114	0.0000	0.0000	0.0000
H2	0.3546	0.2056	0.2056	0.2056
H2O	2.2361	2.4777	2.4778	2.4778
O2	0.0290	0.0000	0.0000	0.0000
OH	0.1340	0.0001	0.0000	0.0000
N2	1.9419	1.9612	1.9612	1.9612
NO	0.0384	0.0000	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000

TABLE 30

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NF3		77.000			
N2H4		23.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NF3	NF3		-32.000	1.532	144.00
N2H4	N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.8707			
N		2.5197			
F		3.2532			
PROPELLANT ENTHALPY		-26.052	KCAL/100 GM		
PROPELLANT DENSITY		1.367	GM/CC	0.0494	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			305.28	337.15	358.28
IVSP(LB-SEC/CU IN)			15.074	16.648	17.691
TEMPERATURE (K)		4201.5	1644.0	1040.4	647.60
CP (CAL/GM-DEG.K)		0.39536	0.35371	0.32683	0.30824
MOL. WT.-EFFECTIVE		21.823	22.169	22.536	23.128
CP/CV -EFFECTIVE		1.2992	1.3394	1.3695	1.3865
CF -APPROX.			1.5786	1.7434	1.8526
PEAE/M (SEC)			21.001	11.838	6.7568
AE/AT -APPROX.			7.3894	30.606	174.69
FROZEN EQUILIBRIA					
ISP (SEC)			297.73	330.47	344.97
TEMPERATURE (K)		4201.5	1503.6	800.96	442.94
C* (FT/SEC)		6222.1			
CF (SEC)			1.5395	1.7088	1.7838
PEAE/M (SEC)			20.007	9.6020	5.0868
AE/AT			7.0396	24.825	131.52

TABLE 31

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4201.5	1644.0	1040.4	647.60
ENTHALPY (KILOCALORIES)	-26.052	-133.16	-156.69	-173.57
ENTROPY (CALORIES/DEG.K)	253.37	253.37	253.37	253.37
HEAT CAPACITY (CAL/K)	39.536	35.371	32.683	30.824
MOLES OF GAS	4.5823	4.5107	4.4372	4.3237
MOLECULAR COMPOSITION:				
H	0.0584	0.0000	0.0000	0.0000
N	0.0010	0.0000	0.0000	0.0000
F	0.4615	0.3778	0.2309	0.0037
H2	0.0103	0.0000	0.0000	0.0000
HF	2.7915	2.8707	2.8707	2.8707
N2	1.2593	1.2599	1.2599	1.2599
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
F2	0.0001	0.0023	0.0758	0.1894

TABLE 32

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CLF3		73.000			
N2H4		27.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CLF3	CLF3		-44.400	1.810	298.16
N2H4	N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.3699			
N		1.6850			
F		2.3687			
CL		0.7896			
PROPELLANT ENTHALPY		-24.904	KCAL/100 GM		
PROPELLANT DENSITY		1.488	GM/CC	0.0537	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			292.76	325.22	344.85
IVSP(LB-SEC/CU IN)			15.735	17.479	18.534
TEMPERATURE (K)	3882.0		1798.0	1083.0	573.80
CP (CAL/GM-DEG.K)	0.37280		0.33706	0.30750	0.28871
MOL. WT.-EFFECTIVE	23.184		24.348	24.351	24.351
CP/CV -EFFECTIVE	1.2986		1.3195	1.3613	1.3940
CF -APPROX.			1.6229	1.6029	1.9117
PEAE/M (SEC)			21.808	11.823	5.9075
AE/AT -APPROX.			8.2264	32.770	163.74
FROZEN EQUILIBRIA					
ISP (SEC)			277.69	310.48	325.84
TEMPERATURE (K)	3882.0		1387.0	679.16	298.16
C* (FT/SEC)	5803.8				
CF (SEC)			1.5394	1.7212	1.8064
PEAE/M (SEC)			18.626	8.1574	3.4123
AE/AT			7.0259	22.610	94.583

TABLE 33

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3882.0	1798.0	1063.0	573.80
ENTHALPY (KILOCALORIES)	-24.904	-123.41	-146.46	-161.58
ENTROPY (CALORIES/DEG.K)	237.91	237.91	237.91	237.91
HEAT CAPACITY (CAL/K)	37.280	33.706	30.750	28.871
MOLES OF GAS	4.3133	4.1072	4.1066	4.1066
MOLECULAR COMPOSITION:				
H	0.1362	0.0002	0.0000	0.0000
N	0.0003	0.0000	0.0000	0.0000
F	0.0378	0.0000	0.0000	0.0000
CL	0.2392	0.0010	0.0000	0.0000
H2	0.1776	0.1062	0.1058	0.1058
HCL	0.5476	0.7886	0.7896	0.7896
HF	2.3306	2.3687	2.3687	2.3687
N2	0.6422	0.8425	0.8425	0.8425
NH	0.0002	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0012	0.0000	0.0000	0.0000
CLF	0.0002	0.0000	0.0000	0.0000

TABLE 34

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CL03F		59.500			
N2H4		40.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CL03F	CL03F		-10.100	1.430	298.16
N2H4	N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION	(GM AT/100GM)				
H		5.0549			
N		2.5274			
O		1.7422			
F		0.5807			
CL		0.5807			
PROPELLANT ENTHALPY		9.3626	KCAL/100 GM		
PROPELLANT DENSITY		1.220	GM/CC	0.0441	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			295.16	332.14	356.68
IVSP(LB-SEC/CU IN)			13.014	14.644	15.726
TEMPERATURE (K)		3465.5	1876.3	1236.1	716.55
CP (CAL/GM-DEG.K)		0.46651	0.42836	0.40149	0.34701
MOL. WT.-EFFECTIVE		21.750	22.868	22.873	22.873
CP/CV -EFFECTIVE		1.2436	1.2545	1.2762	1.3340
CF -APPROX.			1.6519	1.6588	1.9962
PEAE/M (SEC)			24.034	14.067	7.5934
AE/AT -APPROX.			9.1525	39.364	212.48
FROZEN EQUILIBRIA					
ISP (SEC)			279.72	316.76	336.73
TEMPERATURE (K)		3465.5	1448.0	800.26	367.42
C* (FT/SEC)		5748.9			
CF (SEC)			1.5654	1.7728	1.8845
PEAE/M (SEC)			20.578	10.042	4.3373
AE/AT			7.8365	28.102	121.37

TABLE 35

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3465.5	1876.3	1236.1	716.55
ENTHALPY (KILOCALORIES)	9.3626	-90.763	-117.42	-136.85
ENTROPY (CALORIES/DEG.K)	271.44	271.44	271.44	271.44
HEAT CAPACITY (CAL/K)	46.651	42.836	40.149	34.701
MOLES OF GAS	4.5977	4.3730	4.3719	4.3719
MOLECULAR COMPOSITION:				
H	0.0884	0.0006	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0203	0.0000	0.0000	0.0000
F	0.0017	0.0000	0.0000	0.0000
CL	0.0660	0.0010	0.0000	0.0000
H2	0.3916	0.2050	0.2045	0.2045
H2O	1.4670	1.7417	1.7422	1.7422
HCL	0.5141	0.5797	0.5807	0.5807
HF	0.5791	0.5807	0.5807	0.5807
O2	0.0304	0.0000	0.0000	0.0000
OH	0.1557	0.0004	0.0000	0.0000
N2	1.2444	1.2637	1.2637	1.2637
NO	0.0384	0.0000	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0002	0.0000	0.0000	0.0000
CLO	0.0001	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000

TABLE 36

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
	N2O4	56.000			
	N2H4	44.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
	N2O4 N2O4		8.0000	2.220	298.16
	N2H4 N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
	H	5.4918			
	N	3.1308			
	O	2.3098			
	CL	0.3850			
PROPELLANT ENTHALPY		19.624	KCAL/100 GM		
PROPELLANT DENSITY		1.448	GM/CC	0.0523	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
	ISP (SEC)		294.66	332.01	357.30
	IVSP(LB-SEC/CU IN)		15.418	17.372	18.696
	TEMPERATURE (K)	3363.4	1824.7	1222.1	722.02
	CP (CAL/GM-DEG.K)	0.50080	0.45947	0.43128	0.36920
	MOL. WT.-EFFECTIVE	21.271	22.200	22.204	22.204
	CP/CV -EFFECTIVE	1.2293	1.2420	1.2619	1.3200
	CF -APPROX.		1.6486	1.8576	1.9991
	PEAE/M (SEC)		24.117	14.333	7.8686
	AE/AT -APPROX.		9.1815	40.096	220.12
FROZEN EQUILIBRIA					
	ISP (SEC)		281.15	319.35	340.54
	TEMPERATURE (K)	3363.4	1467.2	844.27	407.70
	C* (FT/SEC)	5750.6			
	CF (SEC)		1.5730	1.7867	1.9053
	PEAE/M (SEC)		21.211	10.746	4.8662
	AE/AT		8.0754	30.060	136.13

TABLE 37

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3363.4	1824.7	1222.1	722.02
ENTHALPY (KILOCALORIES)	19.624	-80.159	-107.06	-127.10
ENTROPY (CALORIES/DEG.K)	279.61	279.61	279.61	279.61
HEAT CAPACITY (CAL/K)	50.080	45.947	43.128	36.920
MOLES OF GAS	4.7012	4.5044	4.5038	4.5038
MOLECULAR COMPOSITION:				
H	0.0725	0.0004	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0157	0.0000	0.0000	0.0000
CL	0.0345	0.0004	0.0000	0.0000
H2	0.4187	0.2437	0.2436	0.2436
H2O	2.0377	2.3095	2.3098	2.3098
HCL	0.3502	0.3846	0.3850	0.3850
O2	0.0306	0.0000	0.0000	0.0000
OH	0.1560	0.0003	0.0000	0.0000
N2	1.5458	1.5654	1.5654	1.5654
NO	0.0391	0.0000	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CL2	0.0001	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000

TABLE 38

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NH4CLO4		75.000			
N2H4		25.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NH4CLO4	NH4CLO4		-69.420	1.960	298.16
N2H4	N2H4		12.050	1.004	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.6736			
N		2.1985			
O		2.5532			
CL		0.6383			
PROPELLANT ENTHALPY		-34.912	KCAL/100 GM		
PROPELLANT DENSITY		1.583	GM/CC	0.0572	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		263.45	295.81	317.13
IVSP(LB-SEC/CU IN)		15.069	16.920	18.139
TEMPERATURE (K)	2956.5	1503.1	987.82	583.09
CP (CAL/GM-DEG.K)	0.46130	0.43010	0.36234	0.34307
MOL. WT.-EFFECTIVE	22.872	23.401	23.406	23.476
CP/CV -EFFECTIVE	1.2203	1.2460	1.2854	1.3276
CF -APPROX.		1.6259	1.6256	1.9572
PEAE/M (SEC)		21.079	12.335	6.7713
AE/AT -APPROX.		8.8525	38.063	206.95
FROZEN EQUILIBRIA				
ISP (SEC)		255.44	288.75	308.04
TEMPERATURE (K)	2956.5	1315.9	775.66	395.34
C* (FT/SEC)	5213.2			
CF		1.5765	1.7821	1.9011
PEAE/M (SEC)		19.473	10.154	4.8513
AE/AT		8.1779	31.334	149.70

TABLE 35

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2956.5	1503.1	987.82	583.09
ENTHALPY (KILOCALORIES)	-34.912	-114.68	-135.47	-150.49
ENTROPY (CALORIES/DEG.K)	259.62	259.62	259.62	259.62
HEAT CAPACITY (CAL/K)	48.130	43.010	38.234	34.307
MOLES OF GAS	4.3721	4.2733	4.2723	4.2596
MOLECULAR COMPOSITION:				
H	0.0122	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0049	0.0000	0.0000	0.0000
CL	0.0344	0.0015	0.0001	0.0000
H2	0.1188	0.0001	0.0000	0.0000
H2O	2.3710	2.5185	2.5191	2.5443
HCL	0.6031	0.6361	0.6354	0.5849
O2	0.0376	0.0170	0.0171	0.0044
OH	0.0787	0.0003	0.0000	0.0000
N2	1.0875	1.0990	1.0992	1.0992
NO	0.0234	0.0004	0.0000	0.0000
CL2	0.0004	0.0003	0.0014	0.0267
CLO	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		50.000			
O2		50.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
O2	O2		-3.0800	1.142	90.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		6.6556			
C		1.6639			
N		1.6639			
O		3.1250			
PROPELLANT ENTHALPY		5.7865	KCAL/100 GM		
PROPELLANT DENSITY		0.9311	GM/CC	0.0336	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			286.45	321.43	346.96
IVSP(LB-SEC/CU IN)			9.7039	10.814	11.672
TEMPERATURE (K)		2877.3	1224.3	853.11	703.58
CP (CAL/GM-DEG.K)		0.57628	0.51337	0.47934	0.46370
MOL. WT.-EFFECTIVE		17.093	17.172	17.424	18.541
CP/CV -EFFECTIVE		1.2527	1.2910	1.3122	1.3006
CF -APPROX.			1.5747	1.7547	1.8941
PEAE/M (SEC)			21.370	13.170	9.4558
AE/AT -APPROX.			7.9384	35.947	256.10
FROZEN EQUILIBRIA					
ISP (SEC)			285.44	317.58	336.71
TEMPERATURE (K)		2877.3	1154.0	682.75	353.77
C* (FT/SEC)		5893.6			
CF			1.5583	1.7337	1.8381
PEAE/M (SEC)			20.449	10.874	5.3142
AE/AT			7.5963	29.681	145.06

TABLE 41

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2877.3	1224.3	853.11	703.58
ENTHALPY (KILOCALORIES)	5.7865	-89.834	-112.95	-132.57
ENTROPY (CALORIES/DEG.K)	317.67	317.67	317.67	317.67
HEAT CAPACITY (CAL/K)	57.628	51.337	47.934	46.370
MOLES OF GAS	5.8503	5.8233	5.7992	5.3934
MOLECULAR COMPOSITION:				
H	0.0440	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0001	0.0000	0.0000	0.0000
H2	1.9936	2.2741	2.3025	2.3332
H2O	1.3073	1.0533	0.7408	0.7670
CO	1.5196	1.2559	0.8593	0.5370
CO2	0.1442	0.4079	0.7624	1.0105
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0090	0.0000	0.0000	0.0000
N2	0.8315	0.8319	0.8319	0.8319
NO	0.0005	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0001	0.0021	0.1137
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0001	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0002	0.0001	0.0002	0.0001
CONDENSED PHASES				
C/SOLID/	0	0	0	0.2027

TABLE 42

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		27.000			
F2		73.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
F2	F2		-3.4670	1.510	85.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.5940			
C		0.8985			
N		0.8985			
F		3.8421			
PROPELLANT ENTHALPY		-0.93683	KCAL/100 GM		
PROPELLANT DENSITY		1.209	GM/CC	0.0437	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			340.25	389.12	424.31
IVSP(LB-SEC/CU IN)			14.866	17.001	18.538
TEMPERATURE (K)		4314.2	2800.1	2146.2	1366.6
CP (CAL/GM-DEG.K)		0.44128	0.41825	0.40754	0.37302
MOL. WT.-EFFECTIVE		21.604	23.474	24.226	24.359
CP/CV -EFFECTIVE		1.2633	1.2538	1.2551	1.2799
CF -APPROX.			1.7105	1.9562	2.1331
PEAF/M (SEC)			30.310	19.684	11.432
AE/AT -APPROX.			10.369	49.478	287.35
FROZEN EQUILIBRIA					
ISP (SEC)			309.12	348.29	369.08
TEMPERATURE (K)		4314.2	1690.8	697.04	391.09
C* (FT/SEC)		6400.0			
CF			1.5540	1.7509	1.8554
PEAF/M (SEC)			21.890	10.307	4.2406
AE/AT			7.4881	25.908	106.59

TABLE 43

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4314.2	2800.1	2146.2	1366.6
ENTHALPY (KILOCALORIES)	-0.93683	-133.99	-174.96	-207.85
ENTROPY (CALORIES/DEG.K)	264.13	264.13	264.13	264.13
HEAT CAPACITY (CAL/K)	44.128	41.825	40.354	37.302
MOLES OF GAS	4.6287	4.2601	4.1279	4.1053
MOLECULAR COMPOSITION:				
H	0.1096	0.0022	0.0000	0.0000
C	0.0203	0.0000	0.0000	0.0000
N	0.0006	0.0000	0.0000	0.0000
F	0.4601	0.1929	0.0252	0.0000
H2	0.0254	0.0002	0.0000	0.0000
HF	3.2980	3.5899	3.5939	3.5940
N2	0.2468	0.4434	0.4491	0.4492
F2	0.0001	0.0000	0.0000	0.0000
CH	0.0005	0.0000	0.0000	0.0000
CH2	0.0012	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0281	0.0003	0.0000	0.0000
CF2	0.0195	0.0035	0.0003	0.0000
CF3	0.0052	0.0125	0.0140	0.0001
CF4	0.0001	0.0036	0.0451	0.0619
CN	0.2890	0.0098	0.0002	0.0000
C2N2	0.0088	0.0002	0.0000	0.0000
C2H2	0.0176	0.0000	0.0000	0.0000
CHF3	0.0001	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.0975	0.0016	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0.3843	0.8668	0.6389	0.8364

TABLE 44

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		28.000			
OF2		72.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
OF2	OF2		3.6000	1.530	128.00
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.7271			
C		0.9318			
N		0.9318			
O		1.3333			
F		2.6667			
PROPELLANT ENTHALPY		10.735	KCAL/100 GM		
PROPELLANT DENSITY		1.209	GM/CC	0.0437	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			351.34	390.86	426.29
IVSP(LB-SEC/CU IN)			15.353	17.342	18.628
TEMPERATURE (K)		4458.0	2596.6	1714.9	992.53
CP (CAL/GM-DEG.K)		0.44360	0.41507	0.39120	0.35926
MOL. WT.-EFFECTIVE		19.628	21.634	21.764	21.765
CP/CV -EFFECTIVE		1.2957	1.2842	1.3045	1.3407
CF -APPROX.			1.6710	1.8875	2.0275
PEAE/M (SEC)			29.535	17.166	9.2488
AE/AT -APPROX.			9.5586	40.822	219.94
FROZEN EQUILIBRIA					
ISP (SEC)			324.02	362.06	382.76
TEMPERATURE (K)		4458.0	1610.8	813.76	305.22
C* (FT/SEC)		6764.7			
CF			1.5411	1.7220	1.8204
PEAE/M (SEC)			21.897	9.9003	3.5126
AE/AT			7.0868	23.544	83.532

TABLE 45

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4458.0	2596.6	1714.9	992.53
ENTHALPY (KILOCALORIES)	10.735	-131.13	-170.27	-198.11
ENTROPY (CALORIES/DEG.K)	287.16	287.16	287.16	287.16
HEAT CAPACITY (CAL/K)	44.360	41.507	39.120	35.926
MOLES OF GAS	5.0948	4.6223	4.5948	4.5946
MOLECULAR COMPOSITION:				
H	0.4442	0.0404	0.0005	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0014	0.0000	0.0000	0.0000
O	0.1090	0.0010	0.0000	0.0000
F	0.1629	0.0011	0.0000	0.0000
H2	0.2500	0.2883	0.2993	0.4102
H2O	0.0829	0.2573	0.2306	0.1200
HF	2.5037	2.6655	2.6667	2.6667
CO	0.8961	0.8004	0.7609	0.6502
CO2	0.0355	0.1314	0.1709	0.2815
O2	0.0148	0.0004	0.0000	0.0000
OH	0.1126	0.0099	0.0000	0.0000
N2	0.4488	0.4654	0.4659	0.4659
NO	0.0320	0.0010	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0000	0.0000	0.0000	0.0000
CF2	0.0000	0.0000	0.0000	0.0000
CF3	0.0000	0.0000	0.0000	0.0000
CF4	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
COF2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0006	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 46

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		18.000			
H2O2		82.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
H2O2	H2O2		-44.840	1.443	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		7.2173			
C		0.5990			
N		0.5990			
O		4.8213			
PROPELLANT ENTHALPY		-104.28	KCAL/100 GM		
PROPELLANT DENSITY		1.254	GM/CC	0.0453	LB/CU IN.
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			282.95	322.09	349.45
IVSP(LB-SEC/CU IN)			12.823	14.596	15.836
TEMPERATURE (K)		3001.9	1789.0	1269.7	808.21
CP (CAL/GM-DEG.K)		0.56258	0.55418	0.49160	0.45245
MOL. WT.-EFFECTIVE		21.292	22.132	22.151	22.151
CP/CV -EFFECTIVE		1.1908	1.2020	1.2232	1.2618
CF -APPROX.			1.6575	1.6867	2.0470
PEAE/M (SEC)			24.698	15.386	9.0271
AE/AT -APPROX.			9.8444	45.065	264.39
FROZEN EQUILIBRIA					
ISP (SEC)			272.07	310.31	335.19
TEMPERATURE (K)		3001.9	1466.0	926.64	494.95
C* (FT/SEC)		5492.5			
CF			1.5937	1.6195	1.9634
PEAE/M (SEC)			21.879	12.114	5.9960
AE/AT			8.7210	35.480	175.61

TABLE 47

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3001.9	1789.0	1269.7	805.21
ENTHALPY (KILOCALORIES)	-104.28	-196.29	-223.50	-244.62
ENTROPY (CALORIES/DEG.K)	290.80	290.80	290.80	290.80
HEAT CAPACITY (CAL/K)	56.258	53.418	49.160	43.245
MOLES OF GAS	4.6966	4.5182	4.5145	4.5144
MOLECULAR COMPOSITION:				
H	0.0152	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0092	0.0000	0.0000	0.0000
H2	0.1340	0.0038	0.0000	0.0000
H2O	3.4001	3.6035	3.6086	3.6086
CO	0.1314	0.0023	0.0000	0.0000
CO2	0.4675	0.5966	0.5990	0.5990
O2	0.0956	0.0094	0.0073	0.0073
OH	0.1339	0.0026	0.0000	0.0000
N2	0.2894	0.2992	0.2995	0.2995
NO	0.0203	0.0006	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 18

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		38.000			
N2O4		62.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
N2O4	N2O4		-5.4000	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.0582			
C		1.2646			
N		2.6122			
O		2.6952			
PROPELLANT ENTHALPY		4.4167	KCAL/100 GM		
PROPELLANT DENSITY		1.090	GM/CC	0.0394	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			272.25	303.52	327.00
IVSP(LB-SEC/CU IN)			10.726	11.958	12.883
TEMPERATURE (K)		2905.2	1259.3	851.51	676.48
CP (CAL/GM-DEG.K)		0.51229	0.46293	0.42661	0.40807
MOL. WT.-EFFECTIVE		19.516	19.609	19.708	20.854
CP/CV -EFFECTIVE		1.2481	1.2803	1.3095	1.3047
CF -APPROX.			1.5784	1.7596	1.8958
PEAE/M (SEC)			20.393	12.307	8.5767
AE/AT -APPROX.			8.0450	35.675	248.61
FROZEN EQUILIBRIA					
ISP (SEC)			269.31	300.09	318.46
TEMPERATURE (K)		2905.2	1185.5	709.00	372.28
C* (FT/SEC)		5549.7			
CF			1.5613	1.7397	1.8462
PEAE/M (SEC)			19.502	10.467	5.1788
AE/AT			7.6932	30.340	150.12

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2905.2	1259.3	851.51	676.48
ENTHALPY (KILOCALORIES)	4.4167	-80.768	-101.46	-116.47
ENTROPY (CALORIES/DEG.K)	287.67	287.67	287.67	287.67
HEAT CAPACITY (CAL/K)	51.229	46.293	42.661	40.807
MOLES OF GAS	5.1240	5.0997	5.0741	4.7952
MOLECULAR COMPOSITION:				
H	0.0357	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0002	0.0000	0.0000	0.0000
H2	1.2475	1.4892	1.7415	1.5882
H2O	1.2577	1.0398	0.7419	0.7288
CO	1.1046	0.8737	0.5503	0.1658
CO2	0.1599	0.3909	0.7015	0.9003
O2	0.0001	0.0000	0.0000	0.0000
OH	0.0115	0.0000	0.0000	0.0000
N2	1.3054	1.3060	1.3060	1.3060
NO	0.0011	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0128	0.1060
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0001	0.0001
CONDENSED PHASES				
C/SOLID/	0	0	0	0.0924

TABLE 50

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		28.000			
NF3		72.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
NF3	NF3		-32.000	1.532	144.00
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.7271			
C		0.9318			
N		1.9458			
F		3.0419			
PROPELLANT ENTHALPY		-26.512	KCAL/100 GM		
PROPELLANT DENSITY		1.210	GM/CC	0.0437	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			303.18	340.94	365.46
IVSP(LB-SEC/CU IN)			13.258	14.909	15.982
TEMPERATURE (K)		3749.0	1976.8	1295.4	750.06
CP (CAL/GM-DEG.K)		0.45170	0.41696	0.39233	0.35283
MOL. WT.-EFFECTIVE		22.334	22.945	22.950	22.956
CP/CV -EFFECTIVE		1.2453	1.2622	1.2832	1.3251
CF -APPROX.			1.6539	1.8599	1.9937
PEAE/M (SEC)			24.568	14.314	7.7297
AE/AT -APPROX.			9.1200	39.043	210.84
FROZEN EQUILIBRIA					
ISP (SEC)			286.64	324.41	345.40
TEMPERATURE (K)		3749.0	1554.3	850.47	381.85
C* (FT/SEC)		5897.8			
CF			1.5637	1.7697	1.8842
PEAE/M (SEC)			20.991	10.148	4.2795
AE/AT			7.7920	27.681	116.73

TABLE 51

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3749.0	1976.8	1295.4	750.06
ENTHALPY (KILOCALORIES)	-26.512	-132.15	-160.10	-180.01
ENTROPY (CALORIES/DEG.K)	257.81	257.81	257.81	257.81
HEAT CAPACITY (CAL/K)	45.170	41.696	39.233	35.283
MOLES OF GAS	4.4774	4.3582	4.3574	4.3562
MOLECULAR COMPOSITION:				
H	0.0973	0.0017	0.0000	0.0000
C	0.0010	0.0000	0.0000	0.0000
N	0.0002	0.0000	0.0000	0.0000
F	0.0366	0.0000	0.0000	0.0000
H2	0.1450	0.3362	0.3424	0.3402
HF	3.0033	3.0419	3.0419	3.0419
N2	0.7904	0.9675	0.9728	0.9729
F2	0.0000	0.0000	0.0000	0.0000
CH	0.0001	0.0000	0.0000	0.0000
CH2	0.0024	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0012
CF	0.0005	0.0000	0.0000	0.0000
CF2	0.0004	0.0000	0.0000	0.0000
CF3	0.0001	0.0000	0.0000	0.0000
CF4	0.0000	0.0000	0.0000	0.0000
CN	0.1031	0.0000	0.0000	0.0000
C2N2	0.0080	0.0000	0.0000	0.0000
C2H2	0.0430	0.0002	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.2455	0.0107	0.0002	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0.4765	0.9206	0.9316	0.9306

TABLE 52

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		23.000			
CLF3		77.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
CLF3	CLF3		-44.400	1.810	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.0616			
C		0.7654			
N		0.7654			
F		2.4984			
CL		0.8328			
PROPELLANT ENTHALPY		-32.102	KCAL/100 GM		
PROPELLANT DENSITY		1.393	GM/CC	0.0503	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			274.80	309.46	333.77
IVSP(LB-SEC/CU IN)			13.827	15.572	16.794
TEMPERATURE (K)		3685.1	1902.7	1380.9	864.46
CP (CAL/GM-DEG.K)		0.37326	0.34211	0.32401	0.29821
MOL. WT.-EFFECTIVE		26.143	27.387	28.166	28.470
CP/CV -EFFECTIVE		1.2557	1.2692	1.2784	1.3056
CF -APPROX.			1.6408	1.6477	1.9928
PEAF/M (SEC)			21.857	13.697	7.6652
AE/AT -APPROX.			8.8802	40.891	234.81
FROZEN EQUILIBRIA					
ISP (SEC)			261.05	294.94	312.51
TEMPERATURE (K)		3685.1	1482.5	806.12	382.36
C* (FT/SEC)		5388.6			
CF			1.5586	1.7610	1.8659
PEAF/M (SEC)			18.781	9.0387	4.0462
AE/AT			7.6305	26.984	120.80

TABLE 53

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3685.1	1902.7	1360.9	864.46
ENTHALPY (KILOCALORIES)	-32.102	-118.89	-142.16	-160.13
ENTROPY (CALORIES/DEG.K)	218.80	218.80	218.80	218.80
HEAT CAPACITY (CAL/K)	37.326	34.211	32.401	29.821
MOLES OF GAS	3.8251	3.6513	3.5504	3.5125
MOLECULAR COMPOSITION:				
H	0.0325	0.0000	0.0000	0.0000
C	0.0006	0.0000	0.0000	0.0000
N	0.0001	0.0000	0.0000	0.0000
F	0.0545	0.0003	0.0000	0.0000
CL	0.3538	0.1546	0.0188	0.0000
H2	0.0244	0.0000	0.0000	0.0000
HCL	0.4685	0.5850	0.7155	0.6298
HF	2.4376	2.4765	2.3460	2.2318
N2	0.3250	0.3827	0.3827	0.3827
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0048	0.0465	0.0492	0.0015
CLF	0.0009	0.0001	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0003	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0011	0.0000	0.0000	0.0000
CF2	0.0013	0.0000	0.0000	0.0000
CF3	0.0005	0.0004	0.0000	0.0000
CF4	0.0000	0.0050	0.0381	0.0667
CN	0.0494	0.0000	0.0000	0.0000
C2N2	0.0028	0.0000	0.0000	0.0000
C2H2	0.0065	0.0000	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.0603	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0.6332	0.7599	0.7273	0.6987

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		25.000			
CL03F		75.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
CL03F	CL03F		-10.100	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.3278			
C		0.8319			
N		0.8319			
O		2.1960			
F		0.7320			
CL		0.7320			
PROPELLANT ENTHALPY		-2.0938	KCAL/100 GM		
PROPELLANT DENSITY		1.187	GM/CC	0.0429	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		288.65	329.04	356.89
IVSP(LB-SEC/CU IN)		12.378	14.110	15.304
TEMPERATURE (K)	3685.6	2328.2	1638.0	1028.2
CP (CAL/GM-DEG.K)	0.39429	0.37710	0.35820	0.32758
MOL. WT.-EFFECTIVE	24.965	27.258	27.441	27.444
CP/CV -EFFECTIVE	1.2530	1.2397	1.2534	1.2838
CF -APPROX.		1.6828	1.9182	2.0806
PEAE/M (SEC)		25.584	15.685	9.0760
AE/AT -APPROX.		10.149	45.719	264.55
FROZEN EQUILIBRIA				
ISP (SEC)		267.88	302.20	322.43
TEMPERATURE (K)	3685.6	1506.0	845.37	364.07
C* (FT/SEC)	5519.0			
CF		1.5617	1.7617	1.8797
PEAE/M (SEC)		19.468	9.6875	3.9102
AE/AT		7.7228	28.237	113.98

TABLE 55

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3685.6	2328.2	1638.0	1028.2
ENTHALPY (KILOCALORIES)	-2.0938	-97.851	-126.52	-148.48
ENTROPY (CALORIES/DEG.K)	243.84	243.84	243.84	243.84
HEAT CAPACITY (CAL/K)	39.429	37.710	35.820	32.758
MOLES OF GAS	4.0055	3.6687	3.6442	3.6438
MOLECULAR COMPOSITION:				
H	0.0924	0.0066	0.0001	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0001	0.0000	0.0000	0.0000
O	0.0500	0.0004	0.0000	0.0000
F	0.0060	0.0001	0.0000	0.0000
CL	0.1592	0.0276	0.0005	0.0000
H2	0.1886	0.0965	0.1294	0.2300
H2O	0.6907	0.8410	0.8026	0.7019
HCL	0.5710	0.7042	0.7315	0.7320
HF	0.7260	0.7320	0.7320	0.7320
CO	0.5743	0.5238	0.2705	0.1697
CO2	0.2576	0.5082	0.5615	0.6622
O2	0.0728	0.0017	0.0000	0.0000
OH	0.1797	0.0100	0.0000	0.0000
N2	0.3958	0.4154	0.4160	0.4160
NO	0.0403	0.0011	0.0000	0.0000
CL2	0.0009	0.0001	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		36.000			
NO2CLO4		64.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
NO2CLO4	NO2CLO4		8.0000	2.220	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.7920			
C		1.1980			
N		1.6380			
O		2.6398			
CL		0.4400			
PROPELLANT ENTHALPY		11.151	KCAL/100 GM		
PROPELLANT DENSITY		1.340	GM/CC	0.0484	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			282.49	315.85	339.22
IVSP(LB-SEC/CU IN)			13.676	15.291	16.422
TEMPERATURE (K)		3276.8	1527.6	1017.0	702.73
CP (CAL/GM-DEG.K)		0.47845	0.43395	0.40298	0.38139
MOL. WT.-EFFECTIVE		21.194	21.584	21.595	22.003
CP/CV -EFFECTIVE		1.2437	1.2693	1.2961	1.3103
CF -APPROX.			1.6050	1.7946	1.9273
PEAF/M (SEC)			21.664	12.896	8.1400
AE/AT -APPROX.			8.3755	36.636	231.24
FROZEN EQUILIBRIA					
ISP (SEC)			275.51	309.41	328.76
TEMPERATURE (K)		3276.8	1368.9	793.31	401.03
C* (FT/SEC)		5662.8			
CF			1.5654	1.7580	1.8679
PEAF/M (SEC)			20.269	10.466	4.9761
AE/AT			7.8361	29.731	141.36

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3276.8	1527.8	1017.0	702.73
ENTHALPY (KILOCALORIES)	11.151	-80.562	-103.50	-121.09
ENTROPY (CALORIES/DEG.K)	275.17	275.17	275.17	275.17
HEAT CAPACITY (CAL/K)	47.845	43.393	40.298	38.139
MOLES OF GAS	4.7134	4.6330	4.6329	4.6448
MOLECULAR COMPOSITION:				
H	0.0864	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0027	0.0000	0.0000	0.0000
CL	0.0224	0.0000	0.0000	0.0000
H2	0.9153	1.0697	1.3012	1.5035
H2O	1.2044	1.1063	0.8747	0.6843
HCL	0.4175	0.4400	0.4400	0.4400
CO	1.0201	0.8625	0.6308	0.2524
CO2	0.1779	0.3355	0.5671	0.9016
O2	0.0014	0.0000	0.0000	0.0000
OH	0.0483	0.0000	0.0000	0.0000
N2	0.8160	0.8190	0.8190	0.8190
NO	0.0056	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0441
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C(SOLID)	0	0	0	0

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
UDMH		14.000			
NH4CLO4		86.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
UDMH	C2N2H8		12.740	0.7860	298.16
NH4CLO4	NH4CLO4		-69.420	1.960	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.7913			
C		0.4659			
N		1.1978			
O		2.9277			
CL		0.7319			
PROPELLANT ENTHALPY		-47.843	KCAL/100 GM		
PROPELLANT DENSITY		1.621	GM/CC	0.0586	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			256.98	292.79	315.79
IVSP(LB-SEC/CU IN)			15.168	17.146	18.495
TEMPERATURE (K)		3033.6	1702.3	1159.2	707.11
CP (CAL/GM-DEG.K)		0.44840	0.41180	0.37401	0.33360
MOL. WT.-EFFECTIVE		25.161	26.130	26.134	26.134
CP/CV -EFFECTIVE		1.2138	1.2265	1.2552	1.2952
CF -APPROX.			1.6518	1.8675	2.0142
PEAE/M (SEC)			21.749	13.098	7.4075
AE/AT -APPROX.			9.4392	41.772	236.24
FROZEN EQUILIBRIA					
ISP (SEC)			247.84	281.72	301.78
TEMPERATURE (K)		3033.6	1382.0	822.51	412.43
C* (FT/SEC)		5044.3			
CF			1.5808	1.7969	1.9248
PEAE/M (SEC)			19.160	10.032	4.6959
AE/AT			8.3159	31.993	149.76

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3033.6	1702.3	1159.2	707.11
ENTHALPY (KILOCALORIES)	-47.843	-124.92	-146.36	-162.45
ENTROPY (CALORIES/DEG.K)	244.05	244.05	244.05	244.05
HEAT CAPACITY (CAL/K)	44.840	41.180	37.401	33.360
MOLES OF GAS	3.9744	3.8270	3.8264	3.8264
MOLECULAR COMPOSITION:				
H	0.0135	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0070	0.0000	0.0000	0.0000
CL	0.0508	0.0009	0.0000	0.0000
H2	0.1028	0.0195	0.0263	0.0329
H2O	1.9017	2.0105	2.0033	1.9968
HCL	0.6798	0.7310	0.7319	0.7319
CO	0.1304	0.0148	0.0074	0.0009
CO2	0.3355	0.4511	0.4585	0.4650
O2	0.0532	0.0000	0.0000	0.0000
OH	0.0838	0.0002	0.0000	0.0000
N2	0.5877	0.5989	0.5989	0.5989
NO	0.0224	0.0000	0.0000	0.0000
CL2	0.0006	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 60

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CH2		29.000			
O2		71.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CH2	CH2		-6.5000	0.9200	298.16
O2	O2		-3.0800	1.142	90.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.1352			
C		2.0676			
O		4.4375			
PROPELLANT ENTHALPY		-20.273	KCAL/100 GM		
PROPELLANT DENSITY		1.067	GM/CC	0.0386	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			299.41	340.09	369.43
IVSP(LB-SEC/CU IN)			11.546	13.114	14.246
TEMPERATURE (K)		3627.6	2153.2	1524.4	1022.5
CP (CAL/GM-DEG.K)		0.48655	0.46027	0.43696	0.40858
MOL. WT.-EFFECTIVE		22.762	24.157	24.182	24.183
CP/CV -EFFECTIVE		1.2187	1.2176	1.2316	1.2518
CF -APPROX.			1.6634	1.8894	2.0524
PEAE/M (SEC)			25.739	16.025	9.8943
AE/AT -APPROX.			9.7302	44.515	274.86
FROZEN EQUILIBRIA					
ISP (SEC)			284.37	323.93	347.92
TEMPERATURE (K)		3627.6	1643.4	995.09	497.92
C* (FT/SEC)		5791.3			
CF (SEC)			1.5798	1.7996	1.9329
PEAE/M (SEC)			21.951	11.668	5.4358
AE/AT			8.2984	32.412	151.00

TABLE 61

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3627.6	2153.2	1524.4	1022.5
ENTHALPY (KILOCALORIES)	-20.273	-123.30	-153.20	-177.12
ENTROPY (CALORIES/DEG.K)	273.63	273.63	273.63	273.63
HEAT CAPACITY (CAL/K)	48.655	46.027	43.696	40.858
MOLES OF GAS	4.3933	4.1396	4.1352	4.1352
MOLECULAR COMPOSITION:				
H	0.1328	0.0062	0.0001	0.0000
C	0.0000	0.0000	0.0000	0.0000
O	0.0365	0.0000	0.0000	0.0000
H2	0.4522	0.4971	0.6540	0.9504
H2O	1.4400	1.5661	1.4135	1.1172
CO	1.4845	1.2664	1.1112	0.8148
CO2	0.3830	0.3012	0.9564	1.2527
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0462	0.0000	0.0000	0.0000
OH	0.2178	0.0026	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 62

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
F2		72.500			
CH2		27.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
F2	F2		-3.4670	1.510	85.200
CH2	CH2		-6.5000	0.9200	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.9213			
C		1.9606			
F		3.8158			
PROPELLANT ENTHALPY		-19.359	KCAL/100 GM		
PROPELLANT DENSITY		1.284	GM/CC	0.0464	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			324.55	370.98	404.18
IVSP(LB-SEC/CU IN)			15.052	17.205	18.745
TEMPERATURE (K)		4378.6	2805.0	2039.9	1338.2
CP (CAL/GM-DEG.K)		0.48878	0.45786	0.43602	0.40066
MOL. WT.-EFFECTIVE		24.058	25.696	25.841	25.850
CP/CV -EFFECTIVE		1.2034	1.2032	1.2141	1.2374
CF -APPROX.			1.6796	1.9199	2.0917
PEAE/M (SEC)			29.079	18.398	11.074
AE/AT -APPROX.			10.240	47.606	286.55
FROZEN EQUILIBRIA					
ISP (SEC)			306.57	349.94	378.40
TEMPERATURE (K)		4378.6	2066.1	1292.6	682.38
C* (FT/SEC)		6216.9			
CF			1.5866	1.8110	1.9583
PEAE/M (SEC)			24.219	13.274	6.4804
AE/AT			8.5287	34.347	167.69

TABLE 63

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4378.6	2805.0	2039.9	1338.2
ENTHALPY (KILOCALORIES)	-19.359	-140.41	-177.53	-207.10
ENTROPY (CALORIES/DEG.K)	249.31	249.31	249.31	249.31
HEAT CAPACITY (CAL/K)	48.878	45.786	43.602	40.066
MOLES OF GAS	4.1565	3.8916	3.8699	3.8685
MOLECULAR COMPOSITION:				
H	0.1947	0.0332	0.0026	0.0000
C	0.0243	0.0000	0.0000	0.0000
F	0.3123	0.0128	0.0001	0.0000
H2	0.0738	0.0412	0.0515	0.0527
HF	3.4599	3.8029	3.8157	3.8158
F2	0.0000	0.0000	0.0000	0.0000
CH	0.0009	0.0000	0.0000	0.0000
CH2	0.0037	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0210	0.0000	0.0000	0.0000
CF2	0.0089	0.0000	0.0000	0.0000
CF3	0.0015	0.0000	0.0000	0.0000
CF4	0.0000	0.0000	0.0000	0.0000
C2H2	0.0553	0.0013	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	1.7897	1.9579	1.9605	1.9606

TABLE 64

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
OF2		78.000			
CH2		22.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
OF2	OF2		3.6000	1.530	128.00
CH2	CH2		-6.5000	0.9200	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.1370			
C		1.5685			
O		1.4444			
F		2.6889			
PROPELLANT ENTHALPY		-4.9954	KCAL/100 GM		
PROPELLANT DENSITY		1.335	GM/CC	0.0482	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		347.34	389.90	416.79
IVSP(LB-SEC/CU IN)		16.756	18.809	20.107
TEMPERATURE (K)	4564.0	2522.1	1602.4	917.33
CP (CAL/GM-DEG.K)	0.41949	0.39055	0.36453	0.33556
MOL. WT.-EFFECTIVE	20.655	22.382	22.434	22.551
CP/CV -EFFECTIVE	1.2976	1.2942	1.3210	1.3561
CF -APPROX.		1.6757	1.6810	2.0108
PEAE/M (SEC)		28.048	15.839	8.4379
AE/AT -APPROX.		9.2079	38.206	203.54
FROZEN EQUILIBRIA				
ISP (SEC)		319.31	358.25	376.82
TEMPERATURE (K)	4564.0	1642.7	800.30	326.16
C* (FT/SEC)	6668.9			
CF (SEC)		1.5405	1.7283	1.8179
PEAE/M (SEC)		21.534	9.3509	3.6232
AE/AT		7.0691	22.556	87.399

TABLE 65

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4564.0	2522.1	1602.4	917.33
ENTHALPY (KILOCALORIES)	-4.9954	-143.65	-179.70	-204.64
ENTROPY (CALORIES/DEG.K)	271.84	271.84	271.84	271.84
HEAT CAPACITY (CAL/K)	41.949	39.055	36.453	33.556
MOLES OF GAS	4.8415	4.4678	4.4574	4.4343
MOLECULAR COMPOSITION:				
H	0.3291	0.0198	0.0001	0.0000
C	0.0617	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
F	0.3134	0.0011	0.0000	0.0000
H2	0.1080	0.1147	0.1240	0.1231
H2O	0.0000	0.0000	0.0000	0.0009
HF	2.5754	2.8878	2.8883	2.8889
CO	1.4444	1.4444	1.4444	1.3992
CO2	0.0000	0.0000	0.0000	0.0222
CH	0.0023	0.0000	0.0000	0.0000
CH2	0.0070	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0.0530	0.1240	0.1241	0.1472

TABLE 66

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
H2O2		86.500			
CH2		13.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
H2O2	H2O2		-44.840	1.443	298.16
CH2	CH2		-6.5000	0.9200	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		7.0108			
C		0.9625			
O		5.0858			
PROPELLANT ENTHALPY		-120.28	KCAL/100 GM		
PROPELLANT DENSITY		1.340	GM/CC	0.0484	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			276.80	314.71	341.15
IVSP(LB-SEC/CU IN)			13.402	15.238	16.518
TEMPERATURE (K)		2998.5	1676.4	1197.1	775.16
CP (CAL/GM-DEG.K)		0.57843	0.52402	0.46157	0.43193
MOL. WT.-EFFECTIVE		21.857	22.381	22.382	22.382
CP/CV -EFFECTIVE		1.1865	1.2040	1.2260	1.2588
CF -APPROX.			1.6416	1.6664	2.0232
PEAE/M (SEC)			23.396	14.693	8.7772
AE/AT -APPROX.			9.4416	43.571	260.28
FROZEN EQUILIBRIA					
ISP (SEC)			269.20	308.28	330.78
TEMPERATURE (K)		2998.5	1485.9	971.95	586.88
C* (FT/SEC)		5425.0			
CF (SEC)			1.5965	1.6283	1.9618
PEAE/M (SEC)			21.833	12.471	7.0180
AE/AT			8.6111	36.981	208.11

TABLE 67

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2998.5	1676.4	1197.1	775.16
ENTHALPY (KILOCALORIES)	-120.28	-208.33	-234.10	-254.03
ENTROPY (CALORIES/DEG.K)	285.32	285.32	285.32	285.32
HEAT CAPACITY (CAL/K)	57.843	52.402	48.157	43.193
MOLES OF GAS	4.5752	4.4680	4.4679	4.4679
MOLECULAR COMPOSITION:				
H	0.0177	0.0001	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
O	0.0058	0.0000	0.0000	0.0000
H2	0.1898	0.1945	0.2524	0.3254
H2O	3.2548	3.3108	3.2530	3.1800
CO	0.2849	0.1501	0.0922	0.0191
CO2	0.6776	0.8124	0.8703	0.9434
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0406	0.0000	0.0000	0.0000
OH	0.1038	0.0001	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 68

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CH2		22.000			
N2O4		78.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CH2	CH2		-6.5000	0.9200	298.16
N2O4	N2O4		-5.4000	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.1370			
C		1.5685			
N		1.6954			
O		3.3907			
PROPELLANT ENTHALPY		-14.773	KCAL/100 GM		
PROPELLANT DENSITY		1.274	GM/CC	0.0460	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			272.87	307.47	331.99
IVSP(LB-SEC/CU IN)			12.566	14.159	15.288
TEMPERATURE (K)		3366.0	1745.4	1211.5	799.14
CP (CAL/GM-DEG.K)		0.44367	0.41379	0.39589	0.36314
MOL. WT.-EFFECTIVE		24.402	25.095	25.096	25.098
CP/CV -EFFECTIVE		1.2248	1.2367	1.2500	1.2788
CF -APPROX.			1.6324	1.8394	1.9861
PEAF/M (SEC)			22.037	13.574	8.2919
AE/AT -APPROX.			8.9707	40.602	248.02
FROZEN EQUILIBRIA					
ISP (SEC)			263.54	299.02	318.96
TEMPERATURE (K)		3366.0	1498.4	900.94	484.72
C* (FT/SEC)		5378.1			
CF (SEC)			1.5766	1.7888	1.9081
PEAF/M (SEC)			20.144	10.675	5.3843
AE/AT			8.2001	31.931	161.06

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3366.0	1745.4	1211.5	799.14
ENTHALPY (KILOCALORIES)	-14.773	-100.35	-123.42	-141.14
ENTROPY (CALORIES/DEG.K)	254.39	254.39	254.39	254.39
HEAT CAPACITY (CAL/K)	44.367	41.379	39.589	36.314
MOLES OF GAS	4.0980	3.9849	3.9847	3.9843
MOLECULAR COMPOSITION:				
H	0.0598	0.0003	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0104	0.0000	0.0000	0.0000
H2	0.3225	0.4298	0.6125	0.9206
H2O	1.1682	1.1386	0.9560	0.6475
CO	1.0710	0.8850	0.7023	0.3934
CO2	0.4975	0.6836	0.8662	1.1749
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0002
O2	0.0150	0.0000	0.0000	0.0000
OH	0.0959	0.0000	0.0000	0.0000
N2	0.8376	0.8477	0.8477	0.8477
NO	0.0202	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 70

CASE						
PROPELLANT COMPOSITION		WEIGHT%	MOLAR			
NF3		80.000				
CH2		20.000				
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.	
NF3	NF3		-32.000	1.532	144.00	
CH2	CH2		-6.5000	0.9200	298.16	
ATOMIC COMPOSITION(GM AT/100GM)						
H		2.6518				
C		1.4259				
N		1.1266				
F		3.3799				
PROPELLANT ENTHALPY		-45.321	KCAL/100 GM			
PROPELLANT DENSITY		1.352	GM/CC	0.0488	LB/CU IN	
		CHAMBER	EXHAUST	EXHAUST	EXHAUST	
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000	
SHIFTING EQUILIBRIA						
ISP (SEC)			283.54	323.38	351.43	
IVSP(LB-SEC/CU IN)			13.851	15.798	17.168	
TEMPERATURE (K)		3725.8	2294.6	1656.8	1058.8	
CP (CAL/GM-DEG.K)		0.42537	0.40182	0.36228	0.35212	
MOL. WT.-EFFECTIVE		26.133	28.015	28.197	28.191	
CP/CV -EFFECTIVE		1.2177	1.2144	1.2261	1.2503	
CF -APPROX.			1.6650	1.6989	2.0636	
PEAF/M (SEC)			24.975	15.714	9.2401	
AE/AT -APPROX.			9.9792	46.138	271.29	
FROZEN EQUILIBRIA						
ISP (SEC)			268.89	305.78	328.69	
TEMPERATURE (K)		3725.8	1684.7	1021.1	520.68	
C* (FT/SEC)		5479.1				
CF			1.5790	1.7956	1.9301	
PEAE/M (SEC)			20.728	11.048	5.2408	
AE/AT			8.2825	32.437	153.87	

TABLE 71

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATUPE (KELVIN)	3725.8	2294.6	1656.8	1058.8
ENTHALPY (KILOCALORIES)	-45.321	-137.72	-165.51	-187.26
ENTROPY (CALORIES/DEG.K)	228.79	228.79	228.79	228.79
HEAT CAPACITY (CAL/K)	42.537	40.182	38.228	35.212
MOLES OF GAS	3.8266	3.5696	3.5477	3.5472
MOLECULAR COMPOSITION:				
H	0.0089	0.0000	0.0000	0.0000
C	0.0008	0.0000	0.0000	0.0000
N	0.0001	0.0000	0.0000	0.0000
F	0.2836	0.0197	0.0002	0.0000
H2	0.0016	0.0000	0.0000	0.0000
HF	2.8182	2.8516	2.8518	2.8518
N2	0.5128	0.5631	0.5633	0.5633
F2	0.0001	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0062	0.0000	0.0000	0.0000
CF2	0.0312	0.0005	0.0000	0.0000
CF3	0.0563	0.0291	0.0016	0.0000
CF4	0.0097	0.1050	0.1308	0.1320
CN	0.0711	0.0003	0.0000	0.0000
C2N2	0.0049	0.0000	0.0000	0.0000
C2H2	0.0004	0.0000	0.0000	0.0000
CHF3	0.0005	0.0001	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.0201	0.0001	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	1.2194	1.2908	1.2935	1.2939

TABLE 72

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CLF3		79.000			
CH2		21.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CLF3	CLF3		-44.400	1.810	298.16
CH2	CH2		-6.5000	0.9200	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.9944			
C		1.4972			
F		2.5634			
CL		0.6544			
PROPELLANT ENTHALPY		-47.670	KCAL/100 GM		
PROPELLANT DENSITY		1.504	GM/CC	0.0544	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			251.83	285.78	311.05
IVSP(LB-SEC/CU IN)			13.688	15.533	16.907
TEMPERATURE (K)		3495.2	1873.8	1435.4	994.01
CP (CAL/GM-DEG.K)		0.38610	0.35359	0.33597	0.31531
MOL. WT.-EFFECTIVE		29.217	30.649	31.619	32.187
CP/CV -EFFECTIVE		1.2138	1.2245	1.2301	1.2435
CF -APPROX.			1.6125	1.8299	1.9917
PEAF/M (SEC)			20.990	13.734	8.5837
AE/AT -APPROX.			9.1454	43.971	274.82
FROZEN EQUILIBRIA					
ISP (SEC)			246.90	279.61	299.95
TEMPERATURE (K)		3495.2	1596.8	1015.0	571.32
C* (FT/SEC)		5024.7			
CF			1.5809	1.7904	1.9206
PEAE/M (SEC)			19.138	10.742	5.6363
AE/AT			8.3385	34.391	180.45

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3495.2	1873.8	1435.4	994.01
ENTHALPY (KILOCALORIES)	-47.670	-120.56	-141.53	-158.87
ENTROPY (CALORIES/DEG.K)	200.91	200.91	200.91	200.91
HEAT CAPACITY (CAL/K)	38.610	35.359	33.597	31.531
MOLES OF GAS	3.4226	3.2627	3.1626	3.1068
MOLECULAR COMPOSITION:				
H	0.0119	0.0000	0.0000	0.0000
C	0.0002	0.0000	0.0000	0.0000
F	0.0476	0.0003	0.0000	0.0000
CL	0.3748	0.1648	0.0335	0.0006
H2	0.0082	0.0000	0.0000	0.0000
HCL	0.4588	0.5366	0.6723	0.6294
HF	2.5040	2.4578	2.3221	2.1650
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0096	0.0764	0.0743	0.0122
CLF	0.0016	0.0002	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0001	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0006	0.0000	0.0000	0.0000
CF2	0.0018	0.0000	0.0000	0.0000
CF3	0.0018	0.0012	0.0001	0.0000
CF4	0.0002	0.0253	0.0602	0.0996
C2H2	0.0015	0.0000	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	1.4896	1.4706	1.4369	1.3976

TABLE 74

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CH2		20.000			
CL03F		80.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CH2	CH2		-6.5000	0.9200	298.16
CL03F	CL03F		-10.100	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.8518			
C		1.4259			
O		2.3424			
F		0.7808			
CL		0.7808			
PROPELLANT ENTHALPY		-17.155	KCAL/100 GM		
PROPELLANT DENSITY		1.287	GM/CC	0.0465	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			279.59	315.11	339.17
IVSP(LB-SEC/CU IN)			13.003	14.656	15.774
TEMPERATURE (K)		3694.0	2043.9	1365.9	850.48
CP (CAL/GM-DEG.K)		0.37426	0.35198	0.35120	0.30752
MOL. WT.-EFFECTIVE		25.801	27.504	27.528	27.528
CP/CV -EFFECTIVE		1.2591	1.2583	1.2797	1.3068
CF -APPROX.			1.6580	1.8686	2.0113
PEAE/M (SEC)			22.980	13.614	7.8753
AE/AT -APPROX.			9.2730	40.366	233.50
FROZEN EQUILIBRIA					
ISP (SEC)			262.88	296.97	315.81
TEMPERATURE (K)		3694.0	1484.4	808.50	349.15
C* (FT/SEC)		5425.6			
CF (SEC)			1.5589	1.7611	1.8728
PEAE/M (SEC)			18.922	9.1228	3.7047
AE/AT			7.6353	27.049	109.84

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3694.0	2043.9	1365.9	850.48
ENTHALPY (KILOCALORIES)	-17.155	-106.99	-131.27	-149.36
ENTROPY (CALORIES/DEG.K)	233.31	233.31	233.31	233.31
HEAT CAPACITY (CAL/K)	37.426	35.198	33.120	30.752
MOLES OF GAS	3.8758	3.6359	3.6327	3.6326
MOLECULAR COMPOSITION:				
H	0.0952	0.0018	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
O	0.0295	0.0000	0.0000	0.0000
F	0.0063	0.0000	0.0000	0.0000
CL	0.1659	0.0041	0.0000	0.0000
H2	0.2001	0.1988	0.2915	0.4743
H2O	0.4301	0.4472	0.3536	0.1708
HCL	0.6126	0.7767	0.7808	0.7808
HF	0.7745	0.7808	0.7808	0.7808
CO	1.1289	0.9571	0.8630	0.6801
CO2	0.2970	0.4688	0.5629	0.7458
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0252	0.0000	0.0000	0.0000
OH	0.1092	0.0005	0.0000	0.0000
CLO	0.0003	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0010	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 76

CASE

PROPELLANT COMPOSITION	WEIGHT%	MOLAR
NO2CLO4	79.000	
CH2	21.000	

INGREDIENT DATA:	FORMULA	HEAT OF FORM.	DENSITY	REF. TEMP.
NO2CLO4	NO2CLO4	8.0000	2.220	298.16
CH2	CH2	-6.5000	0.9200	298.16

ATOMIC COMPOSITION(GM AT/100GM)	
H	2.9944
C	1.4972
N	0.5431
O	3.2585
CL	0.5431

PROPELLANT ENTHALPY -5.3872 KCAL/100 GM

PROPELLANT DENSITY 1.712 GM/CC 0.0618 LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		276.24	316.56	343.46
IVSP(LB-SEC/CU IN)		17.210	19.580	21.244
TEMPERATURE (K)	3586.8	2205.3	1553.3	1017.9
CP (CAL/GM-DEG.K)	0.40524	0.36720	0.36880	0.34167
MOL. WT.-EFFECTIVE	26.258	28.203	28.268	28.268
CP/CV -EFFECTIVE	1.2296	1.2225	1.2355	1.2590
CF -APPROX.		1.6751	1.9057	2.0677
PEAE/M (SEC)		24.296	15.008	9.0640
AE/AT -APPROX.		9.9530	45.175	272.84
FROZEN EQUILIBRIA				
ISP (SEC)		261.50	296.87	318.32
TEMPERATURE (K)	3586.8	1575.3	926.63	438.70
C* (FT/SEC)	5344.4			
CF		1.5743	1.7872	1.9164
PEAE/M (SEC)		19.834	10.277	4.5376
AE/AT		8.1251	30.935	136.59

TABLE 77

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3586.8	2205.3	1553.3	1017.9
ENTHALPY (KILOCALORIES)	-5.3872	-94.362	-120.55	-140.96
ENTROPY (CALORIES/DEG.K)	239.44	239.44	239.44	239.44
HEAT CAPACITY (CAL/K)	40.524	38.720	36.880	34.167
MOLES OF GAS	3.8083	3.5457	3.5376	3.5375
MOLECULAR COMPOSITION:				
H	0.0806	0.0049	0.0001	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0336	0.0000	0.0000	0.0000
CL	0.0906	0.0074	0.0001	0.0000
H2	0.2286	0.2030	0.2928	0.4771
H2O	0.9192	1.0221	0.9429	0.7486
HCL	0.4515	0.5357	0.5430	0.5431
CO	0.9918	0.7621	0.6798	0.4845
CO2	0.5054	0.7351	0.8184	1.0127
O2	0.0550	0.0001	0.0000	0.0000
OH	0.1667	0.0035	0.0000	0.0000
N2	0.2584	0.2714	0.2715	0.2715
NO	0.0261	0.0002	0.0000	0.0000
CL2	0.0004	0.0000	0.0000	0.0000
CLO	0.0002	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 78

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NH4CLO4		91.500			
CH2		8.5000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NH4CLO4	NH4CLO4		-69.420	1.960	298.16
CH2	CH2		-6.5000	0.9200	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.3270			
C		0.6060			
N		0.7787			
O		3.1150			
CL		0.7787			
PROPELLANT ENTHALPY		-57.999	KCAL/100 GM		
PROPELLANT DENSITY		1.788	GM/CC	0.0646	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			248.77	281.91	304.38
IVSP(LB-SEC/CU IN)			16.072	18.213	19.665
TEMPERATURE (K)	2975.4		1662.1	1149.1	714.96
CP (CAL/GM-DEG.K)	0.42873		0.39334	0.35924	0.32157
MOL. WT.-EFFECTIVE	26.733		27.668	27.688	27.772
CP/CV -EFFECTIVE	1.2098		1.2234	1.2497	1.2862
CF -APPROX.			1.6495	1.8692	2.0182
PEAE/M (SEC)			20.878	12.728	7.3123
AE/AT -APPROX.			9.4198	42.197	242.42
FROZEN EQUILIBRIA					
ISP (SEC)			238.76	272.34	292.28
TEMPERATURE (K)	2975.4		1372.8	836.12	426.81
C* (FT/SEC)	4852.4				
CF			1.5831	1.8058	1.9380
PEAE/M (SEC)			18.596	9.9289	4.7226
AE/AT			8.3901	32.917	156.57

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2975.4	1662.1	1149.1	714.96
ENTHALPY (KILOCALORIES)	-57.999	-129.12	-149.34	-164.47
ENTROPY (CALORIES/DEG.K)	232.57	232.57	232.57	232.57
HEAT CAPACITY (CAL/K)	42.873	39.334	35.924	32.157
MOLES OF GAS	3.7406	3.6143	3.6117	3.6007
MOLECULAR COMPOSITION:				
H	0.0079	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0075	0.0000	0.0000	0.0000
CL	0.0601	0.0062	0.0007	0.0000
H2	0.0537	0.0002	0.0000	0.0000
H2O	1.7054	1.7772	1.7767	1.7981
HCL	0.7163	0.7709	0.7735	0.7308
CO	0.1116	0.0002	0.0000	0.0000
CO2	0.4944	0.6058	0.6060	0.6060
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0972	0.0618	0.0631	0.0524
OH	0.0845	0.0012	0.0000	0.0000
N2	0.3780	0.3889	0.3893	0.3894
NO	0.0226	0.0010	0.0000	0.0000
CLO	0.0001	0.0000	0.0000	0.0000
CL2	0.0011	0.0008	0.0023	0.0240
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 80

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		55.000			
O2		45.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
O2	O2		-3.0600	1.142	90.200
ATOMIC COMPOSITION(GM AT/100GM)					
C		2.8926			
N		1.4463			
O		2.8125			
PROPELLANT ENTHALPY		81.001	KCAL/100 GM		
PROPELLANT DENSITY		1.040	GM/CC	0.0376	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			297.47	331.23	353.41
IVSP(LB-SEC/CU IN)			11.183	12.452	13.286
TEMPERATURE (K)		5036.3	2163.2	1374.4	914.42
CP (CAL/GM-DEG.K)		0.32640	0.31317	0.30285	0.28210
MOL. WT.-EFFECTIVE		27.897	28.283	28.289	29.160
CP/CV -EFFECTIVE		1.2792	1.2893	1.3020	1.3185
CF -APPROX.			1.5797	1.7590	1.8768
PEAE/M (SEC)			22.230	12.682	7.6715
AE/AT -APPROX.			8.0331	33.674	203.70
FROZEN EQUILIBRIA					
ISP (SEC)			292.74	326.48	346.06
TEMPERATURE (K)		5036.3	1964.7	1166.2	620.01
C* (FT/SEC)		6058.4			
CF			1.5546	1.7338	1.8378
PEAE/M (SEC)			20.800	11.070	5.5526
AE/AT			7.5164	29.394	147.44

TABLE 81

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	5036.3	2163.2	1374.4	914.42
ENTHALPY (KILOCALORIES)	81.001	-20.694	-45.091	-62.543
ENTROPY (CALORIES/DEG.K)	224.16	224.16	224.16	224.16
HEAT CAPACITY (CAL/K)	32.640	31.317	30.285	28.210
MOLES OF GAS	3.5846	3.5357	3.5349	3.4294
MOLECULAR COMPOSITION:				
C	0.0098	0.0000	0.0000	0.0000
N	0.0068	0.0000	0.0000	0.0000
O	0.0020	0.0000	0.0000	0.0000
CO	2.8089	2.8124	2.8111	2.5999
CO2	0.0006	0.0000	0.0007	0.1063
CN	0.0731	0.0001	0.0000	0.0000
C2N2	0.0001	0.0000	0.0000	0.0000
O2	0.0000	0.0000	0.0000	0.0000
N2	0.6828	0.7231	0.7232	0.7232
NO	0.0005	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0.0800	0.0808	0.1864

TABLE 82

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		18.000			
F2		82.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
F2	F2		-3.4670	1.510	85.200
ATOMIC COMPOSITION(GM AT/100GM)					
C		0.9467			
N		0.4733			
F		4.3158			
PROPELLANT ENTHALPY		20.445	KCAL/100 GM		
PROPELLANT DENSITY		1.372	GM/CC	0.0496	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			250.80	291.10	325.30
IVSP(LB-SEC/CU IN)			12.436	14.435	16.131
TEMPERATURE (K)		4037.6	2983.3	2655.1	2354.2
CP (CAL/GM-DEG.K)		0.29182	0.29210	0.29201	0.29173
MOL. WT.-EFFECTIVE		37.449	43.156	45.760	48.684
CP/CV -EFFECTIVE		1.2223	1.1872	1.1747	1.1627
CF -APPROX.			1.6958	1.9683	2.1996
PEAE/M (SEC)			23.830	17.233	12.852
AE/AT -APPROX.			10.964	58.261	434.50
FROZEN EQUILIBRIA					
ISP (SEC)			234.01	267.17	286.22
TEMPERATURE (K)		4037.6	1853.1	1179.8	728.07
C* (FT/SEC)		4758.4			
CF			1.5823	1.8065	1.9353
PEAE/M (SEC)			18.282	10.195	5.8726
AE/AT			8.4116	34.467	198.54

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4037.6	2983.3	2655.1	2354.2
ENTHALPY (KILOCALORIES)	20.445	-51.844	-76.940	-101.17
ENTROPY (CALORIES/DEG.K)	177.88	177.88	177.88	177.88
HEAT CAPACITY (CAL/K)	29.182	29.210	29.201	29.173
MOLES OF GAS	2.6703	2.3172	2.1853	2.0541
MOLECULAR COMPOSITION:				
C	0.0007	0.0000	0.0000	0.0000
N	0.0002	0.0000	0.0000	0.0000
F	1.4970	1.1369	1.0035	0.8713
CF	0.0134	0.0016	0.0005	0.0001
CF2	0.1408	0.0476	0.0252	0.0109
CF3	0.5527	0.4828	0.4103	0.3152
CF4	0.2155	0.4084	0.5076	0.6192
CN	0.0231	0.0062	0.0030	0.0012
C2N2	0.0002	0.0000	0.0000	0.0000
N2	0.2248	0.2335	0.2351	0.2361
F2	0.0019	0.0001	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 84

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		32.000			
OF2		68.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
OF2	OF2		3.6000	1.530	128.00
ATOMIC COMPOSITION(GM AT/100GM)					
C		1.6830			
N		0.6415			
O		1.2592			
F		2.5185			
PROPELLANT ENTHALPY		54.181	KCAL/100 GM		
PROPELLANT DENSITY		1.291	GM/CC	0.0466	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			277.06	316.92	353.11
IVSP(LB-SEC/CU IN)			12.928	14.880	16.476
TEMPERATURE (K)		3991.6	2708.4	2292.8	1967.9
CP (CAL/GM-DEG.K)		0.30162	0.30087	0.29938	0.29770
MOL. WT.-EFFECTIVE		29.296	33.515	35.471	38.110
CP/CV -EFFECTIVE		1.2902	1.2454	1.2302	1.2124
CF -APPROX.			1.6988	1.9554	2.1651
PEAF/M (SEC)			25.216	17.523	12.643
AE/AT -APPROX.			10.521	53.721	387.59
FROZEN EQUILIBRIA					
ISP (SEC)			252.80	284.33	300.65
TEMPERATURE (K)		3991.6	1515.9	846.35	423.50
C* (FT/SEC)		5247.4			
CF			1.5500	1.7433	1.8434
PEAE/M (SEC)			17.697	8.7847	4.1572
AE/AT			7.3835	26.931	127.45

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3991.6	2708.4	2292.8	1967.9
ENTHALPY (KILOCALORIES)	54.181	-34.042	-62.711	-89.118
ENTROPY (CALORIES/DEG.K)	205.88	205.88	205.88	205.88
HEAT CAPACITY (CAL/K)	30.162	30.087	29.938	29.770
MOLES OF GAS	3.4135	2.9837	2.8192	2.8240
MOLECULAR COMPOSITION:				
C	0.0006	0.0000	0.0000	0.0000
N	0.0002	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
F	1.3211	0.8799	0.7154	0.5202
CO	1.2514	1.2414	1.1953	1.1059
CO2	0.0000	0.0001	0.0013	0.0090
O2	0.0000	0.0000	0.0000	0.0000
N2	0.4082	0.4207	0.4207	0.4207
NO	0.0000	0.0000	0.0000	0.0000
F2	0.0011	0.0001	0.0000	0.0000
CF	0.0086	0.0000	0.0000	0.0000
CF2	0.0744	0.0018	0.0000	0.0000
CF3	0.2393	0.0884	0.0177	0.0033
CF4	0.0761	0.3336	0.4073	0.4294
CN	0.0243	0.0000	0.0000	0.0000
C2N2	0.0002	0.0000	0.0000	0.0000
COF2	0.0077	0.0177	0.0603	0.1354
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 86

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		25.000			
H2O2		75.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
H2O2	H2O2		-44.840	1.443	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.4097			
C		1.3148			
N		0.6574			
O		4.4097			
PROPELLANT ENTHALPY		-60.078	KCAL/100 GM		
PROPELLANT DENSITY		1.286	GM/CC	0.0465	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			279.68	319.34	348.35
IVSP(LB-SEC/CU IN)			12.997	14.840	16.188
TEMPERATURE (K)		3319.9	2093.1	1509.7	1013.3
CP (CAL/GM-DEG.K)		0.49055	0.46524	0.43933	0.40086
MOL. WT.-EFFECTIVE		24.469	25.961	25.985	25.985
CP/CV -EFFECTIVE		1.1984	1.1969	1.2108	1.2358
CF -APPROX.			1.6739	1.9113	2.0849
PEAE/M (SEC)			24.923	15.730	9.6783
AE/AT -APPROX.			10.150	47.071	289.62
FROZEN EQUILIBRIA					
ISP (SEC)			265.81	304.24	328.69
TEMPERATURE (K)		3319.9	1597.0	1011.2	533.29
C* (FT/SEC)		5375.7			
CF			1.5909	1.8209	1.9672
PEAE/M (SEC)			21.228	11.744	5.7327
AE/AT			8.6452	35.144	171.55

TABLE 67

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3319.9	2093.1	1509.7	1013.3
ENTHALPY (KILOCALORIES)	-60.078	-149.97	-177.28	-199.54
ENTROPY (CALORIES/DEG.K)	262.21	262.21	262.21	262.21
HEAT CAPACITY (CAL/K)	49.055	46.524	43.933	40.086
MOLES OF GAS	4.0868	3.8519	3.8484	3.8484
MOLECULAR COMPOSITION:				
H	0.0395	0.0021	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0239	0.0000	0.0000	0.0000
H2	0.1776	0.1278	0.1844	0.2919
H2O	1.9158	2.0739	2.0204	1.9129
CO	0.5492	0.2987	0.2403	0.1329
CO2	0.7656	1.0161	1.0745	1.1819
CN	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
O2	0.1031	0.0003	0.0000	0.0000
OH	0.1833	0.0041	0.0000	0.0000
N2	0.3287	0.3287	0.3287	0.3287
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 88

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		36.000			
N2O4		64.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
N2O4	N2O4		-5.4000	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
C		1.8933			
N		2.3377			
O		2.7821			
PROPELLANT ENTHALPY		52.098	KCAL/100 GM		
PROPELLANT DENSITY		1.221	GM/CC	0.0441	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			280.18	320.01	347.39
IVSP(LB-SEC/CU IN)			12.365	14.122	15.331
TEMPERATURE (K)	4126.9		2640.5	1873.2	1179.4
CP (CAL/GM-DEG.K)	0.32559		0.32364	0.31648	0.29467
MOL. WT.-EFFECTIVE	29.484		32.437	32.656	32.656
CP/CV -EFFECTIVE	1.2610		1.2335	1.2380	1.2603
CF -APPROX.			1.6813	1.9203	2.0846
PEAE/M (SEC)			25.119	15.498	8.9881
AE/AT -APPROX.			10.257	46.500	269.68
FROZEN EQUILIBRIA					
ISP (SEC)			260.23	292.95	313.48
TEMPERATURE (K)	4126.9		1683.5	972.26	433.15
C* (FT/SEC)	5361.6				
CF			1.5616	1.7579	1.8811
PEAE/M (SEC)			18.970	9.7322	4.0518
AE/AT			7.7459	29.200	121.57

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4126.9	2640.5	1873.2	1179.4
ENTHALPY (KILOCALORIES)	52.098	-38.124	-65.592	-86.594
ENTROPY (CALORIES/DEG.K)	214.78	214.78	214.78	214.78
HEAT CAPACITY (CAL/K)	32.559	32.364	31.648	29.467
MOLES OF GAS	3.3917	3.0829	3.0622	3.0622
MOLECULAR COMPOSITION:				
C	0.0000	0.0000	0.0000	0.0000
N	0.0006	0.0000	0.0000	0.0000
O	0.1466	0.0052	0.0000	0.0000
CO	1.5162	1.0408	1.0046	1.0046
CO2	0.3771	0.8526	0.8887	0.8888
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
O2	0.1228	0.0112	0.0000	0.0000
N2	1.1088	1.1646	1.1688	1.1689
NC	0.1195	0.0085	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		15.000			
NF3		85.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
NF3	NF3		-32.000	1.532	144.00
ATOMIC COMPOSITION (GM AT/100GM)					
C		0.7889			
N		1.5915			
F		3.5911			
PROPELLANT ENTHALPY		-15.033	KCAL/100 GM		
PROPELLANT DENSITY		1.410	GM/CC	0.0509	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			231.73	269.23	300.60
IVSP (LB-SEC/CU IN)			11.801	13.711	15.308
TEMPERATURE (K)		3679.5	2706.5	2373.8	1969.2
CP (CAL/GM-DEG.K)		0.29957	0.29837	0.29746	0.29538
MOL. WT.-EFFECTIVE		40.393	45.500	47.654	49.362
CP/CV -EFFECTIVE		1.1965	1.1715	1.1630	1.1578
CF -APPROX.			1.6917	1.9654	2.1944
PEAF/M (SEC)			22.192	15.996	11.474
AE/AT -APPROX.			11.024	58.386	418.79
FROZEN EQUILIBRIA					
ISP (SEC)			218.65	249.33	270.42
TEMPERATURE (K)		3679.5	1820.2	1247.9	766.41
C* (FT/SEC)		4407.3			
CF			1.5962	1.8201	1.9741
PEAF/M (SEC)			17.818	10.713	6.0661
AE/AT			8.8508	39.104	221.42

TABLE 91

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3679.5	2706.5	2373.8	1969.2
ENTHALPY (KILOCALORIES)	-15.033	-76.748	-98.339	-118.88
ENTROPY (CALORIES/DEG.K)	171.54	171.54	171.54	171.54
HEAT CAPACITY (CAL/K)	29.957	29.837	29.746	29.538
MOLES OF GAS	2.4757	2.1978	2.0984	2.0259
MOLECULAR COMPOSITION:				
C	0.0000	0.0000	0.0000	0.0000
N	0.0001	0.0000	0.0000	0.0000
F	0.8918	0.6132	0.5138	0.4412
CF	0.0011	0.0000	0.0000	0.0000
CF2	0.0344	0.0036	0.0006	0.0000
CF3	0.3705	0.1697	0.0770	0.0056
CF4	0.3789	0.6154	0.7112	0.7832
CN	0.0039	0.0002	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
N2	0.7937	0.7956	0.7957	0.7957
F2	0.0012	0.0001	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 92

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		13.000			
CLF3		87.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
CLF3	CLF3		-44.400	1.810	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
C		0.6837			
N		0.3418			
F		2.6229			
CL		0.9410			
PROPELLANT ENTHALPY		-21.610	KCAL/100 GM		
PROPELLANT DENSITY		1.627	GM/CC	0.0588	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			202.73	235.07	261.29
IVSP(LB-SEC/CU IN)			11.916	13.817	15.358
TEMPERATURE (K)		3403.8	2432.3	2060.5	1695.7
CP (CAL/GM-DEG.K)		0.24534	0.24489	0.24352	0.24042
MOL. WT.-EFFECTIVE		48.968	53.672	55.788	58.737
CP/CV -EFFECTIVE		1.1982	1.1781	1.1713	1.1638
CF -APPROX.			1.6951	1.9655	2.1847
PEAE/M (SEC)			19.326	13.584	9.5523
AE/AT -APPROX.			10.996	56.791	399.35
FROZEN EQUILIBRIA					
ISP (SEC)			190.82	219.99	237.87
TEMPERATURE (K)		3403.8	1677.6	1101.9	684.76
C* (FT/SEC)		3848.0			
CF			1.5955	1.8394	1.9889
PEAE/M (SEC)			15.522	8.8437	5.0827
AE/AT			8.8310	36.972	212.49

TABLE 93

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3403.8	2432.3	2060.5	1695.7
ENTHALPY (KILOCALORIES)	-21.610	-68.845	-85.117	-100.07
ENTROPY (CALORIES/DEG.K)	141.62	141.62	141.62	141.62
HEAT CAPACITY (CAL/K)	24.534	24.489	24.352	24.042
MOLES OF GAS	2.0422	1.8632	1.7925	1.7025
MOLECULAR COMPOSITION:				
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
F	0.3264	0.1320	0.0830	0.0631
CL	0.7360	0.7971	0.7549	0.6033
CF	0.0003	0.0000	0.0000	0.0000
CF2	0.0139	0.0004	0.0000	0.0000
CF3	0.2526	0.0580	0.0087	0.0002
CF4	0.4162	0.6253	0.6750	0.6835
CN	0.0007	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
N2	0.1706	0.1709	0.1709	0.1709
F2	0.0003	0.0000	0.0000	0.0000
CL2	0.0799	0.0645	0.0862	0.1562
CLF	0.0452	0.0148	0.0138	0.0252
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 94

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		35.000			
CLO3F		65.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
CLO3F	CLO3F		-10.100	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
C		1.8407			
N		0.9204			
O		1.9032			
F		0.6344			
CL		0.6344			
PROPELLANT ENTHALPY		47.894	KCAL/100 GM		
PROPELLANT DENSITY		1.226	GM/CC	0.0443	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			251.25	287.32	315.12
IVSP(LB-SEC/CU IN)			11.133	12.732	13.963
TEMPERATURE (K)		3423.8	2187.8	1756.9	1343.0
CP (CAL/GM-DEG.K)		0.27373	0.27039	0.26690	0.26029
MOL. WT.-EFFECTIVE		29.354	34.075	35.849	37.561
CP/CV -EFFECTIVE		1.3286	1.2750	1.2621	1.2551
CF -APPROX.			1.6823	1.9238	2.1099
PEAE/M (SEC)			22.093	14.747	9.8098
AE/AT -APPROX.			10.066	49.370	328.41
FROZEN EQUILIBRIA					
ISP (SEC)			231.29	255.80	267.68
TEMPERATURE (K)		3423.8	1167.4	609.47	298.16
C* (FT/SEC)		4805.2			
CF			1.5486	1.7128	1.7922
PEAE/M (SEC)			14.867	7.0175	3.2808
AE/AT			6.7736	23.493	109.83

TABLE 95

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3423.8	2187.8	1756.9	1343.0
ENTHALPY (KILOCALORIES)	47.894	-24.654	-46.983	-66.230
ENTROPY (CALORIES/DEG.K)	194.42	194.42	194.42	194.42
HEAT CAPACITY (CAL/K)	27.373	27.039	26.690	26.029
MOLES OF GAS	3.4067	2.9347	2.7894	2.6623
MOLECULAR COMPOSITION:				
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0010	0.0000	0.0000	0.0000
F	0.4960	0.0657	0.0043	0.0000
CL	0.5538	0.4890	0.3310	0.0882
CO	1.7236	1.4998	1.4646	1.4611
CO2	0.0661	0.1113	0.1313	0.1536
N2	0.4602	0.4602	0.4602	0.4602
CL2	0.0256	0.0664	0.1502	0.2731
CLF	0.0293	0.0127	0.0030	0.0001
CF	0.0000	0.0000	0.0000	0.0000
CF2	0.0001	0.0000	0.0000	0.0000
CF3	0.0019	0.0009	0.0002	0.0000
CF4	0.0026	0.0478	0.0686	0.0911
COF2	0.0464	0.1809	0.1760	0.1348
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 96

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NO2CLO4		61.000			
C4N2		39.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NO2CLO4	NO2CLO4		8.0000	2.220	298.16
C4N2	C4N2		118.00	0.9700	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
C		2.0511			
N		1.4449			
O		2.5161			
CL		0.4193			
PROPELLANT ENTHALPY		63.863	KCAL/100 GM		
PROPELLANT DENSITY		1.477	GM/CC	0.0534	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			276.22	310.78	336.00
IVSP(LB-SEC/CU IN)			14.745	16.590	17.936
TEMPERATURE (K)		4272.3	2207.6	1621.9	1095.5
CP (CAL/GM-DEG.K)		0.29825	0.29076	0.28392	0.26600
MOL. WT.-EFFECTIVE		29.636	31.610	32.674	33.466
CP/CV -EFFECTIVE		1.2900	1.2759	1.2726	1.2874
CF -APPROX.			1.6464	1.8525	2.0028
PEAF/M (SEC)			21.860	13.809	8.4232
AE/AT -APPROX.			8.8664	41.154	251.04
FROZEN EQUILIBRIA					
ISP (SEC)			259.90	292.82	309.51
TEMPERATURE (K)		4272.3	1614.9	854.13	381.86
C* (FT/SEC)		5397.7			
CF			1.5492	1.7454	1.8449
PEAE/M (SEC)			18.127	8.5096	3.5992
AE/AT			7.3522	25.362	107.27

TABLE 97

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4272.3	2207.6	1621.9	1095.5
ENTHALPY (KILOCALORIES)	63.863	-23.821	-47.139	-65.887
ENTROPY (CALORIES/DEG.K)	206.55	206.55	206.55	206.55
HEAT CAPACITY (CAL/K)	29.825	29.076	28.392	26.600
MOLES OF GAS	3.3743	3.1636	3.0605	2.9881
MOLECULAR COMPOSITION:				
C	0.0000	0.0000	0.0000	0.0000
N	0.0008	0.0000	0.0000	0.0000
O	0.1108	0.0000	0.0000	0.0000
CL	0.4129	0.3606	0.1545	0.0098
CO	1.6438	1.5863	1.5862	1.5862
CO2	0.2073	0.4648	0.4649	0.4649
O2	0.0422	0.0000	0.0000	0.0000
N2	0.6918	0.7224	0.7224	0.7224
NO	0.0604	0.0001	0.0000	0.0000
CL2	0.0022	0.0294	0.1324	0.2048
CLO	0.0020	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 98

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
C4N2		17.000			
NH4CLO4		83.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
C4N2	C4N2		118.00	0.9700	298.16
NH4CLO4	NH4CLO4		-69.420	1.960	298.16
ATOMIC COMPOSITION (GM AT/100GM)					
H		2.8256			
C		0.8941			
N		1.1534			
O		2.8256			
CL		0.7064			
PROPELLANT ENTHALPY		-22.663	KCAL/100 GM		
PROPELLANT DENSITY		1.670	GM/CC	0.0603	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			255.85	292.90	319.24
IVSP (LB-SEC/CU IN)			15.439	17.675	19.264
TEMPERATURE (K)		3263.6	2096.2	1532.0	986.87
CP (CAL/GM-DEG.K)		0.38362	0.36814	0.35114	0.31682
MOL. WT.-EFFECTIVE		28.592	30.666	30.892	30.895
CP/CV -EFFECTIVE		1.2213	1.2136	1.2243	1.2547
CF -APPROX.			1.6808	1.9242	2.0972
PEAE/M (SEC)			23.098	14.639	8.6509
AE/AT -APPROX.			10.326	48.086	284.16
FROZEN EQUILIBRIA					
ISP (SEC)			240.25	273.14	293.56
TEMPERATURE (K)		3263.6	1466.4	884.75	428.46
C* (FT/SEC)		4897.4			
CF			1.5783	1.7944	1.9286
PEAE/M (SEC)			18.457	9.7949	4.4135
AE/AT			8.2510	32.174	144.97

TABLE 99

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATUPE (KELVIN)	3263.6	2096.2	1532.0	986.87
ENTHALPY (KILOCALORIES)	-22.663	-97.895	-121.26	-139.79
ENTROPY (CALORIES/DEG.K)	221.40	221.40	221.40	221.40
HEAT CAPACITY (CAL/K)	38.362	36.814	35.114	31.682
MOLES OF GAS	3.4975	3.2609	3.2371	3.2368
MOLECULAR COMPOSITION:				
H	0.0199	0.0006	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0190	0.0002	0.0000	0.0000
CL	0.0981	0.0200	0.0006	0.0000
H2	0.0702	0.0115	0.0072	0.0142
H2O	0.9714	1.0544	1.0527	1.0454
HCL	0.6083	0.6864	0.7058	0.7064
CO	0.3184	0.0444	0.0153	0.0079
CO2	0.5757	0.8496	0.8788	0.8861
O2	0.1058	0.0094	0.0090	0.0000
OH	0.1142	0.0066	0.0000	0.0000
N2	0.5570	0.5758	0.5767	0.5767
NO	0.0395	0.0019	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 100

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
B5H9		38.000			
O2		62.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
B5H9	B5H9		7.7400	0.6230	298.16
O2	O2		-3.0800	1.142	90.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.4138			
B		3.0077			
O		3.6750			
PROPELLANT ENTHALPY		-1.3116	KCAL/100 GM		
PROPELLANT DENSITY		0.6674	GM/CC	0.0313	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		316.12	364.22	404.35
IVSP(LB-SEC/CU IN)		9.9069	11.414	12.672
TEMPERATURE (K)	3771.8	2498.2	2030.2	1816.4
CP (CAL/GM-DEG.K)	0.59724	0.57859	0.56741	0.57307
MOL. WT.-EFFECTIVE	21.843	23.437	23.988	25.524
CP/CV -EFFECTIVE	1.1797	1.1717	1.1710	1.1572
CF -APPROX.		1.6676	1.9214	2.1330
PEAF/M (SEC)		29.153	20.090	15.216
AE/AT -APPROX.		10.465	52.089	401.33
FROZEN EQUILIBRIA				
ISP (SEC)		304.11	348.68	379.30
TEMPERATURE (K)	3771.8	1946.1	1355.3	822.82
C* (FT/SEC)	6099.1			
CF		1.6042	1.8394	2.0009
PEAF/M (SEC)		25.330	15.159	8.5864
AE/AT		9.0922	39.983	226.48

TABLE 101

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3771.8	2498.2	2030.2	1816.4
ENTHALPY (KILOCALORIES)	-1.3116	-116.16	-155.77	-189.22
ENTROPY (CALORIES/DEG.K)	296.86	296.86	296.86	296.86
HEAT CAPACITY (CAL/K)	59.724	57.859	56.741	57.307
MOLES OF GAS	4.5782	4.2667	4.1686	3.9179
MOLECULAR COMPOSITION:				
H	0.3917	0.0784	0.0169	0.0109
B	0.0170	0.0003	0.0000	0.0000
O	0.0002	0.0000	0.0000	0.0000
H2	2.1007	2.3270	2.3688	2.4528
H20	0.0198	0.0024	0.0007	0.0002
02	0.0000	0.0000	0.0000	0.0000
OH	0.0021	0.0000	0.0000	0.0000
BO	0.3237	0.0334	0.0039	0.0015
B202	0.8575	0.9601	0.8067	0.6449
B203	0.0865	0.1886	0.3138	0.3107
HB02	0.7772	0.6765	0.6578	0.4968
H3B03	0.0000	0.0000	0.0000	0.0000
H3B306	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0016	0.0000	0.0000	0.000
CONDENSED PHASES				
B203/L/	0	0	0	0.2192
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0.1049	0.1596

TABLE 102

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
F2		80.000			
B5H9		20.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
F2	F2		-3.4670	1.510	85.200
B5H9	B5H9		7.7400	0.6230	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.8494			
B		1.5830			
F		4.2105			
PROPELLANT ENTHALPY		-4.6485	KCAL/100 GM		
PROPELLANT DENSITY		1.175	GM/CC	0.0425	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		358.32	408.94	449.41
IVSP(LB-SEC/CU IN)		15.216	17.365	19.084
TEMPERATURE (K)	4991.0	3105.2	2532.4	2102.5
CP (CAL/GM-DEG.K)	0.40507	0.38897	0.38494	0.38263
MOL. WT.-EFFECTIVE	21.312	24.195	25.584	27.270
CP/CV -EFFECTIVE	1.2990	1.2677	1.2528	1.2353
CF -APPROX.		1.6798	1.9172	2.1069
PEAE/M (SEC)		30.967	20.927	14.832
AE/AT -APPROX.		9.8788	49.054	347.68
FROZEN EQUILIBRIA				
ISP (SEC)		329.10	368.22	388.36
TEMPERATURE (K)	4991.0	1819.6	977.05	460.08
C* (FT/SEC)	6862.8			
CF (SEC)		1.5428	1.7262	1.8208
PEAE/M (SEC)		22.430	10.764	4.8057
AE/AT		7.1554	25.232	112.65

TABLE 103

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4991.0	3105.2	2532.4	2102.5
ENTHALPY (KILOCALORIES)	-4.8485	-152.40	-197.04	-236.96
ENTROPY (CALORIES/DEG.K)	270.61	270.61	270.61	270.61
HEAT CAPACITY (CAL/K)	40.507	38.897	38.494	38.263
MOLES OF GAS	4.6922	4.1331	3.9086	3.6671
MOLECULAR COMPOSITION:				
H	0.6675	0.2436	0.1120	0.0453
B	0.0022	0.0000	0.0000	0.0000
F	0.4208	0.0114	0.0008	0.0000
H2	0.1610	0.3107	0.5245	0.7653
HF	1.8599	1.9844	1.6883	1.2734
F2	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0000	0.0000	0.0000	0.0000
BF	1.3274	1.1748	1.0144	0.8064
BF2	0.1577	0.1846	0.1987	0.1990
BF3	0.0956	0.2236	0.3698	0.5776
CONDENSED PHASES				
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 104

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
OF2		81.500			
B5H9		18.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
OF2	OF2		3.6000	1.530	128.00
B5H9	B5H9		7.7400	0.6230	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.6357			
B		1.4642			
O		1.5092			
F		3.0185			
PROPELLANT ENTHALPY		7.7000	KCAL/100 GM		
PROPELLANT DENSITY		1.205	GM/CC	0.0435	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		366.00	421.50	465.58
IVSP(LB-SEC/CU IN)		15.939	18.356	20.276
TEMPERATURE (K)	5215.3	3567.0	2970.2	2339.1
CP (CAL/GM-DEG.K)	0.41812	0.40810	0.40194	0.39248
MOL. WT.-EFFECTIVE	22.175	25.136	26.395	27.604
CP/CV -EFFECTIVE	1.2728	1.2403	1.2305	1.2246
CF -APPROX.		1.6999	1.9577	2.1624
PEAE/M (SEC)		33.522	23.082	15.736
AE/AT -APPROX.		10.594	53.604	365.43
FROZEN EQUILIBRIA				
ISP (SEC)		334.94	376.16	399.81
TEMPERATURE (K)	5215.3	2055.8	1190.0	609.23
C* (FT/SEC)	6927.2			
CF		1.5556	1.7471	1.8569
PEAE/M (SEC)		23.931	12.335	5.9411
AE/AT		7.5633	28.645	137.97

TABLE 105

TABLE 106

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	5215.3	3567.0	2970.2	2339.1
ENTHALPY (KILOCALORIES)	7.7000	-146.25	-196.48	-241.42
ENTROPY (CALORIES/DEG.K)	273.76	273.76	273.76	273.76
HEAT CAPACITY (CAL/K)	41.812	40.810	40.194	39.248
MOLES OF GAS	4.5096	3.9783	3.7886	3.6227
MOLECULAR COMPOSITION:				
H	0.8985	0.6263	0.4094	0.1260
B	0.0015	0.0000	0.0000	0.0000
O	0.2543	0.0564	0.0120	0.0003
F	0.3643	0.0644	0.0126	0.0006
H2	0.1875	0.2116	0.2924	0.4298
H2O	0.0222	0.0229	0.0311	0.0355
HF	1.2067	1.4967	1.5521	1.5644
O2	0.0121	0.0024	0.0005	0.0000
OH	0.0999	0.0333	0.0142	0.0017
F2	0.0000	0.0000	0.0000	0.0000
BF	0.3383	0.0763	0.0237	0.0041
BF2	0.0207	0.0045	0.0016	0.0006
BF3	0.0062	0.0018	0.0009	0.0008
BOF	1.0491	1.3666	1.4243	1.4459
BO	0.0370	0.0046	0.0009	0.0000
B2O2	0.0001	0.0000	0.0000	0.0000
B2O3	0.0000	0.0000	0.0000	0.0000
HBO2	0.0111	0.0103	0.0128	0.0128
CONDENSED PHASES				
B2O3/GL/	0	0	0	0
B2O3/L/	0	0	0	0
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
B5H9		40.000			
H2O2		60.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
B5H9	B5H9		7.7400	0.6230	298.16
H2O2	H2O2		-44.840	1.443	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		9.2265			
B		3.1660			
O		3.5278			
PROPELLANT ENTHALPY		-74.191	KCAL/100 GM		
PROPELLANT DENSITY		0.9453	GM/CC	0.0342	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		302.98	353.66	396.78
IVSP(LB-SEC/CU IN)		10.348	12.079	13.552
TEMPERATURE (K)	2684.9	2050.8	1824.8	1576.6
CP (CAL/GM-DEG.K)	0.76354	0.77004	0.77085	0.76735
MOL. WT.-EFFECTIVE	17.704	19.616	20.510	21.344
CP/CV -EFFECTIVE	1.1723	1.1515	1.1438	1.1381
CF -APPROX.		1.7016	1.9862	2.2284
PEAE/M (SEC)		29.833	21.750	16.094
AE/AT -APPROX.		11.401	61.079	451.96
FROZEN EQUILIBRIA				
ISP (SEC)		286.19	327.36	355.38
TEMPERATURE (K)	2684.9	1407.0	976.85	636.07
C* (FT/SEC)	5728.7			
CF		1.6073	1.8387	1.9959
PEAE/M (SEC)		24.010	14.571	8.7407
AE/AT		9.1756	40.919	245.45

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2684.9	2050.8	1824.8	1576.6
ENTHALPY (KILOCALORIES)	-74.191	-179.69	-217.93	-255.12
ENTROPY (CALORIES/DEG.K)	325.06	325.06	325.06	325.06
HEAT CAPACITY (CAL/K)	76.354	77.004	77.085	76.735
MOLES OF GAS	5.6484	5.0977	4.8756	4.6850
MOLECULAR COMPOSITION:				
H	0.0310	0.0108	0.0056	0.0017
B	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
H2	4.0552	4.3814	4.4834	4.5713
H2O	0.0121	0.0014	0.0005	0.0001
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0000	0.0000	0.0000	0.0000
BO	0.0072	0.0009	0.0002	0.0000
B2O2	0.3675	0.1809	0.0898	0.0186
B2O3	0.1145	0.0723	0.0430	0.0114
HBO2	1.0606	0.4500	0.2532	0.0820
H3O3	0.0000	0.0000	0.0000	0.0000
H3B3O6	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
B2O3/L/	0.1027	0.6822	0.9040	1.0974
B/LIQUID/	0.9284	0	0	0
B/SOLID/	0	0.8442	0.6389	0.8291

TABLE 108

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
N2O4		75.500			
B5H9		24.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
N2O4	N2O4		-5.4000	1.430	298.16
B5H9	B5H9		7.7400	0.6230	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.4905			
B		1.9392			
N		1.6410			
O		3.2820			
PROPELLANT ENTHALPY		-1.4289	KCAL/100 GM		
PROPELLANT DENSITY		1.086	GM/CC	0.0392	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		304.09	350.34	387.39
IVSP(LB-SEC/CU IN)		11.926	13.740	15.193
TEMPERATURE (K)	4114.6	2722.2	2164.1	1820.4
CP (CAL/GM-DEG.K)	0.49659	0.48456	0.47498	0.47074
MOL. WT.-EFFECTIVE	25.619	27.645	28.152	29.336
CP/CV -EFFECTIVE	1.1851	1.1742	1.1746	1.1681
CF -APPROX.		1.6661	1.9195	2.1225
PEAE/M (SEC)		27.997	19.146	13.849
AE/AT -APPROX.		10.438	52.450	379.40
FROZEN EQUILIBRIA				
ISP (SEC)		292.36	334.82	363.96
TEMPERATURE (K)	4114.6	2095.8	1434.3	878.09
C* (FT/SEC)	5872.2			
CF		1.6016	1.8344	1.9942
PEAE/M (SEC)		24.191	14.457	8.1416
AE/AT		9.0190	39.605	223.04

TABLE 109

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4114.6	2722.2	2164.1	1820.4
ENTHALPY (KILOCALORIES)	-1.4289	-107.70	-142.49	-173.90
ENTROPY (CALORIES/DEG.K)	267.34	267.34	267.34	267.34
HEAT CAPACITY (CAL/K)	49.659	48.458	47.498	47.074
MOLES OF GAS	3.9033	3.6173	3.5522	3.4088
MOLECULAR COMPOSITION:				
H	0.4302	0.1224	0.0286	0.0074
B	0.0037	0.0001	0.0000	0.0000
N	0.0006	0.0000	0.0000	0.0000
O	0.0054	0.0000	0.0000	0.0000
H2	0.8693	1.0930	1.1883	1.2186
H2O	0.0603	0.0101	0.0028	0.0012
O2	0.0002	0.0000	0.0000	0.0000
OH	0.0199	0.0003	0.0000	0.0000
N2	0.8179	0.8205	0.8205	0.7914
NO	0.0036	0.0000	0.0000	0.0000
BN	0.0000	0.0000	0.0000	0.0000
BO	0.2671	0.0411	0.0051	0.0005
B2O2	0.1666	0.1972	0.1668	0.0619
B2O3	0.0777	0.1711	0.2604	0.2844
HBO2	1.1795	1.1614	1.0796	1.0434
H3B03	0.0000	0.0000	0.0000	0.0000
H3B3O6	0.0000	0.0000	0.0000	0.0000
NH	0.0008	0.0000	0.0000	0.0000
NH2	0.0003	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0002	0.0000	0.0000	0.0000
CONDENSED PHASES				
B2O3/L/	0	0	0	0.0721
BN/SOLID/	0	0	0	0.0583
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 110

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NF3		87.000			
B5H9		13.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NF3	NF3		-32.000	1.532	144.00
B5H9	B5H9		7.7400	0.6230	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		1.8521			
B		1.0289			
N		1.2252			
F		3.6756			
PROPELLANT ENTHALPY		-37.614	KCAL/100 GM		
PROPELLANT DENSITY		1.288	GM/CC	0.0465	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			326.21	373.36	410.50
IVSP(LB-SEC/CU IN)			15.177	17.371	19.099
TEMPERATURE (K)		4809.1	3154.5	2500.5	2040.9
CP (CAL/GM-DEG.K)		0.36514	0.35402	0.34957	0.34707
MOL. WT.-EFFECTIVE		25.405	28.767	29.996	31.710
CP/CV -EFFECTIVE		1.2726	1.2424	1.2338	1.2204
CF -APPROX.			1.6887	1.9328	2.1251
PEAE/M (SEC)			29.063	19.304	13.555
AE/AT -APPROX.			10.238	49.965	350.87
FROZEN EQUILIBRIA					
ISP (SEC)			300.37	337.86	359.00
TEMPERATURE (K)		4809.1	1889.0	1072.8	520.08
C* (FT/SEC)		6215.1			
CF (SEC)			1.5550	1.7490	1.8585
PEAE/M (SEC)			21.402	10.807	4.9302
AE/AT			7.5390	27.972	127.61

TABLE III

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4809.1	3154.5	2500.5	2040.9
ENTHALPY (KILOCALORIES)	-37.614	-159.91	-197.82	-231.28
ENTROPY (CALORIES/DEG.K)	241.01	241.01	241.01	241.01
HEAT CAPACITY (CAL/K)	36.514	35.402	34.957	34.707
MOLES OF GAS	3.9363	3.4762	3.3338	3.1536
MOLECULAR COMPOSITION:				
H	0.2360	0.0988	0.0499	0.0189
B	0.0004	0.0000	0.0000	0.0000
N	0.0039	0.0000	0.0000	0.0000
F	0.4776	0.0285	0.0009	0.0000
H2	0.0366	0.0460	0.1608	0.3401
HF	1.5422	1.6614	1.4806	1.1529
N2	0.6104	0.6126	0.6126	0.6126
NH	0.0005	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0000	0.0000	0.0000	0.0000
BN	0.0000	0.0000	0.0000	0.0000
BF	0.6318	0.4717	0.3757	0.2256
BF2	0.1664	0.1576	0.1413	0.1130
BF3	0.2304	0.3996	0.5119	0.6904
CONDENSED PHASES				
BN/SOLID/	0	0	0	0
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 112

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CLF3		89.000			
B5H9		11.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CLF3	CLF3		-44.400	1.810	298.16
B5H9	B5H9		7.7400	0.6230	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		1.5671			
B		0.8706			
F		2.8878			
CL		0.9626			
PROPELLANT ENTHALPY		-41.392	KCAL/100 GM		
PROPELLANT DENSITY		1.496	GM/CC	0.0541	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			289.44	332.43	367.58
IVSP(LB-SEC/CU IN)			15.648	17.972	19.873
TEMPERATURE (K)		4042.0	3007.2	2554.6	2159.6
CP (CAL/GM-DEG.K)		0.29781	0.29063	0.28803	0.28500
MOL. WT.-EFFECTIVE		30.205	34.688	36.846	39.222
CP/CV -EFFECTIVE		1.2836	1.2455	1.2304	1.2162
CF -APPROX.			1.6862	1.9367	2.1415
PEAE/M (SEC)			25.896	18.032	12.951
AE/AT -APPROX.			10.266	52.525	377.24
FROZEN EQUILIBRIA					
ISP (SEC)			266.18	299.24	316.62
TEMPERATURE (K)		4542.0	1736.5	985.66	504.13
C* (FT/SEC)		5522.6			
CF			1.5507	1.7434	1.8443
PEAE/M (SEC)			18.674	9.4281	4.5573
AE/AT			7.4029	27.464	132.77

TABLE 113

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.200
TEMPERATURE (KELVIN)	4542.0	3007.2	2554.6	2159.
ENTHALPY (KILOCALORIES)	-41.392	-137.67	-168.40	-196.6
ENTROPY (CALORIES/DEG.K)	201.36	201.36	201.36	201.36
HEAT CAPACITY (CAL/K)	29.781	29.063	28.803	28.500
MOLES OF GAS	3.3107	2.8828	2.7140	2.5496
MOLECULAR COMPOSITION:				
H	0.1325	0.0430	0.0235	0.011
B	0.0001	0.0000	0.0000	0.000
F	0.2176	0.0109	0.0018	0.000
CL	0.6771	0.4578	0.3014	0.145
H2	0.0272	0.0248	0.0275	0.034
HCL	0.2430	0.4638	0.6191	0.778
HF	1.1372	1.0107	0.8696	0.708
F2	0.0000	0.0000	0.0000	0.000
CL2	0.0038	0.0011	0.0005	0.0001
CLF	0.0015	0.0000	0.0000	0.0000
BCL	0.0006	0.0000	0.0000	0.0000
BCL2	0.0001	0.0000	0.0000	0.0000
BCL3	0.0000	0.0000	0.0000	0.0000
BF	0.4488	0.2901	0.2218	0.1524
BF2	0.1422	0.1237	0.1087	0.0890
BF3	0.2478	0.4201	0.5012	0.5929
BFCL	0.0057	0.0029	0.0020	0.0011
BF2CL	0.0238	0.0318	0.0348	0.0333
BFCL2	0.0014	0.0019	0.0021	0.0019
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 114

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CL03F		77.000			
B5H9		23.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CL03F	CL03F		-10.100	1.430	298.16
B5H9	B5H9		7.7400	0.6230	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.2768			
B		1.8204			
O		2.2546			
F		0.7515			
CL		0.7515			
PROPELLANT ENTHALPY		-4.7725	KCAL/100 GM		
PROPELLANT DENSITY		1.102	GM/CC	0.0398	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			302.86	348.71	384.85
IVSP(LB-SEC/CU IN)			12.056	13.881	15.32
TEMPERATURE (K)	4254.2		2820.6	2301.2	1779.2
CP (CAL/GM-DEG.K)	0.42590		0.41564	0.40866	0.39952
MOL. WT.-EFFECTIVE	26.388		29.081	29.956	30.652
CP/CV -EFFECTIVE	1.2148		1.1968	1.1938	1.1937
CF -APPROX.			1.6710	1.9240	2.1234
PEAE/M (SEC)			27.688	19.047	13.040
AE/AT -APPROX.			10.395	52.534	359.73
FROZEN EQUILIBRIA					
ISP (SEC)			287.22	326.43	352.01
TEMPERATURE (K)	4254.2		1978.9	1275.5	733.04
C* (FT/SEC)	5831.4				
CF			1.5847	1.6010	1.9422
PEAF/M (SEC)			22.574	12.802	6.8229
AE/AT			8.4750	35.317	188.22

TABLE 115

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4254.2	2820.6	2301.2	1779.2
ENTHALPY (KILOCALORIES)	-4.7725	-116.19	-144.52	-174.99
ENTROPY (CALORIES/DEG.K)	248.07	248.07	248.07	248.07
HEAT CAPACITY (CAL/K)	42.590	41.564	40.866	39.952
MOLES OF GAS	3.7896	3.4386	3.3382	3.2624
MOLECULAR COMPOSITION:				
H	0.5079	0.1604	0.0492	0.0049
B	0.0063	0.0003	0.0000	0.0000
O	0.0062	0.0000	0.0000	0.0000
F	0.0004	0.0000	0.0000	0.0000
CL	0.1838	0.0611	0.0190	0.0018
H2	0.6002	0.9744	1.0436	1.1276
H2O	0.0399	0.0053	0.0014	0.0002
HCL	0.5080	0.6522	0.7058	0.7119
HF	0.0227	0.0030	0.0006	0.0001
O2	0.0001	0.0000	0.0000	0.0000
OH	0.0179	0.0003	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0004	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
BCL	0.0173	0.0076	0.0033	0.0006
BCL2	0.0010	0.0010	0.0010	0.0010
BCL3	0.0001	0.0004	0.0011	0.0091
BF	0.1700	0.1299	0.0957	0.0512
BF2	0.0002	0.0000	0.0000	0.0000
BF3	0.0000	0.0000	0.0000	0.0000
BFCL	0.0009	0.0003	0.0002	0.0002
BF2CL	0.0000	0.0000	0.0000	0.0000
BFCL2	0.0001	0.0001	0.0001	0.0003
BOCL	0.0380	0.0269	0.0176	0.0069
BOF	0.5569	0.6182	0.6546	0.6997
BO	0.2525	0.0569	0.0117	0.0005
B2O2	0.0922	0.1718	0.1987	0.1810
B2O3	0.0262	0.0669	0.1032	0.1610
HBO2	0.5399	0.5013	0.4310	0.3042
CONDENSED PHASES				
B2O3/L/	0	0	0	0.0313
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 116

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
B5H9		25.000			
NO2CLO4		75.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
B5H9	B5H9		7.7400	0.6230	298.16
NO2CLO4	NO2CLO4		8.0000	2.220	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.5617			
B		1.9787			
N		0.5156			
O		3.0935			
CL		0.5156			
PROPELLANT ENTHALPY		7.1878	KCAL/100 GM		
PROPELLANT DENSITY		1.353	GM/CC	0.0489	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			299.85	346.15	383.40
IVSP(LB-SEC/CU IN)			14.658	16.921	18.741
TEMPERATURE (K)		4175.0	2817.8	2328.5	1876.4
CP (CAL/GM-DEG.K)		0.46610	0.45584	0.44832	0.43861
MOL. WT.-EFFECTIVE		26.728	29.212	30.032	30.873
CP/CV -EFFECTIVE		1.1898	1.1754	1.1732	1.1720
CF -APPROX.			1.6682	1.9258	2.1330
PEAF/M (SEC)			27.813	19.366	13.706
AE/AT -APPROX.			10.529	53.871	381.26
FROZEN EQUILIBRIA					
ISP (SEC)			287.41	328.47	356.43
TEMPERATURE (K)		4175.0	2095.5	1424.2	872.34
C* (FT/SEC)		5783.0			
CF			1.5990	1.8274	1.9830
PEAF/M (SEC)			23.584	14.026	7.9168
AE/AT			8.9285	39.017	220.23

TABLE 117

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4175.0	2817.8	2328.5	1876.4
ENTHALPY (KILOCALORIES)	7.1878	-96.146	-130.52	-161.75
ENTROPY (CALORIES/DEG.K)	255.38	255.38	255.38	255.38
HEAT CAPACITY (CAL/K)	46.610	45.584	44.832	43.861
MOLES OF GAS	3.7414	3.4232	3.3298	3.2391
MOLECULAR COMPOSITION:				
H	0.4532	0.1603	0.0572	0.0108
B	0.0064	0.0003	0.0000	0.0000
N	0.0004	0.0000	0.0000	0.0000
O	0.0053	0.0000	0.0000	0.0000
CL	0.1098	0.0408	0.0147	0.0028
H2	0.8274	0.9968	1.0721	1.1192
H2O	0.0466	0.0077	0.0025	0.0006
HCL	0.3520	0.4450	0.4828	0.5045
N2	0.2576	0.2578	0.2578	0.2310
BCL	0.0140	0.0048	0.0018	0.0003
BCL2	0.0006	0.0004	0.0003	0.0002
BCL3	0.0001	0.0001	0.0002	0.0005
BOCL	0.0383	0.0239	0.0150	0.0062
BO	0.3316	0.0740	0.0169	0.0014
B2O2	0.2142	0.2986	0.2939	0.1930
B2O3	0.0755	0.1652	0.2421	0.3619
HBO2	1.0084	0.9474	0.8725	0.8068
CONDENSED PHASES				
B2O3/L/	0	0	0	0
BN/SOLID/	0	0	0	0.0536
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 118

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
NH4CL04		78.000			
B5H9		22.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
NH4CL04	NH4CL04		-69.420	1.960	298.16
B5H9	B5H9		7.7400	0.6230	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.7897			
B		1.7413			
N		0.6638			
O		2.6554			
CL		0.6638			
PROPELLANT ENTHALPY		-43.389	KCAL/100 GM		
PROPELLANT DENSITY		1.331	GM/CC	0.0481	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			282.68	327.76	365.81
IVSP(LB-SEC/CU IN)			13.598	15.766	17.597
TEMPERATURE (K)		3109.2	2124.3	1874.7	1610.9
CP (CAL/GM-DEG.K)		0.53793	0.52608	0.53112	0.53571
MOL. WT.-EFFECTIVE		22.281	24.405	25.663	26.865
CP/CV -EFFECTIVE		1.1988	1.1831	1.1707	1.1602
CF -APPROX.			1.6684	1.9345	2.1591
PEAE/M (SEC)			26.623	19.270	14.172
AE/AT -APPROX.			10.692	56.868	418.22
FROZEN EQUILIBRIA					
ISP (SEC)			269.61	306.52	329.77
TEMPERATURE (K)		3109.2	1499.2	976.52	586.07
C* (FT/SEC)		5451.2			
CF			1.5913	1.8091	1.9464
PEAE/M (SEC)			21.577	12.362	6.8963
AE/AT			8.6658	36.482	203.51

TABLE 119

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3169.2	2124.3	1874.7	1610.9
ENTHALPY (KILOCALORIES)	-43.389	-135.22	-166.85	-197.18
ENTROPY (CALORIES/DEG.K)	270.86	270.86	270.86	270.86
HEAT CAPACITY (CAL/K)	53.793	52.608	53.112	53.571
MOLES OF GAS	4.4882	4.0975	3.8967	3.7223
MOLECULAR COMPOSITION:				
H	0.0814	0.0105	0.0052	0.0015
B	0.0004	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
CL	0.0130	0.0019	0.0009	0.0002
H2	2.1241	2.0794	2.2017	2.3638
H2O	0.0153	0.0046	0.0028	0.0017
HCL	0.5939	0.6526	0.6600	0.6631
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0002	0.0000	0.0000	0.0000
N2	0.3318	0.2071	0.2715	0.2806
NO	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
BN	0.0000	0.0000	0.0000	0.0000
BCL	0.0131	0.0002	0.0000	0.0000
BCL2	0.0035	0.0003	0.0000	0.0000
BCL3	0.0027	0.0012	0.0004	0.0001
BOCL	0.0287	0.0050	0.0016	0.0002
BO	0.0320	0.0008	0.0001	0.0000
B2O2	0.3294	0.0604	0.0143	0.0010
B2O3	0.0836	0.1149	0.0626	0.0159
HBO2	0.0347	0.9566	0.7154	0.3941
H3B03	0.0000	0.0000	0.0000	0.0000
H3B3O6	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
B2O3/L/	0	0.0874	0.3345	0.6051
BN/SOLID/	0	0.2497	0.2008	0.1027
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 120

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
ALH3		66.000			
O2		34.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
ALH3	ALH3		10.000	1.720	298.16
O2	O2		-3.0800	1.142	90.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		6.6013			
O		2.1250			
AL		2.2004			
PROPELLANT ENTHALPY		18.732	KCAL/100 GM		
PROPELLANT DENSITY		1.467	GM/CC	0.0530	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			310.32	358.96	399.30
IVSP(LB-SEC/CU IN)			16.453	19.032	21.171
TEMPERATURE (K)		3842.4	2577.1	2234.0	1740.4
CP (CAL/GM-DEG.K)		0.59317	0.56112	0.54097	0.51854
MOL. WT.-EFFECTIVE		23.320	24.971	25.162	25.850
CP/CV -EFFECTIVE		1.1678	1.1653	1.1710	1.1741
CF -APPROX.			1.6697	1.9314	2.1484
PEAE/M (SEC)			28.754	21.384	14.578
AE/AT -APPROX.			10.527	57.528	392.20
FROZEN EQUILIBRIA					
ISP (SEC)			299.04	343.59	373.40
TEMPERATURE (K)		3842.4	2035.9	1417.9	924.47
C* (FT/SEC)		5979.7			
CF (SEC)			1.6090	1.8487	2.0091
PEAE/M (SEC)			25.241	15.300	9.1790
AE/AT			9.2415	41.162	246.94

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3842.4	2577.1	2234.0	1740.4
ENTHALPY (KILOCALORIES)	18.732	-91.940	-129.36	-164.50
ENTROPY (CALORIES/DEG.K)	259.26	259.26	259.26	259.26
HEAT CAPACITY (CAL/K)	59.317	56.112	54.097	51.854
MOLES OF GAS	4.2882	4.0046	3.9742	3.8685
MOLECULAR COMPOSITION:				
H	0.5104	0.1252	0.0662	0.0065
O	0.0010	0.0000	0.0000	0.0000
AL	0.3088	0.2267	0.2207	0.1743
H2	2.9045	3.2265	3.2617	3.2933
H2O	0.1031	0.0023	0.0003	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0104	0.0000	0.0000	0.0000
ALH	0.0653	0.0186	0.0111	0.0082
ALO	0.0231	0.0004	0.0000	0.0000
AL2O	0.3560	0.4049	0.4141	0.3862
AL2O2	0.0055	0.0001	0.0000	0.0000
CONDENSED PHASES				
AL2O3/L/	0.5401	0.5724	0	0
AL2O3/C/	0	0	0.5702	0.5796
AL/LIQUID/	0	0	0	0.0864

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
F2		73.500			
ALH3		26.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
F2	F2		-3.4670	1.510	85.200
ALH3	ALH3		10.000	1.720	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.6505			
F		3.8684			
AL		0.8835			
PROPELLANT ENTHALPY		2.1292	KCAL/100 GM		
PROPELLANT DENSITY		1.560	GM/CC	0.0564	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			352.55	404.78	445.54
IVSP(LB-SEC/CU IN)			19.877	22.822	25.120
TEMPERATURE (K)		5316.6	3586.7	2938.7	2322.5
CP (CAL/GM-DEG.K)		0.35861	0.34319	0.33627	0.33016
MOL. WT.-EFFECTIVE		23.898	27.711	29.186	30.900
CP/CV -EFFECTIVE		1.3019	1.2642	1.2539	1.2419
CF -APPROX.			1.6970	1.9485	2.1447
PEAE/M (SEC)			31.742	21.506	14.585
AE/AT -APPROX.			10.397	51.762	351.04
FROZEN EQUILIBRIA					
ISP (SEC)			320.14	356.64	376.94
TEMPERATURE (K)		5316.6	1919.8	1060.2	506.74
C* (FT/SEC)		6683.8			
CF (SEC)			1.5411	1.7168	1.8145
PEAE/M (SEC)			21.694	10.755	4.8635
AE/AT			7.1060	25.886	117.06

TABLE 123

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	5316.6	3586.7	2938.7	2322.5
ENTHALPY (KILOCALORIES)	2.1292	-140.71	-186.17	-226.00
ENTROPY (CALORIES/DEG.K)	243.10	243.10	243.10	243.10
HEAT CAPACITY (CAL/K)	35.861	34.319	33.627	33.016
MOLES OF GAS	4.1844	3.6087	3.4262	3.2362
MOLECULAR COMPOSITION:				
H	0.7328	0.3783	0.2342	0.0913
F	0.7604	0.1529	0.0213	0.0008
AL	0.0229	0.0036	0.0011	0.0001
H2	0.1096	0.0782	0.1291	0.2986
HF	1.6979	2.1158	2.1581	1.9621
ALH	0.0005	0.0000	0.0000	0.0000
ALF	0.4394	0.3601	0.3163	0.2120
ALF2	0.2915	0.3198	0.3256	0.3205
ALF3	0.1291	0.2000	0.2405	0.3508
F2	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
ALF3/C/	0	0	0	0
AL/LIQUID/	0	0	0	0

TABLE 124

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
ALH3		32.000			
OF2		68.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
ALH3	ALH3		10.000	1.720	298.16
OF2	OF2		3.6000	1.530	128.00
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.2006			
O		1.2592			
F		2.5185			
AL		1.0669			
PROPELLANT ENTHALPY		15.202	KCAL/100 GM		
PROPELLANT DENSITY		1.586	GM/CC	0.0573	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		329.73	383.13	428.61
IVSP(LB-SEC/CU IN)		18.895	21.955	24.561
TEMPERATURE (K)	4574.2	3350.3	2984.9	2629.9
CP (CAL/GM-DEG.K)	0.38241	0.39276	0.39771	0.40056
MOL. WT.-EFFECTIVE	24.248	27.885	29.423	31.079
CP/CV -EFFECTIVE	1.2728	1.2217	1.2046	1.1900
CF -APPROX.		1.7100	1.9869	2.2227
PEAE/M (SEC)		31.504	22.892	17.069
AE/AT -APPROX.		11.117	59.360	442.60
FROZEN EQUILIBRIA				
ISP (SEC)		299.50	333.47	353.53
TEMPERATURE (K)	4574.2	1780.1	1050.6	559.95
C* (FT/SEC)	6204.1			
CF		1.5532	1.7294	1.8334
PEAE/M (SEC)		21.192	11.233	5.6475
AE/AT		7.4782	29.127	146.44

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4574.2	3350.3	2984.9	2629.9
ENTHALPY (KILOCALORIES)	15.202	-109.75	-153.50	-195.92
ENTROPY (CALORIES/DEG.K)	250.79	250.79	250.79	250.79
HEAT CAPACITY (CAL/K)	38.241	39.276	39.771	40.056
MOLES OF GAS	4.1241	3.5862	3.3987	3.2176
MOLECULAR COMPOSITION:				
H	0.5433	0.4223	0.3958	0.3540
O	0.3146	0.1519	0.0958	0.0368
F	0.0680	0.0224	0.0141	0.0064
AL	0.0291	0.0060	0.0028	0.0010
H2	0.3363	0.2920	0.2783	0.2805
H2O	0.2891	0.2894	0.2363	0.1731
HF	1.0456	1.4353	1.6645	1.8867
O2	0.1071	0.0592	0.0320	0.0100
OH	0.3596	0.1801	0.1110	0.0528
F2	0.0000	0.0000	0.0000	0.0000
ALH	0.0015	0.0001	0.0000	0.0000
ALF	0.5998	0.4998	0.3388	0.2477
ALF2	0.2683	0.2064	0.1638	0.1221
ALF3	0.0819	0.0704	0.0568	0.0442
ALOF	0.0226	0.0071	0.0031	0.0009
ALO	0.0509	0.0126	0.0051	0.0013
AL2O	0.0045	0.0009	0.0003	0.0001
AL2O2	0.0019	0.0003	0.0001	0.0000
CONDENSED PHASES				
ALF3/C/	0	0	0	0
AL2O3/L/	0	0.1661	0.2478	0.3247
AL2O3/C/	0	0	0	0
AL/LIQUID/	0	0	0	0

TABLE 126

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
ALH3		56.000			
H202		44.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
ALH3	ALH3		10.000	1.720	298.16
H202	H202		-44.840	1.443	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		8.1881			
O		2.5870			
AL		1.8670			
PROPELLANT ENTHALPY		-39.330	KCAL/100 GM		
PROPELLANT DENSITY		1.586	GM/CC	0.0573	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			323.92	375.64	421.38
IVSP(LB-SEC/CU IN)			18.562	21.525	24.146
TEMPERATURE (K)		3797.9	2670.9	2313.0	1900.8
CP (CAL/GM-DEG.K)		0.70174	0.67422	0.65362	0.62175
MOL. WT.-EFFECTIVE		21.576	23.102	23.396	23.645
CP/CV -EFFECTIVE		1.1511	1.1462	1.1494	1.1563
CF -APPROX.			1.6775	1.9453	2.1822
PEAE/M (SEC)			30.858	22.754	16.494
AE/AT -APPROX.			10.874	58.918	427.08
FROZEN EQUILIBRIA					
ISP (SEC)			312.86	360.86	394.62
TEMPERATURE (K)		3797.9	2125.7	1535.0	1045.0
C* (FT/SEC)		6212.8			
CF (SEC)			1.6202	1.8688	2.0436
PEAE/M (SEC)			27.226	17.046	10.611
AE/AT			9.5940	44.137	274.76

TABLE 127

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3797.9	2670.9	2313.0	1900.8
ENTHALPY (KILOCALORIES)	-39.330	-159.92	-201.50	-243.7
ENTROPY (CALORIES/DEG.K)	281.89	281.89	281.89	281.89
HEAT CAPACITY (CAL/K)	70.174	67.422	65.362	62.175
MOLES OF GAS	4.6348	4.3287	4.2742	4.2293
MOLECULAR COMPOSITION:				
H	0.5417	0.2101	0.1161	0.0284
O	0.0015	0.0000	0.0000	0.0000
AL	0.1216	0.0648	0.0592	0.0590
H2	3.5871	3.9719	4.0323	4.0789
H2O	0.2129	0.0144	0.0023	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0181	0.0002	0.0000	0.0000
ALH	0.0282	0.0050	0.0028	0.0020
ALO	0.0153	0.0005	0.0001	0.0000
AL2O	0.1055	0.0616	0.0614	0.0611
AL2O2	0.0027	0.0001	0.0000	0.0000
CONDENSED PHASES				
AL2O3/L/	0.7428	0.8367	0.4104	0
AL2O3/C/	0	0	0.4306	0.8420
AL/LIQUID/	0	0	0	0

TABLE 128

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
ALH3		48.000			
N2O4		52.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
ALH3	ALH3		10.000	1.720	298.16
N2O4	N2O4		-5.4000	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.8010			
N		1.1302			
O		2.2605			
AL		1.6003			
PROPELLANT ENTHALPY		12.952	KCAL/100 GM		
PROPELLANT DENSITY		1.556	GM/CC	0.0562	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			307.64	358.10	400.42
IVSP(LB-SEC/CU IN)			17.294	20.131	22.510
TEMPERATURE (K)		4226.0	3114.0	2711.6	2313.0
CP (CAL/GM-DEG.K)		0.54976	0.54526	0.53800	0.52566
MOL. WT.-EFFECTIVE		26.827	29.311	30.435	31.532
CP/CV -EFFECTIVE		1.1557	1.1420	1.1381	1.1362
CF -APPROX.			1.6866	1.9632	2.1952
PEAE/M (SEC)			29.857	21.510	15.838
AE/AT -APPROX.			11.138	58.963	434.14
FROZEN EQUILIBRIA					
ISP (SEC)			295.05	339.59	371.66
TEMPERATURE (K)		4226.0	2335.2	1683.4	1118.2
C* (FT/SEC)		5868.7			
CF			1.6176	1.8617	2.0375
PEAE/M (SEC)			25.506	15.976	9.6964
AE/AT			9.5151	43.792	265.79

TABLE 129

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4226.0	3114.0	2711.6	2313.0
ENTHALPY (KILOCALORIES)	12.952	-95.819	-134.42	-171.32
ENTROPY (CALORIES/DEG.K)	246.41	246.41	246.41	246.41
HEAT CAPACITY (CAL/K)	54.976	54.526	53.800	52.566
MOLES OF GAS	3.7275	3.4117	3.2856	3.1714
MOLECULAR COMPOSITION:				
H	0.7063	0.5780	0.4266	0.2377
N	0.0007	0.0000	0.0000	0.0000
O	0.0181	0.0017	0.0002	0.0000
AL	0.1634	0.0903	0.0680	0.0566
H2	1.7165	2.0143	2.1532	2.2760
H2O	0.2780	0.0904	0.0323	0.0052
O2	0.0012	0.0000	0.0000	0.0000
OH	0.0799	0.0098	0.0017	0.0001
N2	0.5594	0.5648	0.5651	0.5651
NO	0.0089	0.0006	0.0001	0.0000
ALH	0.0233	0.0036	0.0016	0.0007
ALO	0.0565	0.0091	0.0023	0.0003
AL2O	0.1054	0.0482	0.0343	0.0296
AL2O2	0.0081	0.0008	0.0002	0.0000
ALN	0.0001	0.0000	0.0000	0.0000
NH	0.0011	0.0000	0.0000	0.0000
NH2	0.0006	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
ALN/C/	0	0	0	0
AL2O3/L/	0.5650	0.6996	0.7297	0.6677
AL2O3/C/	0	0	0	0.0741
AL/LIQUID/	0	0	0	0

TABLE 130

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
ALH3		17.000			
NF3		83.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
ALH3	ALH3		10.000	1.720	298.16
NF3	NF3		-32.000	1.532	144.00
ATOMIC COMPOSITION(GM AT/100GM)					
H		1.7003			
N		1.1689			
F		3.5066			
AL		0.5668			
PROPELLANT ENTHALPY		-31.736	KCAL/100 GM		
PROPELLANT DENSITY		1.561	GM/CC	0.0564	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			319.06	367.19	404.37
IVSP(LB-SEC/CU IN)			17.995	20.709	22.806
TEMPERATURE (K)		4984.8	3398.4	2828.2	1977.4
CP (CAL/GM-DEG.K)		0.33160	0.32060	0.31573	0.30616
MOL. WT.-EFFECTIVE		27.590	31.718	33.268	33.812
CP/CV -EFFECTIVE		1.2775	1.2429	1.2333	1.2376
CF -APPROX.			1.6929	1.9483	2.1456
PEAE/M (SEC)			29.034	20.016	12.504
AE/AT -APPROX.			10.483	53.104	331.73
FROZEN EQUILIBRIA					
ISP (SEC)			292.62	327.94	348.23
TEMPERATURE (K)		4984.8	1931.9	1122.9	570.34
C* (FT/SEC)		6063.7			
CF (SEC)			1.5526	1.7401	1.8477
PEAE/M (SEC)			20.689	10.730	5.1325
AE/AT			7.4697	28.466	136.16

TABLE 131

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4984.8	3398.4	2828.2	1977.4
ENTHALPY (KILOCALORIES)	-31.736	-148.73	-186.69	-219.66
ENTROPY (CALORIES/DEG.K)	222.81	222.81	222.81	222.81
HEAT CAPACITY (CAL/K)	33.160	32.060	31.573	30.616
MOLES OF GAS	3.6245	3.1527	3.0059	2.9576
MOLECULAR COMPOSITION:				
H	0.2098	0.0428	0.0086	0.0000
N	0.0056	0.0002	0.0000	0.0000
F	0.7909	0.3038	0.1548	0.1060
AL	0.0018	0.0000	0.0000	0.0000
H2	0.0209	0.0027	0.0004	0.0000
HF	1.4488	1.6522	1.6909	1.7003
N2	0.5816	0.5844	0.5844	0.5844
ALH	0.0000	0.0000	0.0000	0.0000
ALF	0.1123	0.0197	0.0018	0.0000
ALF2	0.2037	0.1102	0.0359	0.0000
ALF3	0.2490	0.4369	0.5291	0.5668
ALN	0.0000	0.0000	0.0000	0.0000
F2	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
ALF3/C/	0	0	0	0
ALN/C/	0	0	0	0
AL/LIQUID/	0	0	0	0

TABLE 132

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CLF3		64.000			
ALH3		36.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CLF3	CLF3		-44.400	1.810	298.16
ALH3	ALH3		10.000	1.720	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.6007			
F		2.0766			
AL		1.2002			
CL		0.6922			
PROPELLANT ENTHALPY		-18.732	KCAL/100 GM		
PROPELLANT DENSITY		1.776	GM/CC	0.0642	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			284.76	325.50	357.93
IVSP(LB-SEC/CU IN)			18.278	20.893	22.974
TEMPERATURE (K)		3949.3	2418.0	1971.3	1574.4
CP (CAL/GM-DEG.K)		0.35576	0.34124	0.33684	0.33103
MOL. WT.-EFFECTIVE		26.485	29.620	31.014	32.450
CP/CV -EFFECTIVE		1.2673	1.2447	1.2349	1.2270
CF -APPROX.			1.6585	1.8957	2.0846
PEAE/M (SEC)			24.785	16.883	11.720
AE/AT -APPROX.			9.8222	49.162	341.28
FROZEN EQUILIBRIA					
ISP (SEC)			267.02	296.84	317.47
TEMPERATURE (K)		3949.3	1555.6	897.52	458.06
C* (FT/SEC)		5524.4			
CF			1.5551	1.7405	1.8489
PEAE/M (SEC)			19.017	9.8040	4.7101
AE/AT			7.5366	28.549	137.16

TABLE 133

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3949.3	2418.0	1971.3	1574.4
ENTHALPY (KILOCALORIES)	-18.732	-111.92	-140.50	-165.97
ENTROPY (CALORIES/DEG.K)	222.25	222.25	222.25	222.25
HEAT CAPACITY (CAL/K)	35.576	34.124	33.684	33.103
MOLES OF GAS	3.7758	3.3761	3.2244	3.0817
MOLECULAR COMPOSITION:				
H	0.3575	0.0379	0.0081	0.0008
F	0.0052	0.0000	0.0000	0.0000
AL	0.0224	0.0008	0.0001	0.0000
CL	0.0659	0.0052	0.0008	0.0000
H2	1.0935	1.4300	1.5774	1.7193
HCL	0.3541	0.3432	0.2629	0.1175
HF	0.6991	0.3595	0.1749	0.0438
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0001	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
ALH	0.0029	0.0000	0.0000	0.0000
ALCL	0.1576	0.1328	0.1134	0.0896
ALCL2	0.0087	0.0181	0.0278	0.0407
ALCL3	0.0011	0.0065	0.0186	0.0520
ALF	0.6302	0.4272	0.2992	0.1893
ALF2	0.2290	0.3092	0.3179	0.2972
ALF3	0.0579	0.1620	0.2432	0.3268
ALFCL2	0.0033	0.0118	0.0237	0.0431
ALF2CL	0.0200	0.0418	0.0571	0.0641
ALFCL	0.0670	0.0900	0.0993	0.0974
CONDENSED PHASES				
ALF3/C/	0	0	0	0
AL/LIQUID/	0	0	0	0

TABLE 134

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
ALH3		45.000			
CLO3F		55.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
ALH3	ALH3		10.000	1.720	298.16
CLO3F	CLO3F		-10.100	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.5009			
O		1.6104			
F		0.5368			
AL		1.5003			
CL		0.5368			
PROPELLANT ENTHALPY		9.5812	KCAL/100 GM		
PROPELLANT DENSITY		1.547	GM/CC	0.0559	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			301.05	349.42	389.97
IVSP(LB-SEC/CU IN)			16.831	19.535	21.802
TEMPERATURE (K)		4204.9	3041.5	2620.9	2306.6
CP (CAL/GM-DEG.K)		0.46445	0.46271	0.45653	0.44305
MOL. WT.-EFFECTIVE		27.452	30.372	31.614	32.113
CP/CV -EFFECTIVE		1.1846	1.1647	1.1597	1.1624
CF -APPROX.			1.6887	1.9600	2.1875
PEAE/M (SEC)			28.759	20.513	15.924
AE/AT -APPROX.			10.977	57.535	446.64
FROZEN EQUILIBRIA					
ISP (SEC)			284.97	325.43	352.67
TEMPERATURE (K)		4204.9	2112.6	1431.7	898.66
C* (FT/SEC)		5735.6			
CF			1.5986	1.8255	1.9783
PEAF/M (SEC)			23.347	13.855	8.0252
AE/AT			8.9117	38.861	225.08

TABLE 135

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4204.9	3041.5	2620.9	2306.6
ENTHALPY (KILOCALORIES)	9.5812	-94.577	-130.73	-165.19
ENTROPY (CALORIES/DEG.K)	233.13	233.13	233.13	233.13
HEAT CAPACITY (CAL/K)	46.445	46.271	45.653	44.305
MOLES OF GAS	3.6427	3.2925	3.1632	3.1140
MOLECULAR COMPOSITION:				
H	0.6024	0.4185	0.2650	0.2045
O	0.0236	0.0016	0.0001	0.0000
F	0.0023	0.0003	0.0000	0.0000
AL	0.0849	0.0212	0.0080	0.0037
CL	0.0624	0.0455	0.0303	0.0236
H2	1.3677	1.6490	1.7768	1.8294
H2O	0.3192	0.1252	0.0566	0.0239
HCL	0.2488	0.3147	0.3484	0.3703
HF	0.1780	0.2082	0.2189	0.2190
O2	0.0022	0.0000	0.0000	0.0000
OH	0.0979	0.0111	0.0018	0.0004
CLO	0.0001	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
ALCL	0.2255	0.1766	0.1581	0.1429
ALF	0.3157	0.2902	0.2756	0.2733
ALF2	0.0192	0.0178	0.0197	0.0203
ALF3	0.0008	0.0008	0.0010	0.0011
ALO	0.0420	0.0034	0.0005	0.0001
AL2O	0.0450	0.0081	0.0024	0.0008
AL2O2	0.0049	0.0002	0.0000	0.0000
CONDENSED PHASES				
ALF3/C/	0	0	0	0
AL2O3/L/	0.3561	0.4868	0.5164	0
AL2O3/C/	0	0	0	0.5284
AL/LIQUID/	0	0	0	0

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
ALH3		58.000			
NO2CLO4		42.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
ALH3	ALH3		10.000	1.720	298.16
NO2CLO4	NO2CLO4		8.0000	2.220	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.6012			
N		0.2887			
O		1.7324			
AL		1.9337			
CL		0.2887			
PROPELLANT ENTHALPY		21.647	KCAL/100 GM		
PROPELLANT DENSITY		1.900	GM/CC	0.0686	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			298.77	345.52	384.98
IVSP(LB-SEC/CU IN)			20.506	23.715	26.424
TEMPERATURE (K)		3796.6	2510.1	2140.8	1866.0
CP (CAL/GM-DEG.K)		0.53668	0.50898	0.48966	0.48789
MOL. WT.-EFFECTIVE		24.721	26.453	26.653	28.083
CP/CV -EFFECTIVE		1.1762	1.1732	1.1796	1.1696
CF -APPROX.			1.6694	1.9306	2.1512
PEAF/M (SEC)			27.459	20.098	14.922
AE/AT -APPROX.			10.440	56.150	416.89
FROZEN EQUILIBRIA					
ISP (SEC)			286.99	329.18	356.90
TEMPERATURE (K)		3796.6	1957.8	1337.7	856.36
C* (FT/SEC)		5758.0			
CF			1.6036	1.8393	1.9942
PEAF/M (SEC)			23.859	14.212	8.3916
AE/AT			9.0715	39.705	234.45

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3796.8	2510.1	2140.8	1866.0
ENTHALPY (KILOCALORIES)	21.647	-80.941	-115.56	-145.69
ENTROPY (CALORIES/DEG.K)	245.85	245.85	245.85	245.85
HEAT CAPACITY (CAL/K)	53.668	50.898	48.956	48.789
MOLES OF GAS	4.0451	3.7803	3.7518	3.5609
MOLECULAR COMPOSITION:				
H	0.4251	0.0860	0.0355	0.0168
N	0.0001	0.0000	0.0000	0.0000
O	0.0008	0.0000	0.0000	0.0000
AL	0.2261	0.1438	0.1365	0.1161
CL	0.0053	0.0002	0.0000	0.0000
H2	2.5431	2.8451	2.8774	2.8898
H2O	0.0886	0.0015	0.0001	0.0000
HCL	0.0558	0.0096	0.0028	0.0010
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0085	0.0000	0.0000	0.0000
N2	0.1438	0.1444	0.1444	0.0735
NO	0.0003	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
ALH	0.0473	0.0124	0.0078	0.0038
ALCl	0.2242	0.2779	0.2855	0.2875
ALCl2	0.0015	0.0005	0.0002	0.0001
ALCl3	0.0000	0.0000	0.0000	0.0000
ALOCL	0.0003	0.0000	0.0000	0.0000
ALO	0.0171	0.0062	0.0000	0.0000
AL2O	0.2526	0.2566	0.2617	0.1722
AL2O2	0.0039	0.0000	0.0000	0.0000
ALN	0.0000	0.0000	0.0000	0.0000
NH	0.0002	0.0000	0.0000	0.0000
NH2	0.0002	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
ALN/C/	0	0	0	0.1416
AL2O3/L/	0.4521	0.4906	0	0
AL2O3/C/	0	0	0.4902	0.5200
AL/LIQUID/	0	0	0	0

TABLE 138

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
ALH3		42.000			
NH4CLO4		58.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
ALH3	ALH3		10.000	1.720	298.16
NH4CLO4	NH4CLO4		-69.420	1.960	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		6.1754			
N		0.4936			
O		1.9745			
AL		1.4003			
CL		0.4936			
PROPELLANT ENTHALPY		-20.265	KCAL/100 GM		
PROPELLANT DENSITY		1.851	GM/CC	0.0669	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			302.23	350.31	392.60
IVSP(LB-SEC/CU IN)			20.218	23.434	26.262
TEMPERATURE (K)		3833.0	2684.0	2313.0	1912.3
CP (CAL/GM-DEG.K)		0.57128	0.55387	0.53961	0.51579
MOL. WT.-EFFECTIVE		24.856	26.755	27.197	27.546
CP/CV -EFFECTIVE		1.1627	1.1549	1.1566	1.1626
CF -APPROX.			1.6783	1.9453	2.1801
PEAF/M (SEC)			28.697	20.989	15.288
AE/AT -APPROX.			10.844	58.276	424.49
FROZEN EQUILIBRIA					
ISP (SEC)			290.36	335.86	363.78
TEMPERATURE (K)		3833.0	2065.3	1456.8	967.70
C* (FT/SEC)		5793.9			
CF			1.6124	1.8540	2.0201
PEAF/M (SEC)			24.740	15.178	9.2526
AE/AT			9.3485	42.142	256.90

TABLE 139

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3833.0	2684.0	2313.0	1912.3
ENTHALPY (KILOCALORIES)	-20.265	-125.24	-161.30	-197.40
ENTROPY (CALORIES/DEG.K)	251.62	251.62	251.62	251.62
HEAT CAPACITY (CAL/K)	57.128	55.387	53.961	51.579
MOLES OF GAS	4.0231	3.7376	3.6768	3.6303
MOLECULAR COMPOSITION:				
H	0.4445	0.1712	0.0902	0.0241
N	0.0001	0.0000	0.0000	0.0000
O	0.0031	0.0000	0.0000	0.0000
AL	0.0447	0.0038	0.0010	0.0001
CL	0.0269	0.0124	0.0070	0.0019
H2	2.4327	2.7392	2.8287	2.8771
H2O	0.2830	0.0659	0.0226	0.0018
HCL	0.2589	0.3526	0.3824	0.3935
O2	0.0001	0.0000	0.0000	0.0000
OH	0.0303	0.0011	0.0001	0.0000
N2	0.2456	0.2468	0.2468	0.2468
NO	0.0016	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
ALH	0.0090	0.0003	0.0000	0.0000
ALCL	0.1938	0.1170	0.0918	0.0743
ALCL2	0.0059	0.0050	0.0051	0.0082
ALCL3	0.0004	0.0005	0.0006	0.0025
ALOCL	0.0010	0.0000	0.0000	0.0000
ALO	0.0113	0.0002	0.0000	0.0000
AL2O	0.0280	0.0015	0.0003	0.0000
AL2O2	0.0014	0.0000	0.0000	0.0000
ALN	0.0000	0.0000	0.0000	0.0000
NH	0.0004	0.0000	0.0000	0.0000
NH2	0.0003	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
ALN/C/	0	0	0	0
AL2O3/L/	0.5377	0.6352	0.3551	0
AL2O3/C/	0	0	0.2954	0.6576
AL/LIQUID/	0	0	0	0

TABLE IL-0

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		30.000			
O2		70.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEM.
BEH2	BEH2		10.000	0	298.16
O2	O2		-3.0800	1.142	90.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.4402			
BE		2.7201			
O		4.3750			
PROPELLANT ENTHALPY		20.464	KCAL/100 GM		
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			338.34	394.64	444.53
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)		4611.0	3418.3	3033.2	2746.8
CP (CAL/GM-DEG.K)		0.70046	0.70354	0.70235	0.69923
MOL. WT.-EFFECTIVE		24.280	26.385	27.451	26.408
CP/CV -EFFECTIVE		1.1323	1.1199	1.1149	1.1206
CF -APPROX.			1.6768	1.9558	2.2031
PEAE/M (SEC)			33.106	24.207	20.230
AE/AT -APPROX.			11.164	59.984	501.31
FROZEN EQUILIBRIA					
ISP (SEC)			330.43	383.01	422.86
TEMPERATURE (K)		4611.0	2796.7	2158.0	1599.5
C* (FT/SEC)		6491.9			
CF			1.6376	1.8982	2.0957
PEAE/M (SEC)			30.138	20.063	13.469
AE/AT			10.163	49.716	333.75

TABLE 111

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4611.0	3418.3	3033.2	2746.8
ENTHALPY (KILOCALORIES)	20.464	-111.09	-158.52	-206.64
ENTROPY (CALORIES/DEG.K)	317.17	317.17	317.17	317.17
HEAT CAPACITY (CAL/K)	70.046	70.354	70.235	69.923
MOLES OF GAS	4.1186	3.7900	3.6428	3.7868
MOLECULAR COMPOSITION:				
H	0.9844	0.9596	0.9073	1.1177
BE	0.0482	0.0174	0.0090	0.0085
O	0.2777	0.2056	0.1678	0.2081
H2	1.0027	1.0262	1.0158	0.9883
H2O	0.6833	0.9022	1.0186	0.9772
O2	0.0750	0.0709	0.0664	0.0819
OH	0.3230	0.3789	0.3119	0.2950
BEH	0.0064	0.0003	0.0001	0.0000
BEO	0.0301	0.0092	0.0044	0.0034
BEO2H2	0.0756	0.0441	0.0327	0.0193
BEOH	0.4033	0.1564	0.0866	0.0577
BE2O2	0.0006	0.0003	0.0002	0.0002
BE3O3	0.0050	0.0101	0.0112	0.0154
BE4O4	0.0032	0.0079	0.0094	0.0123
BE5O5	0.0003	0.0010	0.0012	0.0015
BE6O6	0.0000	0.0000	0.0000	0.0001
CONDENSED PHASES				
BEO2H2/C/	0	0	0	0
BEO/LIQUID/	2.1262	2.4253	2.5094	0
BEO/SOLID/	0	0	0	2.5273
BE/LIQUID/	0	0	0	0
BE/SOLID/	0	0	0	0

TABLE 11-2

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		21.000			
F2		79.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
BEH2	BEH2		10.000	0	298.16
F2	F2		-3.4670	1.510	85.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.8081			
BE		1.9041			
F		4.1579			
PROPELLANT ENTHALPY		11.833	KCAL/100 GM		
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			394.36	453.27	501.18
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)		5194.2	3438.4	2914.7	2425.1
CP (CAL/GM-DEG.K)		0.46738	0.47241	0.46671	0.45668
MOL. WT.-EFFECTIVE		18.685	21.253	22.520	23.887
CP/CV -EFFECTIVE		1.2791	1.2468	1.2332	1.2216
CF -APPROX.			1.6877	1.9398	2.1448
PEAE/M (SEC)			35.469	24.687	17.506
AE/AT -APPROX.			10.329	52.825	374.59
FROZEN EQUILIBRIA					
ISP (SEC)			362.43	405.81	430.08
TEMPERATURE (K)		5194.2	1998.6	1142.3	586.33
C* (FT/SEC)		7518.1			
CF (SEC)			1.5510	1.7367	1.8405
PEAE/M (SEC)			25.516	13.025	6.3082
AE/AT			7.4304	27.871	134.98

TABLE IL3

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	5194.2	3438.4	2914.7	2424.1
ENTHALPY (KILOCALORIES)	11.833	-166.90	-224.28	-276.84
ENTROPY (CALORIES/DEG.K)	302.70	302.70	302.70	302.70
HEAT CAPACITY (CAL/K)	48.738	47.241	46.671	45.868
MOLES OF GAS	5.3520	4.7053	4.4405	4.1863
MOLECULAR COMPOSITION:				
H	1.6210	1.1142	0.7744	0.3849
BE	0.3377	0.1470	0.0662	0.0104
F	0.2038	0.0090	0.0015	0.0002
H2	0.5370	1.0134	1.2727	1.5260
HF	1.0861	0.6646	0.4878	0.3712
BEH	0.0271	0.0025	0.0005	0.0000
BEF	0.2106	0.0247	0.0062	0.0006
BEF2	1.3287	1.7298	1.8312	1.8930
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
BEF2/L/	0	0	0	0
BEF2/C/	0	0	0	0
BE/LIQUID/	0	0	0	0
BE/SOLID/	0	0	0	0

TABLE III

CASE						
PROPELLANT COMPOSITION		WEIGHT%	MOLAR			
	OF2	64.000				
	BEH2	36.000				
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.	
	OF2	OF2	3.6000	1.530	128.00	
	BEH2	BEH2	10.000	0	298.16	
ATOMIC COMPOSITION(GM AT/100GM)						
	H	6.5282				
	BE	3.2641				
	O	1.1852				
	F	2.3704				
PROPELLANT ENTHALPY		36.908	KCAL/100 GM			
		CHAMBER	EXHAUST	EXHAUST	EXHAUST	
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000	
SHIFTING EQUILIBRIA						
	ISP (SEC)		380.63	442.31	491.00	
	IVSP(LB-SEC/CU IN)					
	TEMPERATURE (K)	4128.0	2823.0	2420.4	1869.4	
	CP (CAL/GM-DEG.K)	0.66463	0.67746	0.66481	0.64404	
	MOL. WT.-EFFECTIVE	16.560	18.028	18.365	18.936	
	CP/CV -EFFECTIVE	1.2125	1.1943	1.1944	1.1947	
	CF -APPROX.		1.6878	1.9613	2.1772	
	PEAE/M (SEC)		35.568	25.762	17.384	
	AE/AT -APPROX.		10.732	57.115	385.42	
FROZEN EQUILIBRIA						
	ISP (SEC)		357.26	406.33	436.88	
	TEMPERATURE (K)	4128.0	1919.5	1232.6	737.69	
	C* (FT/SEC)	7256.0				
	CF		1.5841	1.8017	1.9372	
	PEAE/M (SEC)		28.052	15.837	8.8155	
	AE/AT		8.4638	35.112	195.45	

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4128.0	2823.0	2420.4	1869.4
ENTHALPY (KILOCALORIES)	36.908	-129.60	-187.93	-240.16
ENTROPY (CALORIES/DEG.K)	352.41	352.41	352.41	352.41
HEAT CAPACITY (CAL/K)	68.463	67.746	66.481	64.404
MOLES OF GAS	6.0386	5.5470	5.4452	5.2810
MOLECULAR COMPOSITION:				
H	0.9160	0.3625	0.1962	0.0222
BE	0.8432	0.8837	0.8884	0.8184
O	0.0014	0.0000	0.0000	0.0000
F	0.0025	0.0000	0.0000	0.0000
H2	2.4374	3.0335	3.1508	3.2506
H2O	0.0266	0.0012	0.0001	0.0000
HF	0.2428	0.0458	0.0161	0.0007
OH	0.0067	0.0000	0.0000	0.0000
BEH	0.1508	0.0269	0.0112	0.0040
BEF	0.1141	0.0145	0.0046	0.0004
BEF2	1.0055	1.1551	1.1748	1.1846
BEO	0.0076	0.0002	0.0000	0.0000
BEOH	0.2840	0.0238	0.0030	0.0000
CONDENSED PHASES				
BEO/LIQUID/	0.8588	0.0273	0	0
BEO/SOLID/	0	0.1328	1.1821	1.1852
BE/LIQUID/	0	0	0	0.0715

TABLE 11.6

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		45.000			
H202		55.000			
INGREDIENT DATA:	FORMULA	HEAT OF FORM.	DENSITY	REF. TEMP.	
BEH2	BEH2	10.000	0	298.16	
H202	H202	-44.840	1.443	298.16	
ATOMIC COMPOSITION(GM AT/100GM)					
H		11.3941			
BE		4.0802			
O		3.2338			
PROPELLANT ENTHALPY		-31.700 KCAL/100 GM			
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			374.95	437.94	489.54
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)		3416.5	2512.0	2077.3	1782.3
CP (CAL/GM-DEG.K)		1.0260	0.99088	0.96388	0.94852
MOL. WT.-EFFECTIVE		15.014	15.130	15.566	16.484
CP/CV -EFFECTIVE		1.1481	1.1528	1.1527	1.1456
CF -APPROX.			1.7062	1.9928	2.2276
PEAE/M (SEC)			38.282	26.346	19.096
AE/AT -APPROX.			11.854	59.944	434.47
FROZEN EQUILIBRIA					
ISP (SEC)			357.14	409.82	450.37
TEMPERATURE (K)		3416.5	1954.8	1472.0	1043.4
C* (FT/SEC)		7070.4			
CF			1.6252	1.8649	2.0494
PEAE/M (SEC)			31.519	20.683	13.341
AE/AT			9.7595	47.060	303.54

TABLE III

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3416.5	2512.0	2077.3	1782.3
ENTHALPY (KILOCALORIES)	-31.700	-193.27	-252.12	-307.12
ENTROPY (CALORIES/DEG.K)	400.40	400.40	400.40	400.40
HEAT CAPACITY (CAL/K)	102.60	99.088	96.388	94.852
MOLES OF GAS	6.6602	6.6092	6.4244	6.0666
MOLECULAR COMPOSITION:				
H	0.3522	0.1607	0.0441	0.0155
BE	0.6556	0.8135	0.6992	0.3607
O	0.0000	0.0000	0.0000	0.0000
H2	5.3970	5.5983	5.6689	5.6881
H2O	0.0030	0.0001	0.0000	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0001	0.0000	0.0000	0.0000
BEH	0.1841	0.0330	0.0121	0.0023
BEO	0.0002	0.0000	0.0000	0.0000
BEO2H2	0.0002	0.0000	0.0000	0.0000
BEOH	0.0573	0.0036	0.0001	0.0000
BE2O2	0.0000	0.0000	0.0000	0.0000
BE3O3	0.0002	0.0000	0.0000	0.0000
BE4O4	0.0002	0.0000	0.0000	0.0000
BE5O5	0.0000	0.0000	0.0000	0.0000
BE6O6	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
BEO2H2/C/	0	0	0	0
BEO/LIQUID/	3.1711	0	0	0
BEO/SOLID/	0	3.2300	3.2336	3.2338
BE/LIQUID/	0	0	0.1351	0.4834
BE/SOLID/	0	0	0	0

TABLE 148

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		59.000			
N2O4		41.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
BEH2	BEH2		10.000	0	298.16
N2O4	N2O4		-5.4000	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		10.6991			
BE		5.3495			
N		0.8911			
O		1.7823			
PROPELLANT ENTHALPY		51.089	KCAL/100 GM		
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			344.37	401.44	449.16
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)		3158.1	2304.4	1990.3	1705.7
CP (CAL/GM-DEG.K)		1.0489	1.0174	1.0038	1.0021
MOL. WT.-EFFECTIVE		16.660	17.030	17.699	18.247
CP/CV -EFFECTIVE		1.1283	1.1296	1.1259	1.1219
CF -APPROX.			1.7060	1.9888	2.2252
PEAE/M (SEC)			33.972	24.218	17.993
AE/AT -APPROX.			11.452	59.989	445.70
FROZEN EQUILIBRIA					
ISP (SEC)			331.00	382.65	423.20
TEMPERATURE (K)		3158.1	1935.0	1508.4	1119.9
C* (FT/SEC)		6494.4			
CF			1.6398	1.8957	2.0966
PEAE/M (SEC)			30.337	20.457	13.733
AE/AT			10.227	50.673	340.17

TABLE 119

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3158.1	2304.4	1990.3	1705.7
ENTHALPY (KILOCALORIES)	51.089	-85.200	-134.12	-180.77
ENTROPY (CALORIES/DEG.K)	380.18	380.18	380.18	380.18
HEAT CAPACITY (CAL/K)	104.89	101.74	100.38	100.21
MOLES OF GAS	6.0025	5.8720	5.8499	5.4804
MOLECULAR COMPOSITION:				
H	0.1688	0.0551	0.0226	0.0072
BE	0.4665	0.4834	0.2864	0.1269
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
H2	5.1851	5.3110	5.3356	5.3455
H2O	0.0008	0.0000	0.0000	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0000	0.0000	0.0000	0.0000
N2	0.0229	0.0006	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000
BEH	0.1335	0.0213	0.0053	0.0008
BEO	0.0000	0.0000	0.0000	0.0000
BEO2H2	0.0000	0.0000	0.0000	0.0000
BEOH	0.0195	0.0005	0.0000	0.0000
BE2O2	0.0000	0.0000	0.0000	0.0000
BE3O3	0.0001	0.0000	0.0000	0.0000
BE4O4	0.0000	0.0000	0.0000	0.0000
BE5O5	0.0000	0.0000	0.0000	0.0000
BE6O6	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
BE3N2/C/	0.4226	0.4449	0.4455	0.4456
BEO2H2/C/	0	0	0	0
BEO/LIQUID/	1.7614	0	0	0
BEO/SOLID/	0	1.7818	1.7823	1.7823
BE/LIQUID/	1.6952	1.7277	1.9390	0
BE/SOLID/	0	0	0	2.1028

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		20.000			
NF3		80.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
BEH2	BEH2		10.000	0	298.16
NF3	NF3		-32.000	1.532	144.00
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.6268			
BE		1.8134			
N		1.1266			
F		3.3799			
PROPELLANT ENTHALPY		-17.918	KCAL/100 GM		
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			358.48	411.88	453.72
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)		4578.3	2998.6	2459.4	1922.7
CP (CAL/GM-DEG.K)		0.48266	0.46725	0.45940	0.45129
MOL. WT.-EFFECTIVE		19.977	22.374	23.331	24.282
CP/CV -EFFECTIVE		1.2596	1.2347	1.2276	1.2215
CF -APPROX.			1.6804	1.9308	2.1269
PEAE/M (SEC)			32.324	22.127	15.088
AE/AT -APPROX.			10.311	51.864	353.63
FROZEN EQUILIBRIA					
ISP (SEC)			332.86	374.16	398.68
TEMPERATURE (K)		4578.3	1861.0	1096.0	565.26
C* (FT/SEC)		6863.4			
CF (SEC)			1.5604	1.7540	1.8689
PEAE/M (SEC)			24.196	12.677	6.1360
AE/AT			7.7181	29.714	143.82

TABLE 151

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4578.3	2998.6	2459.4	1922.7
ENTHALPY (KILOCALORIES)	-17.918	-165.60	-212.88	-254.51
ENTROPY (CALORIES/DEG.K)	289.89	289.89	289.89	289.89
HEAT CAPACITY (CAL/K)	48.266	46.725	45.940	45.129
MOLES OF GAS	5.0057	4.4696	4.2861	4.1182
MOLECULAR COMPOSITION:				
H	1.0299	0.4097	0.1537	0.0219
BE	0.3272	0.1898	0.1406	0.0615
N	0.0023	0.0000	0.0000	0.0000
F	0.0248	0.0002	0.0000	0.0000
H2	0.9848	1.5298	1.7160	1.8006
HF	0.5884	0.1531	0.0397	0.0036
N2	0.5622	0.5633	0.5633	0.5422
BEH	0.0390	0.0044	0.0015	0.0002
BEF	0.1276	0.0118	0.0025	0.0002
BEF2	1.3195	1.6073	1.6689	1.6881
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
BE3N2/C/	0	0	0	0.0211
BEF2/L/	0	0	0	0
BEF2/C/	0	0	0	0
BE/LIQUID/	0	0	0	0
BE/SOLID/	0	0	0	0

TABLE 152

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		12.000			
CLF3		88.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
BEH2	BEH2		10.000	0	298.16
CLF3	CLF3		-44.400	1.810	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.1761			
BE		1.0880			
F		2.8554			
CL		0.9518			
PROPELLANT ENTHALPY		-31.379	KCAL/100 GM		
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			320.70	367.63	404.68
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)		4960.9	3213.5	2642.4	2040.0
CP (CAL/GM-DEG.K)		0.34361	0.33254	0.32659	0.31800
MOL. WT.-EFFECTIVE		26.816	30.410	31.946	33.171
CP/CV -EFFECTIVE		1.2750	1.2446	1.2353	1.2321
CF -APPROX.			1.6804	1.9264	2.1205
PEAE/M (SEC)			28.488	19.453	13.139
AE/AT -APPROX.			10.158	50.966	344.24
FROZEN EQUILIBRIA					
ISP (SEC)			296.72	333.75	354.50
TEMPERATURE (K)		4960.9	1945.7	1122.9	574.36
C* (FT/SEC)		6140.1			
CF			1.5548	1.7488	1.8576
PEAE/M (SEC)			21.142	10.848	5.2236
AE/AT			7.5384	28.421	136.86

TABLE 153

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4960.9	3213.5	2642.4	2040.0
ENTHALPY (KILOCALORIES)	-31.379	-149.58	-186.70	-219.59
ENTROPY (CALORIES/DEG.K)	224.62	224.62	224.62	224.62
HEAT CAPACITY (CAL/K)	34.361	33.254	32.659	31.800
MOLES OF GAS	3.7292	3.2884	3.1303	3.0147
MOLECULAR COMPOSITION:				
H	0.6295	0.2777	0.1175	0.0167
BE	0.0418	0.0025	0.0002	0.0000
F	0.1553	0.0072	0.0009	0.0000
CL	0.5035	0.2950	0.1573	0.0294
H2	0.1927	0.2781	0.2921	0.2789
HCL	0.2689	0.5195	0.6859	0.8636
HF	0.6898	0.8227	0.7884	0.7380
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0010	0.0002	0.0001	0.0000
CLF	0.0004	0.0000	0.0000	0.0000
BEH	0.0025	0.0000	0.0000	0.0000
BECL	0.0514	0.0071	0.0011	0.0000
BECL2	0.0073	0.0099	0.0086	0.0041
BEF	0.0494	0.0016	0.0001	0.0000
BEF2	0.8248	0.9570	0.9879	1.0334
BEFCL	0.1110	0.1100	0.0901	0.0504
CONDENSED PHASES				
BEF2/L/	0	0	0	0
BEF2/C/	0	0	0	0
BE/LIQUID/	0	0	0	0
BE/SOLID/	0	0	0	0

TABLE 154

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		32.000			
CL03F		68.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
BEH2	BEH2		10.000	0	298.16
CL03F	CL03F		-10.100	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.8029			
BE		2.9014			
O		1.9911			
F		0.6637			
CL		0.6637			
PROPELLANT ENTHALPY		22.311	KCAL/100 GM		
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			339.00	395.83	446.12
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)		4173.0	2997.9	2737.2	2347.3
CP (CAL/GM-DEG.K)		0.65444	0.65324	0.64936	0.63625
MOL. WT.-EFFECTIVE		21.575	23.515	23.333	24.420
CP/CV -EFFECTIVE		1.1638	1.1486	1.1510	1.1467
CF -APPROX.			1.6815	1.9633	2.2128
PEAE/M (SEC)			32.514	25.623	18.629
AE/AT -APPROX.			10.974	63.546	462.00
FROZEN EQUILIBRIA					
ISP (SEC)			325.58	374.63	407.34
TEMPERATURE (K)		4173.0	2272.4	1633.9	1145.3
C* (FT/SEC)		6486.6			
CF			1.6149	1.8582	2.0204
PEAE/M (SEC)			27.968	17.477	11.267
AE/AT			9.4395	43.344	279.42

TABLE 155

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4173.0	2997.9	2737.2	2347.3
ENTHALPY (KILOCALORIES)	22.311	-109.77	-157.75	-206.42
ENTROPY (CALORIES/DEG.K)	307.00	307.00	307.00	307.00
HEAT CAPACITY (CAL/K)	65.444	65.324	64.036	63.625
MOLES OF GAS	4.6349	4.2526	4.2858	4.0951
MOLECULAR COMPOSITION:				
H	0.7997	0.5074	0.5721	0.3454
BE	0.3376	0.3048	0.3281	0.2906
O	0.0028	0.0001	0.0000	0.0000
F	0.0016	0.0001	0.0000	0.0000
CL	0.0505	0.0246	0.0300	0.0128
H2	2.0931	2.4773	2.4546	2.6298
H2O	0.0518	0.0087	0.0062	0.0007
HCL	0.2318	0.2108	0.2263	0.1710
HF	0.1488	0.0572	0.0499	0.0206
OH	0.0135	0.0006	0.0004	0.0000
BEH	0.0635	0.0093	0.0038	0.0012
BECL	0.2270	0.1708	0.1460	0.1144
BECL2	0.0285	0.0632	0.0668	0.1098
BEF	0.0331	0.0057	0.0032	0.0009
BEF2	0.1914	0.2348	0.2414	0.2482
BEFCL	0.0974	0.1312	0.1277	0.1458
BEO	0.0070	0.0005	0.0003	0.0000
BEOH	0.2556	0.0457	0.0286	0.0038
CONDENSED PHASES				
BEO/LIQUID/	1.6602	1.9355	0	0
BEO/SOLID/	0	0	1.9554	1.9866
BE/LIQUID/	0	0	0	0

TABLE 156

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		43.000			
NO2CLO4		57.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
BEH2	BEH2		10.000	0	298.16
NO2CLO4	NO2CLO4		8.0000	2.220	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		7.7976			
BE		3.8988			
N		0.3918			
O		2.3511			
CL		0.3918			
PROPELLANT ENTHALPY		42.123 KCAL/100 GM			

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		345.36	404.67	454.36
IVSP(LB-SEC/CU IN)				
TEMPERATURE (K)	3444.4	2573.0	2274.1	1973.8
CP (CAL/GM-DEG.K)	0.80791	0.79154	0.78594	0.77770
MOL. WT.-EFFECTIVE	17.692	18.266	19.277	20.333
CP/CV -EFFECTIVE	1.1615	1.1594	1.1510	1.1437
CF -APPROX.		1.7062	1.9992	2.2446
PEAE/M (SEC)		35.264	25.204	18.471
AE/AT -APPROX.		11.854	62.256	456.26
FROZEN EQUILIBRIA				
ISP (SEC)		327.17	374.53	409.59
TEMPERATURE (K)	3444.4	1887.4	1383.9	955.66
C* (FT/SEC)	6512.7			
CF		1.6163	1.8502	2.0235
PEAE/M (SEC)		28.193	18.057	11.402
AE/AT		9.4773	44.604	281.64

TABLE 157

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3444.4	2573.0	2274.1	1973.8
ENTHALPY (KILOCALORIES)	42.123	-94.957	-146.08	-195.14
ENTROPY (CALORIES/DEG.K)	343.72	343.72	343.72	343.72
HEAT CAPACITY (CAL/K)	80.791	79.154	78.594	77.770
MOLES OF GAS	5.6524	5.4747	5.1875	4.9182
MOLECULAR COMPOSITION:				
H	0.2827	0.1559	0.1018	0.0506
BE	0.9551	1.0358	0.8822	0.7333
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
CL	0.0022	0.0008	0.0004	0.0001
H2	3.5918	3.7830	3.8276	3.8639
H2O	0.0014	0.0001	0.0000	0.0000
HCL	0.0481	0.0339	0.0267	0.0152
OH	0.0000	0.0000	0.0000	0.0000
N2	0.1793	0.1342	0.0676	0.0071
BEH	0.2330	0.0374	0.0131	0.0039
BECL	0.2811	0.2216	0.1700	0.1114
BECL2	0.0302	0.0678	0.0974	0.1326
BEOH	0.0475	0.0044	0.0008	0.0001
CONDENSED PHASES				
BE3N2/C/	0.0166	0.0617	0.1284	0.1888
BEO/LIQUID/	2.3021	0	0	0
BEO/SOLID/	0	2.3466	2.3503	2.3510
BE/LIQUID/	0	0	0	0

TABLE 158

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
BEH2		32.000			
NH4CLO4		68.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
BEH2	BEH2		10.000	0	298.16
NH4CLO4	NH4CLO4		-69.420	1.960	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		8.1178			
BE		2.9014			
N		0.5787			
O		2.3150			
CL		0.5787			
PROPELLANT ENTHALPY		-11.162	KCAL/100 GM		
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			339.16	397.58	445.53
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)		3611.5	2668.6	2242.5	1937.4
CP (CAL/GM-DEG.K)		0.78536	0.76737	0.74644	0.73685
MOL. WT.-EFFECTIVE		18.963	19.481	19.976	21.023
CP/CV -EFFECTIVE		1.1540	1.1533	1.1538	1.1472
CF -APPROX.			1.6901	1.9813	2.2202
PEAE/M (SEC)			35.182	24.412	17.883
AE/AT -APPROX.			11.930	60.827	445.58
FROZEN EQUILIBRIA					
ISP (SEC)			325.33	372.88	409.38
TEMPERATURE (K)		3611.5	2027.7	1510.3	1051.4
C* (FT/SEC)		6456.4			
CF			1.6212	1.8581	2.0400
PEAE/M (SEC)			28.416	18.466	11.709
AE/AT			9.6357	46.011	291.74

TABLE 159

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3611.5	2688.6	2242.5	1937.4
ENTHALPY (KILOCALORIES)	-11.162	-143.36	-192.83	-239.29
ENTROPY (CALORIES/DEG.K)	331.74	331.74	331.74	331.74
HEAT CAPACITY (CAL/K)	78.536	76.737	74.644	73.685
MOLES OF GAS	5.2734	5.1333	5.0061	4.7567
MOLECULAR COMPOSITION:				
H	0.4009	0.2414	0.0861	0.0392
BE	0.2428	0.2742	0.2600	0.1243
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
CL	0.0126	0.0051	0.0007	0.0002
H2	3.6732	3.6554	3.9842	4.0201
H2O	0.0128	0.0012	0.0000	0.0000
HCL	0.2030	0.1429	0.0585	0.0378
OH	0.0007	0.0000	0.0000	0.0000
N2	0.2893	0.2894	0.2894	0.2353
BEH	0.0606	0.0101	0.0040	0.0007
BECL	0.2300	0.1760	0.1255	0.0577
BECL2	0.0665	0.1274	0.1970	0.2415
BEOH	0.0807	0.0103	0.0006	0.0000
CONDENSED PHASES				
BE3N2/C/	0	0	0	0.0541
BEO/LIQUID/	2.2207	0	0	0
BEO/SOLID/	0	2.3035	2.3144	2.3149
BE/LIQUID/	0	0	0	0

TABLE 160

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
LIH		38.000			
O2		62.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
LIH	LIH		-21.600	0.6200	298.16
O2	O2		-3.0800	1.142	90.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.7811			
LI		4.7811			
O		3.6750			
PROPELLANT ENTHALPY		-109.24	KCAL/100 GM		
PROPELLANT DENSITY		0.9937	GM/CC	0.0359	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			259.88	302.88	339.49
IVSP(LB-SEC/CU IN)			9.3305	10.874	12.189
TEMPERATURE (K)		3195.2	2215.0	1949.8	1693.8
CP (CAL/GM-DEG.K)		0.75719	0.75353	0.75215	0.75015
MOL. WT.-EFFECTIVE		28.919	29.032	29.915	30.409
CP/CV -EFFECTIVE		1.0998	1.1029	1.0998	1.0983
CF -APPROX.			1.6707	1.9471	2.1825
PEAE/M (SEC)			25.382	18.414	14.185
AE/AT -APPROX.			11.103	59.190	455.97
FROZEN EQUILIBRIA					
ISP (SEC)			258.62	301.67	337.17
TEMPERATURE (K)		3195.2	2167.7	1788.4	1424.2
C* (FT/SEC)		5004.7			
CF			1.6626	1.9394	2.1676
PEAE/M (SEC)			25.059	17.723	12.628
AE/AT			10.962	56.970	405.91

TABLE 161

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3195.2	2215.0	1929.8	1693.8
ENTHALPY (KILOCALORIES)	-109.24	-186.86	-214.67	-241.70
ENTROPY (CALORIES/DEG.K)	306.44	308.44	308.44	308.44
HEAT CAPACITY (CAL/K)	75.719	73.353	73.215	73.015
MOLES OF GAS	3.4580	3.4445	3.3428	3.2885
MOLECULAR COMPOSITION:				
H	0.0532	0.0100	0.0044	0.0020
LI	0.2586	0.2293	0.1785	0.1511
O	0.0011	0.0000	0.0000	0.0000
H2	0.7305	0.7810	0.8125	0.8288
H2O	0.8838	0.7977	0.8109	0.8185
O2	0.0006	0.0000	0.0000	0.0000
OH	0.0258	0.0015	0.0004	0.0001
LI2	0.0026	0.0002	0.0000	0.0000
LIH	0.0334	0.0061	0.0023	0.0008
LIO	0.0025	0.0002	0.0000	0.0000
LI2O	0.0261	0.0124	0.0066	0.0036
LIOH	1.4394	1.6060	1.5270	1.4836
LI2O2H2	0.0003	0.0001	0.0001	0.0000
CONDENSED PHASES				
LI2O/L/	1.4946	1.4570	1.5299	1.1370
LI2O/SOLID/	0	0	0	0.4321
LI/LIQUID/	0	0	0	0

TABLE 162

CASE						
PROPELLANT COMPOSITION		WEIGHT%	MOLAR			
LIH		19.000				
F2		81.000				
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.	
LIH	LIH		-21.600	0.8200	298.16	
F2	F2		-3.4670	1.510	85.200	
ATOMIC COMPOSITION(GM AT/100GM)						
H		2.3905				
LI		2.3905				
F		4.2632				
PROPELLANT ENTHALPY		-59.026	KCAL/100 GM			
PROPELLANT DENSITY		1.302	GM/CC	0.0470	LB/CU IN	
		CHAMBER	EXHAUST	EXHAUST	EXHAUST	
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000	
SHIFTING EQUILIBRIA						
ISP (SEC)			361.53	406.18	443.22	
IVSP(LB-SEC/CU IN)			17.005	19.199	20.847	
TEMPERATURE (K)		4830.5	2726.0	1985.8	1599.6	
CP (CAL/GM-DEG.K)		0.43359	0.40496	0.39487	0.39035	
MOL. WT.-EFFECTIVE		19.928	21.925	22.776	24.636	
CP/CV -EFFECTIVE		1.2987	1.2884	1.2836	1.2605	
CF -APPROX.			1.6658	1.8808	2.0422	
PEAE/M (SEC)			29.733	18.467	12.665	
AE/AT -APPROX.			9.3223	42.544	291.78	
FROZEN EQUILIBRIA						
ISP (SEC)			334.36	375.12	396.04	
TEMPERATURE (K)		4830.5	1744.9	898.88	389.06	
C* (FT/SEC)		6982.7				
CF (SEC)			1.5406	1.7284	1.8248	
PEAE/M (SEC)			22.640	10.396	4.2619	
AE/AT			7.0985	23.951	98.187	

TABLE 163

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4830.5	2726.0	1985.8	1599.6
ENTHALPY (KILOCALORIES)	-59.026	-209.24	-250.51	-284.79
ENTROPY (CALORIES/DEG.K)	290.06	290.06	290.06	290.06
HEAT CAPACITY (CAL/K)	43.359	40.496	39.487	39.035
MOLES OF GAS	5.0180	4.5610	4.3905	4.0591
MOLECULAR COMPOSITION:				
H	0.4719	0.0617	0.0042	0.0005
LI	0.1756	0.0286	0.0022	0.0002
F	0.3580	0.0019	0.0000	0.0000
H2	0.1091	0.2145	0.2557	0.2586
HF	1.6954	1.8995	1.8749	1.8728
LI2	0.0002	0.0000	0.0000	0.0000
LIH	0.0049	0.0002	0.0000	0.0000
LIF	2.1992	2.3501	2.1750	1.6434
LI2F2	0.0003	0.0014	0.0218	0.1038
LI3F3	0.0033	0.0029	0.0565	0.1798
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
LIF/LIQUID/	0	0	0	0
LIF/SOLID/	0	0	0	0
LI/LIQUID/	0	0	0	0

TABLE 164

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
OF2		72.500			
LIH		27.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
OF2	OF2		3.6000	1.530	128.00
LIH	LIH		-21.600	0.8200	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.4600			
LI		3.4600			
O		1.3426			
F		2.6852			
PROPELLANT ENTHALPY		-69.902	KCAL/100 GM		
PROPELLANT DENSITY		1.236	GM/CC	0.0446	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			330.20	376.56	413.60
IVSP(LB-SEC/CU IN)			14.743	16.812	18.466
TEMPERATURE (K)		3843.6	2298.8	1882.3	1582.9
CP (CAL/GM-DEG.K)		0.51161	0.46625	0.47985	0.47872
MOL. WT.-EFFECTIVE		19.294	21.226	22.565	24.164
CP/CV -EFFECTIVE		1.2521	1.2335	1.2248	1.2074
CF -APPROX.			1.6567	1.0893	2.0751
PEAE/M (SEC)			28.357	19.152	13.693
AE/AT -APPROX.			9.6812	48.046	343.52
FROZEN EQUILIBRIA					
ISP (SEC)			311.45	351.49	373.66
TEMPERATURE (K)		3843.6	1582.8	915.74	474.77
C* (FT/SEC)		6412.6			
CF			1.5626	1.7635	1.8748
PEAE/M (SEC)			22.772	11.674	5.6935
AE/AT			7.7746	29.286	142.83

TABLE 165

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3843.6	2298.8	1882.3	1562.9
ENTHALPY (KILOCALORIES)	-69.902	-195.21	-232.86	-266.50
ENTROPY (CALORIES/DEG.K)	316.96	316.96	316.96	316.96
HEAT CAPACITY (CAL/K)	51.161	48.625	47.985	47.872
MOLES OF GAS	5.1828	4.7113	4.4316	4.1383
MOLECULAR COMPOSITION:				
H	0.2344	0.0171	0.0034	0.0007
LI	0.4638	0.1744	0.0926	0.0422
O	0.0388	0.0000	0.0000	0.0000
F	0.0033	0.0000	0.0000	0.0000
H2	0.3042	0.6769	0.7259	0.7531
H2O	0.5423	0.6522	0.6285	0.6492
HF	0.3481	0.0939	0.0344	0.0143
OH	0.1486	0.0027	0.0002	0.0000
LI2	0.0026	0.0001	0.0000	0.0000
LIH	0.0336	0.0035	0.0010	0.0002
LIF	2.2076	2.3013	1.9977	1.6559
LI2F2	0.0018	0.0146	0.0490	0.1308
LI3F3	0.0409	0.0869	0.1850	0.2511
LI2O	0.0112	0.0031	0.0017	0.0006
LIOH	0.6012	0.6844	0.7122	0.6400
LI2O2H2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
LIF/LIQUID/	0	0	0	0
LI2O/L/	0	0	0	0
LI2O/SOLID/	0	0	0	0.0527

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
LIH		40.000			
H2O2		60.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
LIH	LIH		-21.600	0.6200	298.16
H2O2	H2O2		-44.840	1.443	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		8.5605			
LI		5.0327			
O		3.5278			
PROPELLANT ENTHALPY		-187.80	KCAL/100 GM		
PROPELLANT DENSITY		1.107	GM/CC	0.0400	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		252.37	299.19	345.57
IVSP(LB-SEC/CU IN)		10.091	11.963	13.818
TEMPERATURE (K)	2334.5	1693.8	1623.4	1397.8
CP (CAL/GM-DEG.K)	0.98734	0.96998	0.96930	0.93745
MOL. WT.-EFFECTIVE	22.380	22.772	22.411	22.971
CP/CV -EFFECTIVE	1.0988	1.0989	1.1007	1.1017
CF -APPROX.		1.6692	1.9789	2.2526
PEAF/M (SEC)		25.482	20.931	15.448
AE/AT -APPROX.		11.468	69.221	510.86
FROZEN EQUILIBRIA				
ISP (SEC)		251.44	292.99	326.50
TEMPERATURE (K)	2334.5	1587.1	1312.1	1055.7
C* (FT/SEC)	4864.4			
CF		1.6631	1.9379	2.1595
PEAE/M (SEC)		24.384	17.301	12.491
AE/AT		10.974	57.215	413.07

TABLE 167

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2334.5	1693.8	1623.4	1397.8
ENTHALPY (KILOCALORIES)	-187.80	-260.99	-290.68	-321.10
ENTROPY (CALORIES/DEG.K)	336.53	336.53	336.53	336.53
HEAT CAPACITY (CAL/K)	98.734	96.998	96.930	93.745
MOLES OF GAS	4.4683	4.3913	4.4621	4.3532
MOLECULAR COMPOSITION:				
H	0.0053	0.0005	0.0007	0.0002
LI	0.0183	0.0052	0.0150	0.0031
O	0.0000	0.0000	0.0000	0.0000
H2	3.2504	3.2656	3.2605	3.2672
H2O	0.8605	0.9088	0.8531	0.9431
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0002	0.0000	0.0000	0.0000
LI2	0.0000	0.0000	0.0000	0.0000
LIH	0.0066	0.0004	0.0005	0.0000
LIO	0.0000	0.0000	0.0000	0.0000
LI2O	0.0006	0.0001	0.0001	0.0000
LIOH	0.3260	0.2107	0.3321	0.1396
LI2O2H2	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
LI2O/L/	2.3401	2.0276	0	0
LI2O/SOLID/	0	0.3805	2.3424	2.4450
LI/LIQUID/	0	0	0	0

TABLE 168

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
LIH		26.000			
N2O4		74.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
LIH	LIH		-21.600	0.6200	298.16
N2O4	N2O4		-5.4000	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.2713			
LI		3.2713			
N		1.6084			
O		3.2168			
PROPELLANT ENTHALPY		-75.002	KCAL/100 GM		
PROPELLANT DENSITY		1.198	GM/CC	0.0433	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			250.08	290.31	324.76
IVSP(LB-SEC/CU IN)			10.827	12.568	14.060
TEMPERATURE (K)		3170.5	2167.7	1868.5	1665.3
CP (CAL/GM-DEG.K)		0.60000	0.58359	0.58632	0.58422
MOL. WT.-EFFECTIVE		30.340	31.361	32.510	32.282
CP/CV -EFFECTIVE		1.1225	1.1218	1.1164	1.1178
CF -APPROX.			1.6656	1.9335	2.1629
PEAF/M (SEC)			23.896	17.116	13.733
AE/AT -APPROX.			10.829	56.997	457.30
FROZEN EQUILIBRIA					
ISP (SEC)			246.94	286.87	317.75
TEMPERATURE (K)		3170.5	1985.2	1557.3	1166.1
C* (FT/SEC)		4831.0			
CF			1.6446	1.9105	2.1162
PEAF/M (SEC)			22.909	15.469	10.458
AE/AT			10.382	51.512	348.24

TABLE 169

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3170.5	2167.7	1868.5	1665.3
ENTHALPY (KILOCALORIES)	-75.002	-146.88	-171.86	-196.22
ENTROPY (CALORIES/DEG.K)	272.26	272.26	272.26	272.26
HEAT CAPACITY (CAL/K)	60.000	58.359	58.632	58.422
MOLES OF GAS	3.2960	3.1887	3.0760	3.0976
MOLECULAR COMPOSITION:				
H	0.0179	0.0017	0.0006	0.0003
LI	0.0868	0.0339	0.0198	0.0207
N	0.0000	0.0000	0.0000	0.0000
O	0.0064	0.0001	0.0000	0.0000
H2	0.0993	0.0425	0.0450	0.0441
H2O	0.8336	0.8882	0.9775	0.9565
O2	0.0218	0.0012	0.0001	0.0000
OH	0.0593	0.0048	0.0011	0.0003
N2	0.7945	0.8037	0.8041	0.8042
NO	0.0194	0.0009	0.0001	0.0000
LI2	0.0003	0.0000	0.0000	0.0000
LIH	0.0043	0.0002	0.0001	0.0000
LIO	0.0057	0.0004	0.0001	0.0000
LI2O	0.0230	0.0079	0.0031	0.0021
LIOH	1.3235	1.4028	1.2242	1.2692
LI2O2H2	0.0002	0.0001	0.0001	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
LI3N/C/	0	0	0	0
LI2O/L/	0.9019	0.9089	1.0104	0
LI2O/SOLID/	0	0	0	0.9885
LI/LIQUID/	0	0	0	0

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
LIH		23.000			
NF3		77.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
LIH	LIH		-21.600	0.8200	298.16
NF3	NF3		-32.000	1.532	144.00
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.8938			
LI		2.8938			
N		1.0844			
F		3.2532			
PROPELLANT ENTHALPY		-97.207	KCAL/100 GM		
PROPELLANT DENSITY		1.277	GM/CC	0.0461	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			307.07	350.26	385.20
IVSP(LB-SEC/CU IN)			14.167	16.160	17.772
TEMPERATURE (K)		3542.3	2124.4	1771.8	1510.5
CP (CAL/GM-DEG.K)		0.47431	0.46072	0.45847	0.46792
MOL. WT.-EFFECTIVE		20.068	22.772	24.352	26.160
CP/CV -EFFECTIVE		1.2639	1.2337	1.2165	1.1938
CF -APPROX.			1.6422	1.8732	2.0600
PEAE/M (SEC)			26.266	17.959	12.960
AE/AT -APPROX.			9.5581	48.022	346.53
FROZEN EQUILIBRIA					
ISP (SEC)			291.28	327.14	347.22
TEMPERATURE (K)		3542.3	1416.9	824.46	441.36
C* (FT/SEC)		6016.2			
CF (SEC)			1.5577	1.7495	1.8569
PEAE/M (SEC)			20.957	10.858	5.4763
AE/AT			7.6262	29.032	146.43

TABLE 171

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3542.3	2124.4	1771.8	1510.5
ENTHALPY (KILOCALORIES)	-97.207	-205.57	-238.20	-267.73
ENTROPY (CALORIES/DEG.K)	293.04	293.04	293.04	293.04
HEAT CAPACITY (CAL/K)	47.431	46.072	45.847	46.792
MOLES OF GAS	4.9830	4.3912	4.1064	3.8226
MOLECULAR COMPOSITION:				
H	0.1788	0.0085	0.0017	0.0004
LI	0.2157	0.0179	0.0033	0.0006
N	0.0000	0.0000	0.0000	0.0000
F	0.0014	0.0000	0.0000	0.0000
H2	1.0450	1.2535	1.2646	1.2667
HF	0.6001	0.3778	0.3627	0.3600
N2	0.5422	0.5422	0.5422	0.5422
LI2	0.0008	0.0000	0.0000	0.0000
LIH	0.0249	0.0006	0.0000	0.0000
LIF	2.2331	1.6308	1.4094	1.0724
LI2F2	0.0042	0.0353	0.0857	0.1760
LI3F3	0.1367	0.3246	0.4365	0.4042
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
LI3N/C/	0	0	0	0
LIF/LIQUID/	0	0	0	0.2560
LIF/SOLID/	0	0	0	0
LI/LIQUID/	0	0	0	0

TABLE 172

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
LIH		14.000			
CLF3		86.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
LIH	LIH		-21.600	0.8200	298.16
CLF3	CLF3		-44.400	1.810	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		1.7614			
LI		1.7614			
F		2.7905			
CL		0.9302			
PROPELLANT ENTHALPY		-79.346	KCAL/100 GM		
PROPELLANT DENSITY		1.548	GM/CC	0.0559	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			288.98	325.73	355.04
IVSP(LB-SEC/CU IN)			16.165	18.221	19.861
TEMPERATURE (K)	4187.5		2114.4	1697.2	1435.2
CP (CAL/GM-DEG.K)	0.33611		0.31744	0.31352	0.32341
MOL. WT.-EFFECTIVE	25.972		27.937	29.802	32.148
CP/CV -EFFECTIVE	1.2947		1.2888	1.2702	1.2363
CF -APPROX.			1.6309	1.8383	2.0037
PEAF/M (SEC)			22.644	15.116	10.872
AE/AT -APPROX.			8.6958	42.655	306.78
FROZEN EQUILIBRIA					
ISP (SEC)			273.58	307.41	324.01
TEMPERATURE (K)	4187.5		1539.0	818.96	399.38
C* (FT/SEC)	5701.0				
CF (SEC)			1.5440	1.7349	1.8286
PEAF/M (SEC)			18.726	8.8682	4.1032
AE/AT			7.1911	25.024	115.78

TABLE 173

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4187.5	2114.4	1697.2	1435.2
ENTHALPY (KILOCALORIES)	-79.346	-175.32	-201.28	-224.22
ENTROPY (CALORIES/DEG.K)	230.06	230.06	230.06	230.06
HEAT CAPACITY (CAL/K)	33.611	31.744	31.352	32.341
MOLES OF GAS	3.8502	3.5795	3.3555	3.1106
MOLECULAR COMPOSITION:				
H	0.0883	0.0000	0.0000	0.0000
LI	0.0211	0.0000	0.0000	0.0000
F	0.1281	0.0064	0.0010	0.0002
CL	0.2360	0.1688	0.1269	0.0894
H2	0.0293	0.0000	0.0000	0.0000
HCL	0.1375	0.0501	0.0366	0.0303
HF	1.4766	1.7113	1.7249	1.7311
CLF	0.0005	0.0006	0.0004	0.0001
LI2	0.0000	0.0000	0.0000	0.0000
LIH	0.0004	0.0000	0.0000	0.0000
LICL	0.5544	0.6885	0.6961	0.7012
LI2CL2	0.0001	0.0003	0.0006	0.0006
LIF	1.1729	0.6726	0.5503	0.3252
LI2F2	0.0003	0.0106	0.0388	0.0691
LI3F3	0.0039	0.0594	0.1454	0.1094
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0007	0.0107	0.0345	0.0539
CONDENSED PHASES				
LICL/L/	0	0	0	0
LIF/LIQUID/	0	0	0	0.2674
LIF/SOLID/	0	0	0	0
LI/LIQUID/	0	0	0	0

TABLE 174

CASE						
PROPELLANT COMPOSITION		WEIGHT%	MOLAR			
	CL03F	70.000				
	LIH	30.000				
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.	
	CL03F	CL03F	-10.100	1.430	298.16	
	LIH	LIH	-21.600	0.6900	298.16	
ATOMIC COMPOSITION(GM AT/100GM)						
	H	3.7745				
	LI	3.7745				
	O	2.0496				
	F	0.6832				
	CL	0.6832				
PROPELLANT ENTHALPY		-88.430	KCAL/100 GM			
PROPELLANT DENSITY		1.169	GM/CC	0.0422	LB/CU IN	
		CHAMBER	EXHAUST	EXHAUST	EXHAUST	
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000	
SHIFTING EQUILIBRIA						
	ISP (SEC)		264.59	305.62	341.48	
	IVSP(LB-SEC/CU IN)		11.176	12.909	14.424	
	TEMPERATURE (K)	3057.6	2047.6	1759.4	1565.8	
	CP (CAL/GM-DEG.K)	0.55092	0.55648	0.56129	0.56294	
	MOL. WT.-EFFECTIVE	24.956	27.344	28.621	28.856	
	CP/CV -EFFECTIVE	1.1690	1.1502	1.1412	1.1394	
	CF -APPROX.		1.6516	1.9077	2.1315	
	PEAF/M (SEC)		24.470	17.390	13.738	
	AE/AT -APPROX.		10.393	54.276	428.77	
FROZEN EQUILIBRIA						
	ISP (SEC)		258.16	296.14	322.69	
	TEMPERATURE (K)	3057.6	1635.3	1171.7	786.63	
	C* (FT/SEC)	5154.4				
	CF		1.6114	1.8485	2.0142	
	PEAF/M (SEC)		21.945	13.707	8.4451	
	AE/AT		9.3208	42.779	263.57	

TABLE 175

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3057.6	2047.6	1759.4	1565.8
ENTHALPY (KILOCALORIES)	-88.430	-168.88	-195.77	-222.44
ENTROPY (CALORIES/DEG.K)	280.28	280.28	280.28	28[illegible].28
HEAT CAPACITY (CAL/K)	55.092	55.648	56.129	56.294
MOLES OF GAS	4.0070	3.6572	3.4939	3.4655
MOLECULAR COMPOSITION:				
H	0.0418	0.0042	0.0013	0.0006
LI	0.2801	0.1000	0.0452	0.0326
O	0.0003	0.0000	0.0000	0.0000
F	0.0000	0.0000	0.0000	0.0000
CL	0.0001	0.0000	0.0000	0.0000
H2	0.8487	0.9866	1.0178	1.0249
H2O	0.4939	0.5150	0.5734	0.6123
HCL	0.0036	0.0004	0.0002	0.0001
HF	0.0292	0.0106	0.0075	0.0057
O2	0.0001	0.0000	0.0000	0.0000
OH	0.0088	0.0002	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
LI2	0.0032	0.0001	0.0000	0.0000
LIH	0.0382	0.0033	0.0005	0.0002
LIOH	0.6773	0.6818	0.6823	0.6828
LI2CL2	0.0011	0.0005	0.0003	0.0002
LIF	0.5578	0.5578	0.5267	0.5677
LI2F2	0.0015	0.0074	0.0162	0.0235
LI3F3	0.0310	0.0334	0.0389	0.0209
LIO	0.0010	0.0000	0.0000	0.0000
LI2O	0.0189	0.0032	0.0009	0.0004
LIO2	0.0027	0.0002	0.0000	0.0000
LIOH	0.4673	0.7524	0.5823	0.4935
LI2O2H2	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
LICL/L/	0	0	0	0
LIF/LIQUID/	0	0	0	0
LIF/SOLID/	0	0	0	0
LI2O/L/	0.5536	0.7783	0.8928	0
LI2O/SOLID/	0	0	0	0.9434
LI/LIQUID/	0	0	0	0

TABLE 176

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
LIH		27.000			
NO2CLO4		73.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
LIH	LIH		-21.600	0.8200	298.16
NO2CLO4	NO2CLO4		8.0000	2.220	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.3971			
LI		3.3971			
N		0.5018			
O		3.0110			
CL		0.5018			
PROPELLANT ENTHALPY		-69.362	KCAL/100 GM		
PROPELLANT DENSITY		1.520	GM/CC	0.0549	LB/CU IN
	CHAMBER		EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0		14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			258.28	296.71	332.93
IVSP(LB-SEC/CU IN)			14.180	16.399	18.278
TEMPERATURE (K)	3278.8		2193.7	1883.7	1663.9
CP (CAL/GM-DEG.K)	0.54380		0.53262	0.53762	0.53843
MOL. WT.-EFFECTIVE	28.780		30.444	31.820	32.095
CP/CV -EFFECTIVE	1.1454		1.1397	1.1314	1.1299
CF -APPROX.			1.6596	1.9194	2.1393
PEAF/M (SEC)			24.120	17.134	13.463
AE/AT -APPROX.			10.546	55.048	432.55
FROZEN EQUILIBRIA					
ISP (SEC)			253.30	292.57	321.40
TEMPERATURE (K)	3278.8		1897.2	1414.6	1091.9
C* (FT/SEC)	5007.1				
CF			1.6276	1.8800	2.0652
PEAF/M (SEC)			22.499	14.524	9.3646
AE/AT			9.8376	46.665	300.87

TABLE 177

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3278.8	2193.7	1863.7	1663.9
ENTHALPY (KILOCALORIES)	-69.362	-146.03	-171.91	-196.75
ENTROPY (CALORIES/DEG.K)	269.31	269.31	269.31	269.31
HEAT CAPACITY (CAL/K)	54.380	53.262	53.762	53.843
MOLES OF GAS	3.4746	3.2847	3.1426	3.1157
MOLECULAR COMPOSITION:				
H	0.0286	0.0031	0.0011	0.0005
LI	0.1527	0.0667	0.0384	0.0335
N	0.0000	0.0000	0.0000	0.0000
O	0.0086	0.0001	0.0000	0.0000
CL	0.0004	0.0000	0.0000	0.0000
H2	0.1346	0.1024	0.1156	0.1181
H2O	0.7664	0.8397	0.9335	0.9514
HCL	0.0038	0.0004	0.0002	0.0001
O2	0.0200	0.0003	0.0000	0.0000
OH	0.0692	0.0036	0.0007	0.0002
N2	0.2451	0.2508	0.2509	0.2509
NO	0.0116	0.0003	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
LI2	0.0008	0.0000	0.0000	0.0000
LIH	0.0082	0.0007	0.0002	0.0001
LICL	0.4967	0.5011	0.5015	0.5017
LI2CL2	0.0004	0.0001	0.0001	0.0000
LIO	0.0081	0.0004	0.0000	0.0000
LI2O	0.0341	0.0100	0.0038	0.0020
LIOH	1.4848	1.5049	1.2963	1.2570
LI2O2H2	0.0002	0.0001	0.0001	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
LI3N/C/	0	0	0	0
LICL/L/	0	0	0	0
LI2O/L/	0.5876	0.6513	0.7763	0
LI2O/SOLID/	0	0	0	0.8002
LI/LIQUID/	0	0	0	0

TABLE 178

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
LIH		25.000			
NH4CLO4		75.000			
INGREDIENT DATA:	FORMULA	HEAT OF FORM.	DENSITY	REF. TEMP.	
LIH	LIH	-21.600	0.8200	298.16	
NH4CLO4	NH4CLO4	-69.420	1.960	298.16	
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.6987			
LI		3.1454			
N		0.6383			
O		2.5532			
CL		0.6383			
PROPELLANT ENTHALPY		-112.25 KCAL/100 GM			
PROPELLANT DENSITY		1.454 GM/CC	0.0526 LB/CU IN		

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		245.65	287.49	322.57
IVSP(LB-SEC/CU IN)		12.909	15.108	16.951
TEMPERATURE (K)	2524.8	1693.8	1535.7	1251.3
CP (CAL/GM-DEG.K)	0.65176	0.64651	0.64283	0.61725
MOL. WT.-EFFECTIVE	24.290	25.508	25.659	26.204
CP/CV -EFFECTIVE	1.1435	1.1370	1.1370	1.1401
CF -APPROX.		1.6515	1.9328	2.1686
PEAE/M (SEC)		23.370	17.999	12.799
AE/AT -APPROX.		10.691	60.505	430.25
FROZEN EQUILIBRIA				
ISP (SEC)		242.18	279.06	305.85
TEMPERATURE (K)	2524.8	1465.0	1104.1	795.45
C* (FT/SEC)	4765.6			
CF		1.6281	1.8761	2.0562
PEAE/M (SEC)		21.531	14.083	9.2572
AE/AT		9.8500	47.341	311.18

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2524.8	1693.8	1535.7	1251.3
ENTHALPY (KILOCALORIES)	-112.25	-181.61	-207.24	-231.83
ENTROPY (CALORIES/DEG.K)	283.60	283.60	283.60	283.60
HEAT CAPACITY (CAL/K)	65.176	64.651	64.283	61.725
MOLES OF GAS	4.1169	3.9203	3.8973	3.8162
MOLECULAR COMPOSITION:				
H	0.0085	0.0003	0.0002	0.0000
LI	0.0300	0.0028	0.0020	0.0001
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
CL	0.0000	0.0000	0.0000	0.0000
H2	1.5239	1.5479	1.5485	1.5496
H2O	1.0387	1.1870	1.2105	1.2866
HCL	0.0044	0.0006	0.0003	0.0003
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0013	0.0000	0.0000	0.0000
N2	0.3190	0.3192	0.3192	0.3192
NO	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
LI2	0.0001	0.0000	0.0000	0.0000
LIH	0.0069	0.0002	0.0000	0.0000
LICL	0.6268	0.6315	0.6349	0.6310
LI2CL2	0.0036	0.0031	0.0015	0.0035
LIO	0.0000	0.0000	0.0000	0.0000
LI2O	0.0017	0.0000	0.0000	0.0000
LIOH	0.5516	0.2275	0.1800	0.0259
LI2C2H2	0.0002	0.0001	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
LI3N/C/	0	0	0	0
LICL/L/	0	0	0	0
LI2O/L/	0.9595	0.9578	0	0
LI2O/SOLID/	0	0.1807	1.1626	1.2407
LI/LIQUID/	0	0	0	0

TABLE 180

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
MGH2		69.000			
O2		31.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
MGH2	MGH2		-17.000	1.450	298.16
O2	O2		-3.0800	1.142	90.200
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.2400			
O		1.9375			
MG		2.6200			
PROPELLANT ENTHALPY		-47.524	KCAL/100 GM		
PROPELLANT DENSITY		1.338	GM/CC	0.0483	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			270.17	316.20	354.15
IVSP(LB-SEC/CU IN)			13.062	15.287	17.122
TEMPERATURE (K)		3076.2	2460.4	2145.1	1685.0
CP (CAL/GM-DEG.K)		0.52097	0.52617	0.51780	0.49282
MOL. WT.-EFFECTIVE		28.053	29.012	29.879	30.266
CP/CV -EFFECTIVE		1.1574	1.1497	1.1474	1.1537
CF -APPROX.			1.7762	2.0788	2.3282
PEAE/M (SEC)			27.138	19.630	13.591
AE/AT -APPROX.			12.140	64.526	446.76
FROZEN EQUILIBRIA					
ISP (SEC)			246.26	282.51	310.03
TEMPERATURE (K)		3076.2	1706.7	1253.9	860.33
C* (FT/SEC)		4893.9			
CF (SEC)			1.6190	1.8573	2.0382
PEAE/M (SEC)			21.358	13.679	8.5521
AE/AT			9.5547	44.964	281.12

TABLE 181

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3076.2	2460.4	2145.1	1685.0
ENTHALPY (KILOCALORIES)	-47.524	-131.41	-162.43	-191.66
ENTROPY (CALORIES/DEG.K)	225.95	225.95	225.95	225.95
HEAT CAPACITY (CAL/K)	52.097	52.617	51.780	49.282
MOLES OF GAS	3.5646	3.4468	3.3468	3.3040
MOLECULAR COMPOSITION:				
H	0.0680	0.0612	0.0325	0.0032
O	0.0000	0.0000	0.0000	0.0000
MG	0.6349	0.7086	0.6883	0.6816
H2	2.2563	2.4640	2.5718	2.6175
H2O	0.0542	0.0379	0.0096	0.0001
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0006	0.0002	0.0000	0.0000
MGH	0.1024	0.0119	0.0038	0.0009
MGO	0.0002	0.0000	0.0000	0.0000
MGOH	0.4479	0.1630	0.0407	0.0007
CONDENSED PHASES				
MGO/C/	0	1.7364	1.8871	1.9367
MGO2H2/C/	0	0	0	0
MGO/L/	1.4345	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 182

CASE					
PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
	MGH2	24.000			
	F2	76.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
	MGH2	MGH2	-17.000	1.450	298.16
	F2	F2	-3.4670	1.510	85.200
ATOMIC COMPOSITION(GM AT/100GM)					
	H	1.8226			
	F	4.0000			
	MG	0.9113			
PROPELLANT ENTHALPY		-22.426	KCAL/100 GM		
PROPELLANT DENSITY		1.495	GM/CC	0.0540	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
	ISP (SEC)		327.38	377.02	414.36
	IVSP(LB-SEC/CU IN)		17.685	20.367	22.384
	TEMPERATURE (K)	4992.6	3456.1	2884.8	2008.7
	CP (CAL/GM-DEG.K)	0.32593	0.31490	0.31060	0.30547
	MOL. WT.-EFFECTIVE	26.289	30.516	32.114	32.919
	CP/CV -EFFECTIVE	1.3020	1.2607	1.2488	1.2463
	CF -APPROX.		1.7057	1.9643	2.1589
	PEAE/M (SEC)		29.910	20.599	12.732
	AE/AT -APPROX.		10.604	53.662	331.67
FROZEN EQUILIBRIA					
	ISP (SEC)		295.71	330.18	348.62
	TEMPERATURE (K)	4992.6	1800.7	992.20	481.15
	C* (FT/SEC)	6175.3			
	CF (SEC)		1.5407	1.7203	1.8164
	PEAE/M (SEC)		20.026	9.8828	4.5390
	AE/AT		7.0997	25.745	118.24

TABLE 183

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4992.6	3456.1	2884.8	2008.7
ENTHALPY (KILOCALORIES)	-22.426	-145.60	-185.79	-219.75
ENTROPY (CALORIES/DEG.K)	223.11	223.11	223.11	223.11
HEAT CAPACITY (CAL/K)	32.593	31.490	31.060	30.547
MOLES OF GAS	3.8039	3.2769	3.1139	3.0378
MOLECULAR COMPOSITION:				
H	0.1822	0.0381	0.0064	0.0000
F	1.0864	0.5446	0.3801	0.3548
MG	0.1115	0.0368	0.0033	0.0000
H2	0.0147	0.0016	0.0002	0.0000
HF	1.6090	1.7814	1.8159	1.8226
MGH	0.0019	0.0000	0.0000	0.0000
MGF	0.2917	0.0749	0.0120	0.0000
MGF2	0.5062	0.7995	0.8960	0.8603
F2	0.0002	0.0000	0.0000	0.0000
CONDENSED PHASES				
MGF2/C/	0	0	0	0
MGF2/L/	0	0	0	0.0509
MG/LIQUID/	0	0	0	0

TABLE 184

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
MGH2		33.000			
OF2		67.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
MGH2	MGH2		-17.000	1.450	298.16
OF2	OF2		3.6000	1.530	128.00
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.5061			
O		1.2407			
F		2.4815			
MG		1.2530			
PROPELLANT ENTHALPY		-16.835	KCAL/100 GM		
PROPELLANT DENSITY		1.503	GM/CC	0.0543	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			303.23	351.82	394.06
IVSP(LB-SEC/CU IN)			16.462	19.100	21.394
TEMPERATURE (K)		4371.6	3039.1	2747.0	2465.8
CP (CAL/GM-DEG.K)		0.35387	0.34766	0.35819	0.36469
MOL. WT.-EFFECTIVE		26.949	30.552	32.068	33.757
CP/CV -EFFECTIVE		1.2632	1.2302	1.2092	1.1925
CF -APPROX.			1.6913	1.9623	2.1979
PEAE/M (SEC)			28.362	21.051	16.027
AE/AT -APPROX.			10.764	58.706	446.95
FROZEN EQUILIBRIA					
ISP (SEC)			279.17	312.58	331.16
TEMPERATURE (K)		4371.6	1743.2	1024.2	559.14
C* (FT/SEC)		5768.5			
CF			1.5571	1.7434	1.8470
PEAE/M (SEC)			20.033	10.512	5.4169
AE/AT			7.6031	29.315	151.07

TABLE 185

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4371.6	3039.1	2747.0	2465.8
ENTHALPY (KILOCALORIES)	-16.835	-122.51	-159.09	-195.30
ENTROPY (CALORIES/DEG.K)	232.02	232.02	232.02	232.02
HEAT CAPACITY (CAL/K)	35.387	34.766	35.819	36.469
MOLES OF GAS	3.7108	3.2731	3.1184	2.9624
MOLECULAR COMPOSITION:				
H	0.1917	0.0646	0.0610	0.0538
O	0.2538	0.0933	0.0758	0.0569
F	0.1083	0.0156	0.0109	0.0069
MG	0.2279	0.1800	0.1833	0.1712
H2	0.0819	0.0406	0.0357	0.0286
H2O	0.1187	0.1782	0.1564	0.1260
HF	1.3597	1.4952	1.7229	1.9516
O2	0.1451	0.1615	0.1320	0.1010
OH	0.1985	0.0976	0.0714	0.0466
F2	0.0000	0.0000	0.0000	0.0000
MGH	0.0087	0.0005	0.0002	0.0000
MGF	0.2604	0.0771	0.0452	0.0221
MGF2	0.3765	0.4468	0.3512	0.2504
MGO	0.0332	0.0115	0.0060	0.0025
MGOH	0.3464	0.4104	0.2664	0.1447
CONDENSED PHASES				
MGO/C/	0	0.1267	0.4007	0.6621
MGF2/C/	0	0	0	0
MGO2H2/C/	0	0	0	0
MGO/L/	0	0	0	0
MGF2/L/	0	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 186

CASE						
PROPELLANT COMPOSITION		WEIGHT%	MOLAR			
MGH2		61.000				
H2O2		39.000				
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.	
MGH2	MGH2		-17.000	1.450	298.16	
H2O2	H2O2		-44.840	1.443	298.16	
ATOMIC COMPOSITION(GM AT/100GM)						
H		6.9255				
O		2.2930				
MG		2.3162				
PROPELLANT ENTHALPY		-90.786	KCAL/100 GM			
PROPELLANT DENSITY		1.447	GM/CC		0.0523	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST	
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000	
SHIFTING EQUILIBRIA						
ISP (SEC)			279.58	327.26	367.72	
IVSP(LB-SEC/CU IN)			14.619	17.112	19.228	
TEMPERATURE (K)		3073.1	2420.1	2145.1	1815.7	
CP (CAL/GM-DEG.K)		0.60998	0.60886	0.60023	0.58215	
MOL. WT.-EFFECTIVE		24.961	26.736	27.664	28.476	
CP/CV -EFFECTIVE		1.1501	1.1390	1.1360	1.1362	
CF -APPROX.			1.7307	2.0258	2.2763	
PEAE/M (SEC)			27.992	20.486	14.991	
AE/AT -APPROX.			11.791	63.405	464.00	
FROZEN EQUILIBRIA						
ISP (SEC)			261.77	300.97	329.64	
TEMPERATURE (K)		3073.1	1721.1	1248.1	844.23	
C* (FT/SEC)		5197.5				
CF (SEC)			1.6204	1.8631	2.0406	
PEAE/M (SEC)			22.774	14.363	8.8708	
AE/AT			9.5927	44.457	274.56	

TABLE 187

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3073.1	2420.1	2145.1	1815.7
ENTHALPY (KILOCALORIES)	-90.786	-180.62	-213.87	-246.19
ENTROPY (CALORIES/DEG.K)	247.20	247.20	247.20	247.20
HEAT CAPACITY (CAL/K)	60.998	60.886	60.023	58.215
MOLES OF GAS	4.0063	3.7403	3.6148	3.5117
MOLECULAR COMPOSITION:				
H	0.0810	0.0604	0.0384	0.0121
O	0.0000	0.0000	0.0000	0.0000
MG	0.2159	0.1714	0.1084	0.0404
H2	2.9077	3.2059	3.3333	3.4369
H2O	0.2276	0.1508	0.0857	0.0173
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0023	0.0006	0.0001	0.0000
MGH	0.0373	0.0031	0.0007	0.0001
MGO	0.0003	0.0000	0.0000	0.0000
MGOH	0.5341	0.1482	0.0482	0.0048
CONDENSED PHASES				
MGO/C/	0.9925	1.9935	2.1590	2.2709
MGO2H2/C/	0	0	0	0
MGO/L/	0.5362	0	0	0
MG/LIQUID/	0	0	0	0

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
MGH2		64.000			
N2O4		36.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
MGH2	MGH2		-17.000	1.450	298.16
N2O4	N2O4		-5.4000	1.430	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.8603			
N		0.7825			
O		1.5649			
MG		2.4301			
PROPELLANT ENTHALPY		-43.425	KCAL/100 GM		
PROPELLANT DENSITY		1.443	GM/CC	0.0521	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			260.09	298.45	328.30
IVSP(LB-SEC/CU IN)			13.558	15.557	17.113
TEMPERATURE (K)		2957.3	1950.5	1438.7	1228.7
CP (CAL/GM-DEG.K)		0.51371	0.48647	0.45898	0.45450
MOL. WT.-EFFECTIVE		26.208	27.143	27.135	28.901
CP/CV -EFFECTIVE		1.1732	1.1772	1.1898	1.1782
CF -APPROX.			1.6939	1.9437	2.1381
PEAE/M (SEC)			23.887	15.359	11.196
AE/AT -APPROX.			10.586	50.015	364.58
FROZEN EQUILIBRIA					
ISP (SEC)			246.12	283.40	308.60
TEMPERATURE (K)		2957.3	1519.7	999.08	582.11
C* (FT/SEC)		4940.2			
CF (SEC)			1.6029	1.8457	2.0098
PEAE/M (SEC)			20.369	11.630	6.2226
AE/AT			9.0268	37.870	202.63

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2957.3	1950.5	1438.7	1228.7
ENTHALPY (KILOCALORIES)	-43.425	-121.17	-145.79	-167.29
ENTROPY (CALORIES/DEG.K)	220.93	220.93	220.93	220.93
HEAT CAPACITY (CAL/K)	51.371	48.647	45.898	45.450
MOLES OF GAS	3.8156	3.6842	3.6853	3.4600
MOLECULAR COMPOSITION:				
H	0.0482	0.0034	0.0001	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
MG	0.7731	0.8546	0.8626	0.6950
H2	2.1865	2.4219	2.4288	2.4299
H2O	0.0226	0.0001	0.0000	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0002	0.0000	0.0000	0.0000
N2	0.3912	0.3912	0.3912	0.3347
NO	0.0000	0.0000	0.0000	0.0000
MGH	0.1148	0.0106	0.0025	0.0005
MGO	0.0001	0.0000	0.0000	0.0000
MGOH	0.2788	0.0023	0.0000	0.0000
CONDENSED PHASES				
MGO/C/	1.2632	1.5626	1.5649	1.5649
MG3N2/C/	0	0	0	0.0566
MGO2H2/C/	0	0	0	0
MGO/L/	0	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 190

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
MGH2		24.000			
NF3		76.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
MGH2	MGH2		-17.000	1.450	298.16
NF3	NF3		-32.000	1.532	144.00
ATOMIC COMPOSITION(GM AT/100GM)					
H		1.8226			
N		1.0703			
F		3.2109			
MG		0.9113			
PROPELLANT ENTHALPY		-49.742	KCAL/100 GM		
PROPELLANT DENSITY		1.511	GM/CC	0.0546	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			300.99	343.13	377.18
IVSP(LB-SEC/CU IN)			16.437	18.738	20.598
TEMPERATURE (K)		4579.9	2816.7	2282.1	1961.9
CP (CAL/GM-DEG.K)		0.33238	0.31904	0.32361	0.33635
MOL. WT.-EFFECTIVE		28.200	31.057	32.902	35.789
CP/CV -EFFECTIVE		1.2690	1.2509	1.2295	1.1977
CF -APPROX.			1.6805	1.9158	2.1060
PEAE/M (SEC)			26.052	17.477	12.565
AE/AT -APPROX.			9.8978	48.790	350.78
FROZEN EQUILIBRIA					
ISP (SEC)			278.56	313.91	332.92
TEMPERATURE (K)		4579.9	1806.8	1007.4	504.89
C* (FT/SEC)		5762.4			
CF (SEC)			1.5553	1.7527	1.8588
PEAE/M (SEC)			19.886	9.8392	4.6496
AE/AT			7.5552	27.468	129.80

TABLE 191

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4579.9	2816.7	2282.1	1961.9
ENTHALPY (KILOCALORIES)	-49.742	-153.86	-185.05	-213.24
ENTROPY (CALORIES/DEG.K)	217.93	217.93	217.93	217.93
HEAT CAPACITY (CAL/K)	33.238	31.904	32.361	33.635
MOLES OF GAS	3.5461	3.2199	3.0393	2.7941
MOLECULAR COMPOSITION:				
H	0.1584	0.0359	0.0140	0.0069
N	0.0019	0.0000	0.0000	0.0000
F	0.3120	0.0048	0.0002	0.0000
MG	0.1273	0.1182	0.0877	0.0616
H2	0.0327	0.0536	0.1135	0.1495
HF	1.5955	1.6791	1.5814	1.5167
N2	0.5342	0.5351	0.5352	0.5352
MGH	0.0032	0.0003	0.0001	0.0000
MGF	0.2582	0.0585	0.0176	0.0053
MGF2	0.5226	0.7342	0.6896	0.5190
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
MGF2/C/	0	0	0	0
MG3N2/C/	0	0	0	0
MGF2/L/	0	0	0.1163	0.3254
MG/LIQUID/	0	0	0	0

TABLE 192

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
MGH2		18.000			
CLF3		82.000			
INGREDIENT DATA:	FORMULA	HEAT OF FORM.	DENSITY	REF. TEMP.	
MGH2	MGH2	-17.000	1.450	298.16	
CLF3	CLF3	-44.400	1.810	298.16	
ATOMIC COMPOSITION(GM AT/100GM)					
H		1.3670			
F		2.6607			
MG		0.6835			
CL		0.6869			
PROPELLANT ENTHALPY		-50.997	KCAL/100 GM		
PROPELLANT DENSITY		1.732	GM/CC	0.0626	LB/CU IN
	CHAMBER	EXHAUST	EXHAUST	EXHAUST	
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000	
SHIFTING EQUILIBRIA					
ISP (SEC)		263.34	300.53	330.95	
IVSP(LB-SEC/CU IN)		16.485	18.813	20.717	
TEMPERATURE (K)	4347.3	2540.1	2164.1	1837.6	
CP (CAL/GM-DEG.K)	0.26791	0.27076	0.28146	0.29027	
MOL. WT.-EFFECTIVE	33.609	37.207	39.914	42.816	
CP/CV -EFFECTIVE	1.2832	1.2457	1.2149	1.1903	
CF -APPROX.		1.6540	1.6876	2.0787	
PEAF/M (SEC)		22.413	15.598	11.212	
AE/AT -APPROX.		9.5793	48.984	352.10	
FROZEN EQUILIBRIA					
ISP (SEC)		246.89	277.91	293.98	
TEMPERATURE (K)	4347.3	1662.9	939.77	493.75	
C* (FT/SEC)	5122.5				
CF		1.5507	1.7456	1.8465	
PEAF/M (SEC)		17.326	8.6987	4.3204	
AE/AT		7.4050	27.318	135.68	

TABLE 193

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	4347.3	2540.1	2164.1	1837.6
ENTHALPY (KILOCALORIES)	-50.997	-130.70	-154.80	-176.87
ENTROPY (CALORIES/DEG.K)	182.23	182.23	182.23	182.23
HEAT CAPACITY (CAL/K)	26.791	27.076	28.146	29.027
MOLES OF GAS	2.9754	2.6877	2.5054	2.3356
MOLECULAR COMPOSITION:				
H	0.0350	0.0001	0.0000	0.0000
F	0.3913	0.1139	0.0550	0.0171
MG	0.0098	0.0000	0.0000	0.0000
CL	0.5337	0.6643	0.7069	0.7194
H2	0.0036	0.0000	0.0000	0.0000
HCL	0.0977	0.0312	0.0227	0.0196
HF	1.2268	1.3356	1.3442	1.3473
F2	0.0001	0.0000	0.0000	0.0000
CL2	0.0037	0.0178	0.0259	0.0386
MGH	0.0001	0.0000	0.0000	0.0000
MGCL	0.0029	0.0000	0.0000	0.0000
MGCL2	0.0126	0.0055	0.0038	0.0032
MGF	0.0537	0.0000	0.0000	0.0000
MGF2	0.3843	0.3744	0.2489	0.1261
MGFCL	0.2201	0.1447	0.0979	0.0643
CONDENSED PHASES				
MGF2/C/	0	0	0	0
MGF2/L/	0	0.1588	0.3328	0.4899
MGCL2/C/	0	0	0	0
MGCL2/L/	0	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 194

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
CLO3F		43.500			
MGH2		56.500			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
CLO3F	CLO3F		-10.100	1.430	298.16
MGH2	MGH2		-17.000	1.450	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.2907			
O		1.2737			
F		0.4246			
MG		2.1454			
CL		0.4246			
PROPELLANT ENTHALPY		-40.759	KCAL/100 GM		
PROPELLANT DENSITY		1.441	GM/CC	0.0521	LB/CU IN

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA				
ISP (SEC)		260.25	303.32	336.33
IVSP(LB-SEC/CU IN)		13.552	15.794	17.617
TEMPERATURE (K)	3101.5	2381.2	2020.3	1675.2
CP (CAL/GM-DEG.K)	0.43447	0.44183	0.43254	0.42326
MOL. WT.-EFFECTIVE	29.350	30.827	31.790	33.219
CP/CV -EFFECTIVE	1.1846	1.1708	1.1689	1.1646
CF -APPROX.		1.7576	2.0484	2.2849
PEAF/M (SEC)		25.660	18.114	12.886
AE/AT -APPROX.		11.792	61.168	435.14
FROZEN EQUILIBRIA				
ISP (SEC)		237.08	270.46	294.45
TEMPERATURE (K)	3101.5	1573.5	1066.6	685.20
C* (FT/SEC)	4764.0			
CF		1.6011	1.8265	1.9886
PEAF/M (SEC)		19.551	11.835	6.8548
AE/AT		8.9846	39.963	231.47

TABLE 195

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3101.5	2381.2	2020.3	1675.2
ENTHALPY (KILOCALORIES)	-40.759	-116.60	-146.49	-172.31
ENTROPY (CALORIES/DEG.K)	213.20	213.20	213.20	213.20
HEAT CAPACITY (CAL/K)	43.447	44.183	43.254	42.326
MOLES OF GAS	3.4072	3.2439	3.1456	3.0103
MOLECULAR COMPOSITION:				
H	0.0617	0.0361	0.0127	0.0025
O	0.0000	0.0000	0.0000	0.0000
F	0.0000	0.0000	0.0000	0.0000
MG	0.5396	0.6043	0.5600	0.4966
CL	0.0019	0.0009	0.0002	0.0000
H2	1.6808	1.9105	2.0142	2.0928
H2O	0.0506	0.0152	0.0017	0.0000
HCL	0.0930	0.0837	0.0425	0.0139
HF	0.1875	0.2292	0.1901	0.0874
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0007	0.0000	0.0000	0.0000
F2	0	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
MGH	0.0773	0.0089	0.0026	0.0006
MGCL	0.0105	0.0020	0.0005	0.0001
MGCL2	0.0847	0.0972	0.1040	0.1196
MGF	0.0350	0.0100	0.0044	0.0011
MGF2	0.0262	0.0208	0.0233	0.0238
MGFCL	0.1497	0.1436	0.1735	0.1713
MGO	0.0003	0.0000	0.0000	0.0000
MGOH	0.4075	0.0814	0.0109	0.0005
CONDENSED PHASES				
MGO/C/	0	1.1770	1.2611	1.2731
MGF2/C/	0	0	0	0
MGO2H2/C/	0	0	0	0
MGO/L/	0.8146	0	0	0
MGF2/L/	0	0	0	0.0586
MGCL2/C/	0	0	0	0
MGCL2/L/	0	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 196

CASE

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
MGH2		60.000			
NO2CLO4		40.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.
MGH2	MGH2		-17.000	1.450	298.16
NO2CLO4	NO2CLO4		8.0000	2.220	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.5565			
N		0.2750			
O		1.6499			
MG		2.2782			
CL		0.2750			
PROPELLANT ENTHALPY		-36.530	KCAL/100 GM		
PROPELLANT DENSITY		1.684	GM/CC	0.0608	LB/CU IN
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)			262.37	300.95	343.97
IVSP(LB-SEC/CU IN)			15.959	18.671	20.923
TEMPERATURE (K)		3117.6	2464.2	2154.9	1745.9
CP (CAL/GM-DEG.K)		0.47135	0.47885	0.47245	0.45441
MOL. WT.-EFFECTIVE		29.595	30.882	31.912	32.676
CP/CV -EFFECTIVE		1.1661	1.1552	1.1518	1.1545
CF -APPROX.			1.7647	2.0645	2.3135
PEAE/M (SEC)			26.294	19.020	13.429
AE/AT -APPROX.			12.034	63.962	451.62
FROZEN EQUILIBRIA					
ISP (SEC)			239.85	274.62	300.41
TEMPERATURE (K)		3117.6	1661.0	1213.2	812.42
C* (FT/SEC)		4783.6			
CF			1.6132	1.8470	2.0205
PEAE/M (SEC)			20.474	12.905	7.9003
AE/AT			9.3704	43.400	265.68

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.7	2.000	0.2000
TEMPERATURE (KELVIN)	3117.6	2464.2	2154.9	1745.9
ENTHALPY (KILOCALORIES)	-36.530	-115.64	-144.81	-172.51
ENTROPY (CALORIES/DEG.K)	216.75	216.75	216.75	216.75
HEAT CAPACITY (CAL/K)	47.135	47.885	47.245	45.441
MOLES OF GAS	3.3789	3.2382	3.1336	3.0603
MOLECULAR COMPOSITION:				
H	0.0678	0.0554	0.0307	0.0050
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
MG	0.5210	0.5761	0.5430	0.5034
CL	0.0021	0.0017	0.0007	0.0000
H2	1.8671	2.0770	2.1866	2.2614
H2O	0.0623	0.0384	0.0112	0.0002
HCL	0.1008	0.1123	0.0877	0.0260
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0008	0.0002	0.0000	0.0000
N2	0.1374	0.1375	0.1375	0.1375
NO	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
MGH	0.0793	0.0092	0.0029	0.0007
MGCL	0.0104	0.0022	0.0008	0.0001
MGCL2	0.0808	0.0794	0.0929	0.1244
MGO	0.0003	0.0000	0.0000	0.0000
MGOH	0.4485	0.1487	0.0396	0.0015
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
MGO/C/	0	1.4626	1.5991	1.6482
MG3N2/C/	0	0	0	0
MGO2H2/C/	0	0	0	0
MGO/L/	1.1379	0	0	0
MGCL2/C/	0	0	0	0
MGCL2/L/	0	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 198

CASE						
PROPELLANT COMPOSITION		WEIGHT%	MOLAR			
	MGH2	56.000				
	NH4CLO4	44.000				
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.	
	MGH2	MGH2	-17.000	1.450	298.16	
	NH4CLO4	NH4CLO4	-69.420	1.960	298.16	
ATOMIC COMPOSITION(GM AT/100GM)						
	H	5.7506				
	N	0.3745				
	O	1.4979				
	MG	2.1264				
	CL	0.3745				
PROPELLANT ENTHALPY		-62.144	KCAL/100 GM			
PROPELLANT DENSITY		1.637	GM/CC	0.0592	LB/CU IN	
		CHAMBER	EXHAUST	EXHAUST	EXHAUST	
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000	
SHIFTING EQUILIBRIA						
	ISP (SEC)		261.12	301.61	330.60	
	IVSP(LB-SEC/CU IN)		15.448	17.785	19.559	
	TEMPERATURE (K)	2914.1	1986.6	1501.8	1187.5	
	CP (CAL/GM-DEG.K)	0.52970	0.50440	0.47689	0.45773	
	MOL. WT.-EFFECTIVE	25.684	26.994	27.092	28.124	
	CP/CV -EFFECTIVE	1.1710	1.1709	1.1816	1.1826	
	CF -APPROX.		1.6948	1.9511	2.1458	
	PEAF/M (SEC)		24.369	15.943	11.042	
	AE/AT -APPROX.		10.763	51.741	358.35	
FROZEN EQUILIBRIA						
	ISP (SEC)		247.18	284.37	309.94	
	TEMPERATURE (K)	2914.1	1508.8	1003.1	592.94	
	C* (FT/SEC)	4957.0				
	CF		1.6044	1.8458	2.0117	
	PEAF/M (SEC)		20.547	11.874	6.4398	
	AE/AT		9.0748	38.535	208.99	

TABLE 199

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2914.1	1986.6	1501.8	1187.5
ENTHALPY (KILOCALORIES)	-62.144	-140.50	-166.00	-187.76
ENTROPY (CALORIES/DEG.K)	225.14	225.14	225.14	225.14
HEAT CAPACITY (CAL/K)	52.970	50.440	47.689	45.773
MOLES OF GAS	3.6934	3.7046	3.6911	3.5557
MOLECULAR COMPOSITION:				
H	0.0463	0.0048	0.0002	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
MG	0.4531	0.4472	0.4404	0.3396
CL	0.0010	0.0000	0.0000	0.0000
H2	2.6019	2.6556	2.6737	2.8752
H2O	0.0352	0.0003	0.0000	0.0000
HCL	0.1036	0.0242	0.0015	0.0001
C2	0.0000	0.0000	0.0000	0.0000
OH	0.0002	0.0000	0.0000	0.0000
N2	0.1871	0.1872	0.1872	0.1534
NO	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
MGH	0.0718	0.0062	0.0015	0.0002
MGCL	0.0082	0.0005	0.0000	0.0000
MGCL2	0.1308	0.1749	0.1865	0.1872
MGO	0.0001	0.0000	0.0000	0.0000
MGOH	0.2538	0.0037	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0002	0.0000	0.0000	0.0000
CONDENSED PHASES				
MGO/C/	1.2086	1.4939	1.4979	1.4979
MG3N2/C/	0	0	0	0.0338
MG02H2/C/	0	0	0	0
MGO/L/	0	0	0	0
MGCL2/C/	0	0	0	0
MGCL2/L/	0	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 200

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LIST OF NOMENCLATURE

A = cross-sectional area of the nozzle at any general position
A = a chemical reactant in the general equation of equilibrium
A' = frontal area of an individual particle in multiphase flow
A^* = area of the nozzle at the throat, i.e. at Mach 1
A_e = area of the nozzle at its exit position
A_{ij} = atoms of the i th element present in the j th exhaust specie
A'_j = a numerical coefficient which relates an incremental change in concentration to an incremental change in free energy
a = the number of moles of reactant A in the general equation of equilibrium
a = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
a' = acceleration of a solid particle during flow through the nozzle
a_1 = mass fraction of the gas phase in multiphase flow
a_2 = mass fraction of the condensed phase in multiphase flow
a_{ij} = a coefficient which relates the amount of an exhaust specie present to the maximum amount which could theoretically exist, according to the mass balance

B = a chemical reactant in the general equation of equilibrium
B_j = the maximum number of moles of a given specie which can theoretically exist for a given propellant composition
B_o = the maximum total moles of gas which can theoretically exist for a given propellant composition
B'_j = a numerical coefficient which relates an incremental change in concentration to one in free energy
b = the number of moles of reactant B in the general equation of equilibrium
b = an arbitrary parameter proportional to boost velocity
b = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature

C = a chemical product of combustion in the general equation of equilibrium
C'_j = a numerical coefficient which relates an incremental change in concentration to one in free energy
C_D = drag coefficient
c = the number of moles of product C in the general equation of equilibrium
c = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
c = velocity of pressure wave propagation
c^* = characteristic exhaust velocity, or the velocity of sound at the nozzle throat
c_F = thrust coefficient
c_p = specific heat capacity at constant pressure
c_v = specific heat capacity at constant volume
c_w = discharge coefficient
cv_g = constant colume specific heat capacity of the gas phase in multiphase flow
cp_g = constant pressure specific heat capacity of the gas phase in multiphase flow
cp_s = constant pressure specific heat capacity of the condensed phase in multiphase flow
cp_l = constant pressure specific heat capacity of a newly-formed condensed phase, either solid or liquid

D = a chemical product of combustion in the general equation of equilibrium
D = substantial derivative
d = the number of moles of product D in the general equation of equilibrium
d = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
d = standard derivative

E = internal energy of the system
E = a chemical product of combustion in the general equation of equilibrium
E' = energy emitted from an individual condensed particle by radiation
E_i = total gram-atoms of the i th element present in a given propellant formulation
e = the number of moles of product E in the general equation of equilibrium
e = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
e = base of natural logarithms

F = Gibbs' free energy of the system
F = a chemical product of combustion in the general equation of equilibrium
F° = ideal free energy at 1 atm pressure
F' = thrust
F_i = field forces
F_p = force acting on an individual condensed particle in multiphase flow
f = the number of moles of product F in the general equation of equilibrium
f = mass ratio of condensed species to gas species in multiphase flow

g = acceleration of gravity (32.174 ft/sec^2)
g' = local acceleration of gravity

H = enthalpy of the system
H' = reference enthalpy at a reference temperature
H_o = stagnation enthalpy of the system
H_c = enthalpy of the combustion products in the chamber
H_e = enthalpy of the combustion products at the nozzle exit
H_j = enthalpy of the j th specie
ΔH_v = molar latent heat of phase change
ΔH_{f_j} = heat-of-formation of the j th component at a standard reference temperature
h = average heat transfer coefficient
h_{bo} = height of a missile at time of burnout

I = total impulse, lb-sec
Isp = specific impulse, lb-sec/lb
Ivsp = volumetric specific impulse
i = designation for any element in a propellant formulation

J = mechanical equivalent of heat
j = designation for any product of combustion

K = thermodynamic equilibrium constant
K' = empirical constant
K_p = thermodynamic equilibrium pressure constant
K_n = thermodynamic equilibrium concentration constant
$\underline{k}$ = mean ratio of specific heat capacities, C_p/C_v, at any general time
$\bar{k}$ = mean specific heat ratio during nozzle expansion

ln = natural logarithm to the base e = 2.718

M = Mach number
M_j = moles of a given specie j at any general time
M_o = total moles of gas existing at any general time
MW = mean molecular weight of the combustion products
MW* = mean molecular weight of the combustion products at the throat, i.e. at Mach 1
m = mass rate of flow
m = designation for any gaseous element in the products of combustion
m' = mass of an individual condensed particle in multiphase flow

n_A, n_B, n_C,...n_j = molar equilibrium concentrations of the respective species in the general equation of equilibrium
n_T = total moles of gas
n_g = moles of gas in multiphase flow
n = designation for any gaseous molecule in the products of combustion
n_j = moles of the j th specie
$n_{T_{max}}$ = maximum possible moles of gas which can theoretically be formed from a given propellant composition
Δn = total moles of products minus total moles of reactants

r = radius of nozzle cross-section at any general position
p = pressure
p = designation for any condensed phase in the products of combustion
p_a = external pressure of the surrounding fluid medium
p_c = pressure in the combustion chamber
p_e = pressure of the combustion products at the nozzle exit
p_o = stagnation pressure of the fluid ($p_o = p_c$)
p^* = pressure at the throat of the nozzle, i.e. at Mach 1
p_T = total pressure at any given position
p_j = partial pressure of the j th specie
pV = work of expansion
p_A, p_B, p_C,...p_j = equilibrium partial pressures of the combustion products in the general equation of equilibrium

q = energy absorbed by the system from its surroundings
q' = total heat transferred between the gas and condensed phases in multiphase flow
q_r = reversible energy change at constant temperature

R = universal gas constant
R_e = Reynolds' number
$\bar{R}$ = R/MW
r = radius of an individual condensed particle in multiphase flow

S = absolute entropy of the system
S° = ideal entropy at 1 atm pressure
S' = reference entropy at a reference temperature and 1 atm pressure
S_j = entropy of the j th specie
S_{x_b} = horizontal distance of a missile from its launching position at time of burnout
s = empirical constant dependent upon missile design conditions

T = temperature of the system
T_o = stagnation temperature of the system
T_c = combustion or chamber temperature ($T_o = T_c$)
T_e = temperature of the products of combustion at the nozzle exit
T^* = temperature of the system at the nozzle throat, i.e. at Mach 1
T_g = temperature of the gas phase in multiphase flow
T_s = temperature of the condensed phase in multiphase flow
t = time

$\underline{\underline{U}}$ = unit tensor

V = volume of the fluid system at any general time
V' = specific volume of fluid system
V'_g = specific volume of the gas phase in multiphase flow
V_p = volume of propellant in a missile
V_o = velocity vector of the fluid system
v = fluid velocity at any general position
v' = effective exhaust velocity
v_e = velocity of the products of combustion at the nozzle exit
v^* = fluid velocity at the nozzle throat, i.e. at Mach 1
v_{max} = maximum attainable exhaust velocity
v_x = one-dimensional contribution to fluid velocity ($v_x = v$ for unidirectional flow)
v_g = velocity of the gas phase in multiphase flow
v_s = velocity of the condensed phase in multiphase flow
v_{g_o} = velocity of the gas phase at the instant a condensed particle enters the gas stream
v_b = incremental boost velocity imparted to a missile

W_f = mass of missile hardware, or the total mass of a missile at burnout
W_i = total initial mass of the missile hardware and its propellant
W_m = total mass of the missile ($W_m = W_i$)
W_p = total mass of propellant consumed during combustion in time t
W_o = non-expansion work done by the system
w = work done by the system on its surroundings

x = linear distance along the nozzle axis
x = general concentration of a specie in the products of combustion
x_j = the ratio of the moles of specie j in the combustion products to the total possible moles of specie j which could theoretically be formed
x_o = the ratio of the total moles of gas in the combustion products to the total possible moles of gas which could theoretically be formed

y = general mathematical representation of the free energy of mixing and pressure as a function of concentration

y = empirical coefficient dependent upon physical conditions of the system and surrounding, e.g. missile surface area, density of surrounding medium, etc.

z = potential energy of position

α = half-angle of nozzle divergence

ρ = density of the fluid system or of the propellant

ρ_c = stagnation density of the fluid system

ρ^* = density of the fluid system at the nozzle throat, i.e. at Mach 1

ρ_g = density of the gas phase in multiphase flow

ρ_s = density of the condensed phase in multiphase flow

μ = fluid viscosity

μ_g = viscosity of the gas phase in multiphase flow

ϕ = mean ratio of the specific heat capacities, C_p/C_v, for multiphase flow

∇ = vector operator

Δ = incremental change in a property

σ = Stefan-Boltzmann constant

ϵ = emissivity constant

β = angle of missile trajectory with the horizontal

∂ = partial derivative

η = ideal cycle efficiency

π = 3.1416