THIRD ANNUAL PROGRESS REPORT

ANALYTICAL STUDY OF CATALYTIC REACTORS FOR HYDRAZINE DECOMPOSITION

by

Arthur S. Kesten

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May, 1969

CONTRACT NAS 7-458

United Aircraft Research Laboratories

UNITED AIRCRAFT CORPORATION

EAST HARTFORD, CONNECTICUT
THIRD ANNUAL PROGRESS REPORT

ANALYTICAL STUDY OF CATALYTIC REACTORS FOR HYDRAZINE DECOMPOSITION

by
Arthur S. Kesten

prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May, 1969

CONTRACT NAS 7-458

United Aircraft Research Laboratories

UNITED AIRCRAFT CORPORATION
EAST HARTFORD, CONNECTICUT
# Analytical Study of Catalytic Reactors for Hydrazine Decomposition

Third Annual Progress Report

April 15, 1968 - April 14, 1969

Contract NAS 7-458

## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>FOREWORD</td>
<td>ii</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>DESCRIPTION OF THE TRANSIENT MODEL</td>
<td>3</td>
</tr>
<tr>
<td>RESULTS OF CALCULATIONS</td>
<td>10</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>14</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>15</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>18</td>
</tr>
<tr>
<td>FIGURES</td>
<td>25</td>
</tr>
</tbody>
</table>
ABSTRACT

Analytical studies of catalyzed hydrazine decomposition reaction chambers were performed in order to establish procedures capable of predicting the effects of pulse operation of the reactor for an arbitrary duty cycle on the transient behavior of the system. These studies included an extension of a computer program previously developed to calculate temperature and reactant concentrations as functions of time and axial position in typical reaction chamber configurations. The extended program includes consideration of the effects of heat conduction and diffusion when flow is stopped. In addition, reaction chamber fluid dynamics are taken into account by allowing for feed pressure and mass flow rate changes with time. The effects of these changes on thermal and catalytic decomposition of reactants, along with heat and mass transfer between the free-gas phase and the gas within the pores of the catalyst pellets, are considered.

A series of calculations was made using the computer program to evaluate the effects of duty cycle, nominal chamber pressure, bed loading, and catalyst bed configuration on the transient temperature, pressure, and reactant concentration distributions in the reactor system. The results of these calculations are illustrated in the report.
FOREGROUND

This work was performed by United Aircraft Research Laboratories for
the National Aeronautics and Space Administration under Contract NAS 7-458
initiated April 15, 1966.

Included among those who cooperated in performance of the work under
Contract NAS 7-458 were Dr. A. S. Kesten, Program Manager, Dr. W. G. Burwell,
Chief, Kinetics and Thermal Sciences Section, Mr. D. B. Smith, and Mrs. E. Smith
of UARL.

This work was conducted under program management of the NASA Chief,
Liquid Propulsion Experimental Engineering Systems, NASA Headquarters,
Washington, D. C., and the Technical Manager was Mr. T. W. Price, Jet
Propulsion Laboratory, Pasadena, California.
Analytical Study of Catalytic Reactors for Hydrazine Decomposition

Third Annual Progress Report

April 15, 1968 - April 14, 1969

Contract No. NAS 7-458

SUMMARY

The Research Laboratories of United Aircraft Corporation under Contract NAS 7-458 with the National Aeronautics and Space Administration have been performing an analytical study of catalytic reactors for hydrazine decomposition. This third annual technical report summarizes work performed under this contract from April 15, 1968 to April 14, 1969. Work during this period has included the development of a computer program representing a transient model of a distributed-feed catalyzed hydrazine decomposition reaction chamber. The model describes the behavior of reactors operated under conditions of continuous flow as well as pulsed flow for an arbitrary duty cycle. Both thermal and catalytic decomposition of reactants are considered along with simultaneous heat and mass transfer between the free-gas phase and the gas within the pores of the catalyst pellets. The effects of heat conduction and diffusion when flow is stopped are included in the model. In addition, reaction chamber fluid dynamics are taken into account in order to allow consideration of chamber pressure and mass flow rate changes with time. Calculations have been made of temperature and species concentration distributions as functions of time and axial position in typical hydrazine reaction chambers for a number of pulse duty cycles, mass flow rate distributions, and catalyst bed configurations.

Calculated transient temperature profiles in a continuous flow reactor have been compared with temperatures measured as a function of time in a small scale engine run at Jet Propulsion Laboratory. Generally good agreement between theoretical and experimental results was found.

The computer programs representing both the steady-state and transient models of a catalyzed hydrazine reactor have been described in detail in two computer manuals. These manuals contain operating instructions for these programs as well as descriptions of input and output formats.
INTRODUCTION

Under Contract NAS 7-458, the Research Laboratories of United Aircraft Corporation are performing analytical studies of the behavior of distributed-feed catalytic reactors for hydrazine decomposition. The specific objectives of this program are (a) to develop computer programs for predicting the temperature and concentration distributions in monopropellant hydrazine catalytic reactors in which hydrazine can be injected at arbitrary locations in the reaction chamber and (b) to perform calculations using these computer programs to demonstrate the effects of various system parameters on the performance of the reactor.

Progress previously reported in the first annual report (Ref. 1) included the development of computer programs which describe the steady-state and transient behavior of a hydrazine reactor operated under conditions of constant, continuous flow, in which complete radial mixing in the free-gas (or liquid) phase was assumed. Progress previously reported in the second annual report (Ref. 2) included an extension of the steady-state program to include radial as well as axial variations in temperature and concentrations in order to permit an analysis of various injection schemes and catalyst bed configurations which exhibit radial nonuniformities. These programs had been used to calculate temperature and reactant concentration distributions as functions of initial bed temperature, feed temperature, chamber pressure, mass flow rate distribution, catalyst size distribution, and axial injector locations.

During the third year of contract effort attention has been focused on extending the transient model of the reactor system to take the effects of reaction chamber fluid dynamics on transient response into account, and to permit consideration of pulse operation of the reactor for an arbitrary duty cycle. In addition, computer manuals have been prepared describing to potential users the operation of both the steady-state and transient computer programs (Refs. 3 and 4). Included in succeeding sections of this report are detailed descriptions of (a) the development of the equations representing the transient model of the reactor system, (b) the use of the computer program representing the transient model to compute transient temperature profiles in a typical continuous flow reactor in order to test the validity of the model by comparing the calculated results with measured temperature profiles, and (c) the use of the transient computer program to calculate the effects on transient temperature and reactant concentration distributions of initial bed temperature, chamber pressure, mass flow rate distribution, catalyst size distribution, and pulse duty cycle.
DESCRIPTION OF THE TRANSIENT MODEL

The analysis of a hydrazine engine reaction system pertains to a reaction chamber packed with catalyst particles into which liquid hydrazine is injected at arbitrarily selected axial locations. Catalyst particles are represented as "equivalent" spheres with a diameter taken as a function of the particle size and shape. Both thermal and catalytic vapor phase decomposition of hydrazine and ammonia are considered in developing equations describing the concentration distributions of these reactants. Diffusion of reactants from the free-gas phase to the outside surface of the catalyst pellets is taken into account. Since the catalyst material is impregnated on the interior and exterior surfaces of porous particles, the diffusion of reactants into the porous structure must also be considered. In addition, the conduction of heat within the porous particles must be taken into account since the decomposition reactions are accompanied by the evolution or absorption of heat.

In generalizing the transient model described in Ref. 1 to consider reactor shutdown as well as start-up, the temperature and the concentration of reactants in the interstitial (free-gas) phase are still assumed to vary only with time and axial distance along the bed. In this system film coefficients are used to describe heat and mass transfer between the interstitial phase and the outside surface of the catalyst pellets. The reactant concentrations, \( c_p \), and the temperature, \( T_p \), are taken as uniform within the interior of the porous particles. Heat and mass diffusion within the particles are taken into account by multiplying the reaction rates computed on the basis of uniform \( c_p \) and \( T_p \) by a utilization factor determined by analogy with the steady-state system (see Ref. 1). In addition, it is assumed that during reactor operation liquid velocities are sufficiently low relative to other rate processes so that, for all practical purposes, steady-state in the liquid and liquid-vapor regions is achieved as soon as the liquid reaches a given axial location in the reactor. No consideration is given to regression of the liquid-vapor interface as the chamber pressure builds up since the overall length of the liquid region in typical reactors is very small compared to the length of the vapor region (Ref. 1). When flow into the reactor is stopped it is easily shown that the residual liquid hydrazine in the reactor vaporizes in just a few milliseconds due to the very rapid decomposition of hydrazine in the liquid region. Therefore, even during reactor shutdown, the liquid regions plays a very small role in determining the transient behavior of the reactor system.

The transient model is concerned then with the vapor region only. The general equations describing the rates of change of enthalpy and reactant concentrations with time and axial distance in the interstitial phase are
\[
\delta \frac{\partial}{\partial t} \left[ \rho_i h_i \right] = - \frac{\partial}{\partial z} \left[ gh_i \right] - H_{N_2 H_4} \rho_{\text{hom}} \delta + F \eta_F \\
- A_c A_p (T_i - T_p) - \frac{4A_w}{d_c} (T_i - T_w) - h_i \sum_j A_p k_c^{ij} (C_i^{ij} - C_p^{ij})
\] (1)

\[
\delta \frac{\partial C_i^{N_2 H_4}}{\partial t} = -G \frac{\partial w_i^{N_2 H_4}}{\partial z} - w_i^{N_2 H_4} \frac{\partial G}{\partial z} + F - \rho_{\text{hom}} \delta - A_p k_c^{N_2 H_4} (C_i^{N_2 H_4} - C_p^{N_2 H_4})
\] (2)

\[
\delta \frac{\partial C_i^{N H_3}}{\partial t} = -G \frac{\partial w_i^{N H_3}}{\partial z} - w_i^{N H_3} \frac{\partial G}{\partial z} + \rho_{\text{hom}} \delta \frac{M_{N H_3}}{M_{N_2 H_4}} - A_p k_c^{N H_3} (C_i^{N H_3} - C_p^{N H_3})
\] (3)

\[
\delta \frac{\partial C_i^{N_2}}{\partial t} = -G \frac{\partial w_i^{N_2}}{\partial z} - w_i^{N_2} \frac{\partial G}{\partial z} + \rho_{\text{hom}} \delta \frac{M_{N_2}}{2M_{N_2 H_4}} - A_p k_c^{N_2} (C_i^{N_2} - C_p^{N_2})
\] (4)

\[
\delta \frac{\partial C_i^{H_2}}{\partial t} = -G \frac{\partial w_i^{H_2}}{\partial z} - w_i^{H_2} \frac{\partial G}{\partial z} + \rho_{\text{hom}} \delta \frac{M_{H_2}}{2M_{N_2 H_4}} - A_p k_c^{H_2} (C_i^{H_2} - C_p^{H_2})
\] (5)

where

\[
W_i^{ij} = \frac{C_i^{ij}}{\rho_i} = \frac{C_i^{ij}}{\sum_j C_i^{ij}}
\] (6)

Equations (1) through (5) can be reduced to a somewhat simpler form with the aid of an overall equation of continuity which can be written as

\[
\delta \frac{\partial \rho_i}{\partial t} = F - \frac{\partial G}{\partial z} - \sum_j A_p k_c^{ij} (C_i^{ij} - C_p^{ij})
\] (7)
Equations (1) through (5) can now be written as

\[
\frac{\delta P}{\delta t} \frac{\partial h_i}{\partial z} = -G \frac{\partial h_i}{\partial z} - A_c A_p (T_i - T_P) - H_{N_2H_4} \rho_{hom} \delta F (h_i - h_f) - 4 \frac{A_w}{d_c} (T_i - T_w)
\]  

(8)

\[
\frac{\delta P}{\delta t} \frac{\partial w_i N_2H_4}{\partial t} + G \frac{\partial w_i N_2H_4}{\partial z} = F - \rho_{hom} \delta - A_p k_c N_2H_4 (c_i N_2H_4 - c_P N_2H_4)
\]

- \[w_i N_2H_4 F + w_i N_2H_4 \sum J A_p k_c (c_i - c_P)
\]

(9)

\[
\frac{\delta P}{\delta t} \frac{\partial w_i NH_3}{\partial t} + G \frac{\partial w_i NH_3}{\partial z} = \rho_{hom} \delta \frac{M_{NH_3}}{M_{N_2H_4}} - A_p k_c NH_3 (c_i NH_3 - c_P NH_3)
\]

- \[w_i NH_3 F + w_i NH_3 \sum J A_p k_c (c_i - c_P)
\]

(10)

\[
\frac{\delta P}{\delta t} \frac{\partial w_i N_2}{\partial t} + G \frac{\partial w_i N_2}{\partial z} = \rho_{hom} \delta \frac{M_{N_2}}{2M_{N_2H_4}} - A_p k_c N_2 (c_i N_2 - c_P N_2)
\]

- \[w_i N_2 F + w_i N_2 \sum J A_p k_c (c_i - c_P)
\]

(11)

\[
\frac{\delta P}{\delta t} \frac{\partial w_i H_2}{\partial t} + G \frac{\partial w_i H_2}{\partial z} = \rho_{hom} \delta \frac{M_{H_2}}{2M_{N_2H_4}} - A_p k_c H_2 (c_i H_2 - c_P H_2)
\]

- \[w_i H_2 F + w_i H_2 \sum J A_p k_c (c_i - c_P)
\]

(12)

The last term on the right side of Eq. (8) represents the heat loss from the bulk vapor to the wall of the reactor. Taking the reactor wall temperature as uniform, the rate of change of wall temperature with time is

\[
m_w c_w \frac{dT_w}{dt} = \pi d_c \int_0^L k_w (T_i - T_w) dz - k_w A_w (T_w - T_a)
\]  

(13)

where the last term on the right side of Eq. (13) represents the heat loss by forced convection from the reactor to the surrounding atmosphere. Heat loss by natural convection or radiation can be represented in Eq. (13) by adding a term of the form \(k_w A_w (T_w - T_a)^{1.25}\) or \(k_w A_w (T_w^4 - T_a^4)\), respectively.

The mass flow rate, \(G\), may be calculated as a function of time and axial position from the inlet mass flow rate, which is a function of pressure, and from Eq. (7). The inlet mass flow rate at any time may be calculated in terms of the steady-state (SS) inlet mass flow rate using
For choked nozzle and for a rate of change of vapor density with time which is approximately uniform throughout the reactor, Eq. (7) reduces to

\[
\frac{\partial G}{\partial z} = F - \sum_j A_p k_c^j (c_i^j - c_p^j) - \frac{A_c}{V_c} \left\{ G - \left( \frac{G}{P \sqrt{M/T_i}} \right) \left( \frac{G}{P \sqrt{M/T_i}} \right)_{ss} \right\}_{z=L} \tag{15}
\]

At a given axial location the rates of change of temperature and reactant concentrations in the catalyst particles with time are given by

\[
\frac{d T_p}{dt} = \frac{1}{\rho_s c_s} \left[ (H r_{het})_{N_2H_4} + (H r_{het})_{NH_3} \right] + \frac{3 \dot{A}_c}{\alpha \rho_s c_s} (T_i - T_p) \tag{17}
\]

\[
\frac{d c_{P,N_2H_4}}{dt} = - \frac{1}{a} r_{het} N_2H_4 + \frac{3 k_c}{a} \left( c_i N_2H_4 - c_p N_2H_4 \right) \tag{18}
\]

\[
\frac{d c_{P,NH_3}}{dt} = \frac{1}{a} \left[ r_{het} N_2H_4 - r_{het} NH_3 \right] + \frac{3 k_c}{a} \left( c_i NH_3 - c_p NH_3 \right) \tag{19}
\]
\[
\frac{dC_{p}^{N_{2}}}{dt} = \frac{1}{a_{p}} \left[ r_{\text{het}}^{N_{2}H_{4}} \frac{M_{N_{2}}}{2M_{N_{2}H_{4}}} + r_{\text{het}}^{NH_{3}} \frac{M_{N_{2}}}{2M_{NH_{3}}} \right] + \frac{3k_{C}^{N_{2}}}{a_{p}a} \left( C_{i}^{N_{2}} - C_{p}^{N_{2}} \right)
\]  
\[
\frac{dC_{p}^{H_{2}}}{dt} = \frac{1}{a_{p}} \left[ r_{\text{het}}^{N_{2}H_{4}} \frac{M_{H_{2}}}{2M_{N_{2}H_{4}}} + r_{\text{het}}^{NH_{3}} \frac{3M_{H_{2}}}{2M_{NH_{3}}} \right] + \frac{3k_{C}^{H_{2}}}{a_{p}a} \left( C_{i}^{H_{2}} - C_{p}^{H_{2}} \right)
\]

where the film coefficients, \( h_{c}, h_{w}, \) and \( k_{c} \), may be estimated from (Ref. 5)

\[
h_{w} = h_{c} = 0.74 \left( \frac{G}{A_{p}\mu} \right)^{-0.41} \left( \frac{C_{p}G}{r} \right) + \frac{k_{i}}{a}
\]  

and

\[
k_{c}^{J} = \left( \frac{0.67G}{\rho_{i}} \right) \left( \frac{\mu}{\rho_{i}D_{i}^{J}} \right)^{-0.667} \left( \frac{G}{A_{p}\mu} \right)^{-0.41} + \frac{D_{i}^{J}}{a}
\]  

It should be noted that the thermal conduction term in Eq. (22) and the simple diffusion term in Eq. (23) become significant only when the mass flow rate is quite small, as it is during reactor shutdown.

Recalling that the reaction of hydrazine on the catalyst surfaces is extremely fast, so that the reaction rate is controlled by the rate of transport of hydrazine to the catalyst surfaces, Eq. (18) can be used to define \( r_{\text{het}}^{N_{2}H_{4}} \) by noting that \( (dC_{p}^{N_{2}H_{4}}/dt) \) and \( C_{p}^{N_{2}H_{4}} \) are both approximately equal to zero. The reaction rate is then given by

\[
r_{\text{het}}^{N_{2}H_{4}} = \frac{3k_{C}^{N_{2}H_{4}}}{a} C_{i}^{N_{2}H_{4}}
\]  

The reaction rate of ammonia on the catalyst surfaces, \( r_{\text{het}}^{NH_{3}} \), can be computed by multiplying the rate of reaction calculated on the basis of uniform \( T_{p} \) and \( C_{p} \) by the utilization factor determined by analogy with the steady-state system (see Refs. 1, 6 and 7).
This general system of equations is applicable to both normal reactor operation and reactor shutdown. Partial differential equations may be simplified considerably by noting first that, during the "on" portion of a pulse duty cycle (or during continuous reactor operation), gas velocities are so great that the time lag from the entrance to the vapor region to any axial position for the fluid is negligible compared with other transient effects. Here Eqs. (8) through (12) may be approximated by

\[ \frac{\partial h_i}{\partial z} = - \frac{H^2}{G} r_{\text{hom}} \delta - \frac{A_p}{G} \left[ k_C (T_i - T_P) \right] - \frac{F}{G} (h_i - h_F) - \frac{4 \rho_w}{Gd_c} (T_i - T_w) \]  

(25)

\[ G \frac{\partial w_i^{N_2H_4}}{\partial z} = F - r_{\text{hom}} \delta - A_p k_C^{N_2H_4} (c_i^{N_2H_4} - c_p^{N_2H_4}) \]

\[ \quad - w_i^{N_2H_4} F + w_i^{N_2H_4} \sum_j A_p k_C^j (c_i^j - c_p^j) \]  

(26)

\[ G \frac{\partial w_i^{NH_3}}{\partial z} = r_{\text{hom}} \delta - \frac{M_{NH_3}}{M_{N_2H_4}} - A_p k_C^{NH_3} (c_i^{NH_3} - c_p^{NH_3}) \]

\[ \quad - w_i^{NH_3} F + w_i^{NH_3} \sum_j A_p k_C^j (c_i^j - c_p^j) \]  

(27)

\[ G \frac{\partial w_i^{N_2}}{\partial z} = r_{\text{hom}} \delta - \frac{M_{N_2}}{2M_{N_2H_4}} - A_p k_C^{N_2} (c_i^{N_2} - c_p^{N_2}) \]

\[ \quad - w_i^{N_2} F + w_i^{N_2} \sum_j A_p k_C^j (c_i^j - c_p^j) \]  

(28)

\[ G \frac{\partial w_i^{H_2}}{\partial z} = r_{\text{hom}} \delta - \frac{M_{H_2}}{2M_{N_2H_4}} - A_p k_C^{H_2} (c_i^{H_2} - c_p^{H_2}) \]

\[ \quad - w_i^{H_2} F + w_i^{H_2} \sum_j A_p k_C^j (c_i^j - c_p^j) \]  

(29)

Some simplification of the partial differential equations may be achieved in describing reactor operation during the "off" portion of a duty cycle by noting that, here, gas velocities are sufficiently low so that the terms in Eqs. (8) through (12) involving \( G \frac{\partial}{\partial z} \) may be approximated when integrating these equations over small time intervals without introducing any significant error into the calculations.
Finite difference methods have been used to program for digital computation the differential equations describing the changes in temperature and concentrations in the reactor system. These methods are similar to those discussed in Ref. 1, where each of the differential equations is treated as an ordinary differential equation (by integrating with respect to time at a fixed position or vice versa). Each equation is rearranged in the form

\[
\frac{dg}{ds} = \alpha - \beta g
\]  (30)

where the quantities \(\alpha\) and \(\beta\) are taken as constant while integrating the equations from \(s_{k-1}\) to \(s_k\) (corresponding to \(\Delta t\) or \(\Delta z\)). Equation (30) can be integrated to obtain

\[
g_k = g_{k-1}e^{-\beta(s_k - s_{k-1})} + \frac{\alpha}{\beta} \left[ 1 - e^{-\beta(s_k - s_{k-1})} \right]
\]  (31)

where \(g_k\) is the value of \(g\) at \(s_k\), and \(g_{k-1}\) is the value of \(g\) at \(s_{k-1}\). An alternative form of Eq. (31) is

\[
g_k = g_{k-1} + \left(\frac{dg}{ds}\right)_{k-1} \left[ \frac{1 - e^{-\beta(s_k - s_{k-1})}}{\beta} \right]
\]  (32)

It is convenient to use equations of the form of Eq. (31) to compute particle concentrations and temperatures, and to use equations of the form of Eq. (32) to compute interstitial concentrations and temperatures.

The equations representing the transient model of a hydrazine catalytic reactor have been programmed using FORTRAN IV source language for the UNIVAC 1108 digital computer. This computer program is discussed in detail in a computer manual (Ref. 4). The manual includes input and output descriptions and a description of possible operational problems associated with the program.
RESULTS OF CALCULATIONS

A series of calculations of the transient behavior of a typical continuous flow reactor for which experimental information is available (Ref. 8) was made in order to examine the effectiveness of the transient model. The calculations pertain to a 50 lb$_f$ nominal thrust hydrazine reactor 2.4 in. in diameter into which liquid hydrazine is injected at the upstream end of the reactor only. The catalyst bed packing was taken to consist of 25-30 mesh catalyst particles for the first 0.25 in. and $1/8$ in. x $1/8$ in. cylindrical pellets for the remainder of the bed. This configuration is referred to in the figures as "mixed bed #1". The steady-state chamber pressure was taken as 200 psia, the steady-state mass flow rate as 6.5 lb/ft$^2$-sec, and the initial chamber pressure as 14.7 psia. The results of these calculations are shown in Figs. 1 through 4. Gas temperatures are plotted as function of time at each of four axial positions in Fig. 1* for a case in which the initial bed temperature was taken as 530 deg R. Measured gas temperature profiles (Ref. 8) are also shown in Fig. 1 for purposes of comparison. Generally good agreement between theoretical and experimental results may be noted, particularly during the early stages of the transient. While the differences between measured and calculated rates of response are in part due to the thermocouple response time, the use of steady-state utilization factors to describe heat and mass diffusion within catalyst particles under transient conditions results in calculated response rates which are a little too high. The calculated mole-fraction profiles for hydrazine and ammonia, corresponding to the temperature profiles shown in Fig. 1, are illustrated in Fig. 2, and the corresponding mole-fraction profiles for nitrogen and hydrogen are illustrated in Fig. 3. Here, the mole-fractions are plotted as functions of axial position at various times.

Temperatures are plotted as functions of time at a fixed axial position in Fig. 4 for cases in which the initial bed temperatures were taken as 530, 950, and 1420 deg R respectively. The comparison between calculated and measured temperature profiles is similar for low and elevated initial bed temperature cases.

Additional calculations were made for the reactor configuration noted above in order to examine the effect of pulsed flow on initial transient response. The calculated results illustrated in Figs. 5 through 11 refer to a reactor operated under pulsed flow conditions at a steady-state chamber pressure of 260 psia, a steady-state mass flow rate of 5.8 lb/ft$^2$-sec, an initial chamber pressure of 14.7 psia, and an initial bed temperature at 530 deg R. Calculations were made for the first two pulses of a duty cycle consisting of alternate on and off times of 50 msec and 100 msec respectively.

* A plot similar to Fig. 1 was included in Ref. 8; the calculated temperature profiles illustrated in that plot were slightly in error.
The temperature in the interstitial phase is plotted in Fig. 5 as a function of time at various axial locations in the reaction chamber. The temperature rises rapidly after reactor startup, particularly in the upstream portion of the chamber. When flow into the reactor is turned off, the gas temperature in the upstream section of the reactor rises extremely rapidly at first because of thermal decomposition of residual hydrazine in this region. In the regions of the reactor downstream of the small catalyst particles, where the gas temperature is too low after 50 msec to permit significant thermal decomposition of hydrazine, the temperature falls due to heat transfer from the gas to the colder catalyst pellets and to the chamber walls. The heat gained by the catalyst pellets in these regions results in a very small temperature change because of the large mass of the particles. This is illustrated in Fig. 6 where catalyst particle temperature is plotted as a function of time at the same axial locations chosen for Fig. 5.

The rapid pressure buildup and decay resulting from pulse operation of the reactor for this case is shown in Fig. 7. The species mole-fraction profiles associated with this pressure variation and the temperature distributions illustrated in Figs. 5 and 6 and shown in Figs. 8 through 11. The variation of mole-fraction of hydrazine with time at various axial locations is plotted in Fig. 8. This plot illustrates the very rapid thermal decomposition of residual hydrazine in the hotter upstream regions of the reaction chamber during reactor shutdown as well as the somewhat slower catalytic decomposition in the cooler downstream regions of the reactor. The variation of mole-fraction of ammonia with time is illustrated at various axial locations in Fig. 9. Following reactor shutdown the residual ammonia near the upstream end of the reactor decomposes catalytically in the hot catalyst particles. In the cooler downstream regions, ammonia is displaced gradually by the nitrogen and hydrogen formed from hydrazine and ammonia decomposition upstream. These decomposition products flow downstream during shutdown as the chamber pressure decays. These processes lead to the ammonia mole-fraction profiles shown in Fig. 9 and the mole-fraction profiles of nitrogen and hydrogen shown in Figs. 10 and 11 respectively.

The effects of various reactor operating conditions on the transient behavior of typical hydrazine reactors are illustrated in Figs. 12 through 38. The calculated results refer to a 23 lb_f nominal thrust engine 1.4 in. in diameter with a packed length of 1.2 in. into which liquid hydrazine is injected at a temperature of 530 deg R. A reference case was chosen in which hydrazine injection was taken at the reactor inlet only and in which the steady-state mass flow rate was taken as 5.76 lb/ft^2-sec (0.04 lb/in^2-sec), the injector pressure as 150 psia, the initial chamber pressure as 14.7 psia,
the initial bed temperature as 530 deg R, the pulse duty cycle as alternating
60 msec on and 60 msec off, and the catalyst bed configuration as 0.2 in. of
25-30 mesh catalyst particles followed by 1.0 in. of 14-18 mesh catalyst
particles. This bed configuration is referred to in the figures as "mixed
bed #2". Injector pressure, mass flow rate, axial injection profile, catalyst
bed configuration, and pulse duty cycle were then varied in turn and the
calculated interstitial temperatures at two axial positions in the bed were
then plotted as a function of time. The transient behavior of the reference
case is illustrated in Figs. 12 through 22. Transient interstitial tempera-
ture profiles are plotted in Fig. 12 for two axial positions, one at the end
of the bed and one at approximately the midpoint of the bed. Also plotted
in Fig. 12 are the temperature profiles computed at these same points for
the reactor operating under conditions of continuous rather than pulsed flow.
The transient particle temperature profiles associated with the interstitial
temperatures shown in Fig. 12 are plotted in Fig. 13, while the chamber
pressure is plotted as a function of time in Fig. 14. The associated mole-
fraction profiles for hydrazine are plotted in Figs. 15 and 16, for ammonia
in Figs. 17 and 18, for nitrogen in Figs. 19 and 20, and for hydrogen in
Figs. 21 and 22.

In Fig. 23, transient interstitial temperature profiles are plotted for
an injector pressure of 500 psia with all other conditions taken as those of
the reference case. The very slight effect of pressure on transient response
may be noted by comparing Figs. 12 and 23. A direct comparison of exit gas
temperature profiles associated with the two different pressures is shown in
Fig. 24 for the reactor operating under conditions of continuous flow.

Transient interstitial temperature profiles are plotted for steady-state
mass flow rates of 1.44 lb/ft$^2$-sec (0.01 lb/in.$^2$-sec) in Fig. 25 and 14.4
lb/ft$^2$-sec (0.10 lb/in.$^2$-sec) in Fig. 26 with all other conditions taken the
same as those of the reference case.* The marked effect of mass flow rate
on transient response is further illustrated in Fig. 27 for a continuous flow
system. Here, exit gas temperatures are plotted versus time for the three
different steady-state mass flow rates.

The effects of distributed injectors on transient temperature profiles
are illustrated in Figs. 28 through 30. Temperature are plotted as functions
of time at the midpoint and at the end of the bed in Figs. 28 and 29 respec-
tively for a case in which $\frac{1}{4}$ of the hydrazine is injected at the inlet and
the remaining $\frac{3}{4}$ is injected uniformly over the first $\frac{1}{2}$ in. of the reactor.

*An injector pressure of 500 psia was used in calculations for the high mass
flow rate case since the high pressure drop associated with this flow rate
precludes use of the reference injector pressure.
The exit gas temperature profiles for this case and for the reference case of all inlet injection are compared in Fig. 30 under conditions of continuous flow.

Transient interstitial temperature profiles are plotted for different catalyst bed configurations in Figs. 31 through 35. Temperature profiles associated with beds packed with all 25-30 mesh particles are shown in Fig. 31, all 14-18 mesh particles in Fig. 32, and the mixture of 25-30 mesh particles and 1/8 in. x 1/8 in. cylindrical pellets in Figs. 33 and 34. Exit gas temperature profiles for these cases are compared in Fig. 35 under conditions of continuous flow.

The transient temperature profiles at two axial positions for a pulse duty cycle consisting of alternate on and off times of 60 msec and 120 msec respectively are illustrated in Fig. 36. The temperature profiles associated with a 60 msec/240 msec pulse duty cycle are shown in Fig. 37. The effects of duty cycle on the transient response of the exit gas temperature are summarized in Fig. 38.

Additional calculations were made to illustrate the transient behavior of a high thrust hydrazine engine. The calculations pertain to a 600 lbf nominal thrust hydrazine reactor 4.2 in. in diameter with a packed length of 1.0 in. into which liquid hydrazine is injected at the upstream end of the reactor only. The catalyst bed packing was taken to consist of all 25-30 mesh catalyst particles; the steady-state mass flow rate was taken as 40.3 lb/ft$^2$-sec, the injector pressure as 1405 psia, the initial chamber pressure as 0.1 psia, the initial bed temperature as 530 deg R, and the pulse duty cycle as alternating 50 msec on and 250 msec off. For this case, interstitial temperature, particle temperature, chamber pressure, and the mole-fractions of hydrazine, ammonia, nitrogen and hydrogen are plotted as functions of time at the end of the bed in Figs. 39, 40, 41, 42, 43, 44 and 45 respectively. These figures illustrate the very rapid transient response associated with this high flow rate system.
REFERENCES


LIST OF SYMBOLS

a  Radius of spherical particle, ft

\(A_c\)  Cross-sectional area of reaction chamber, \(\text{ft}^2\)

\(A_p\)  Total external surface of catalyst particle per unit volume of bed, \(\text{ft}^{-1}\)

\(A_w\)  Total surface area of chamber walls, \(\text{ft}^2\)

\(c_i\)  Reactant concentration in interstitial fluid, \(\text{lb/ft}^3\)

\(c_p\)  Reactant concentration in gas phase within the porous particle, \(\text{lb/ft}^3\)

\(C_F\)  Specific heat of fluid in the interstitial phase, Btu/\(\text{lb} \cdot \text{deg R}\)

\(\bar{C}_F\)  Average specific heat of fluid in the interstitial phase, Btu/\(\text{lb} \cdot \text{deg R}\)

\(C_s\)  Specific heat of catalyst particle, Btu/\(\text{lb} \cdot \text{deg R}\)

\(C_W\)  Specific heat of chamber walls, Btu/\(\text{lb} \cdot \text{deg R}\)

\(d_c\)  Diameter of reaction chamber, ft

\(D_i\)  Diffusion coefficient of reactant gas in the interstitial fluid, \(\text{ft}^2/\text{sec}\)

\(D_p\)  Diffusion coefficient of reactant gas in the porous particle, \(\text{ft}^2/\text{sec}\)

\(F\)  Rate of feed of hydrazine from distributed injectors into the system, \(\text{lb/ft}^3 \cdot \text{sec}\)

\(G\)  Mass flow rate, \(\text{lb/ft}^2 \cdot \text{sec}\)

\(h\)  Enthalpy, Btu/\(\text{lb}\)

\(h_a\)  Heat transfer coefficient for forced convection between chamber and surrounding atmosphere, Btu/\(\text{ft}^2 \cdot \text{sec} \cdot \text{deg R}\)

\(h'_a\)  Heat transfer coefficient for natural convection between chamber and surrounding atmosphere, Btu/\(\text{ft}^2 \cdot \text{sec} \cdot \text{deg R}\)\(^{1.25}\)

\(h''_a\)  Radiation heat transfer coefficient between chamber and surrounding atmosphere, Btu/\(\text{ft}^2 \cdot \text{sec} \cdot \text{deg R}\)\(^4\)

\(h_c\)  Heat transfer coefficient between bulk fluid and particles, Btu/\(\text{ft}^2 \cdot \text{sec} \cdot \text{deg R}\)
\( \dot{H}_{w} \)  Heat transfer coefficient between bulk fluid and chamber walls, Btu/ft\(^2\)-sec-deg R

\( H \)  Heat of reaction (negative for exothermic reaction), Btu/lb

\( k_c \)  Mass transfer coefficient, ft/sec

\( K_l \)  Thermal conductivity of interstitial fluid, Btu/ft-sec-deg R

\( K_p \)  Thermal conductivity of the porous catalyst particle, Btu/ft-sec-deg R

\( L \)  Length of reaction chamber, ft

\( m_w \)  Thermal mass of chamber walls, lb

\( M \)  Molecular weight, lb/lb mole

\( \bar{M} \)  Average molecular weight, lb/lb mole

\( P \)  Chamber pressure, psia

\( r_{het} \)  Rate of (heterogeneous) chemical reaction on the catalyst surfaces, lb/ft\(^3\)-sec

\( r_{hom} \)  Rate of (homogeneous) chemical reaction in the interstitial phase, lb/ft\(^3\)-sec

\( R \)  Gas constant, equals 10.73 psia - ft\(^3\)/lb mole - deg R

\( t \)  Time, sec

\( T \)  Temperature, deg R

\( V_c \)  Volume of reactor up to nozzle throat exclusive of volume occupied by catalyst particles, ft\(^3\)

\( w_i \)  Weight fraction of reactant in interstitial phase

\( z \)  Axial distance, ft

\( \alpha_p \)  Intraparticle void fraction

\( \delta \)  Interparticle void fraction

\( \mu \)  Viscosity of interstitial fluid, lb/ft\(-\)sec
\( \rho_i \) Density of interstitial fluid, \( \text{lb/ft}^3 \)

\( \rho_b \) Bulk density of catalyst particle, \( \text{lb/ft}^3 \)

**Subscripts**

- \( a \) Refers to surrounding atmosphere
- \( F \) Refers to feed
- \( i \) Refers to interstitial phase
- \( p \) Refers to gas within the porous catalyst particle
- \( s \) Refers to surface of catalyst particle
- \( \text{SS} \) Refers to steady-state
- \( w \) Refers to chamber wall

**Superscripts**

- \( J \) Refers to chemical species
# APPENDIX I

## DISTRIBUTION LIST FOR THIRD ANNUAL PROGRESS REPORT

<table>
<thead>
<tr>
<th>Address</th>
<th>Copies</th>
<th>Address</th>
<th>Copies</th>
</tr>
</thead>
</table>
| National Aeronautics & Space Administration  
Washington, D. C. 20546  
Attn: Chief, Liq. Prop. Res. & Tech., BPL | 1 | NASA Lewis Research Center  
21000 Brookpark Road  
Cleveland, Ohio 44135  
Attn: Mr. I. A. Johnsonen | 1 |
| National Aeronautics & Space Administration  
Washington, D. C. 20546  
Huntville, Alabama 35812  
Attn: Mr. Kieth Coates | 1 |
| National Aeronautics & Space Administration  
Washington, D. C. 20546  
Attn: Dir., Launch Vehicles & Prop., SV | 1 | Department of Chemical Engineering  
University of British Columbia  
Vancouver 8, Canada | 1 |
| National Aeronautics & Space Administration  
Washington, D. C. 20546  
Attn: Dir., Advanced Manned Missions, MT | 1 | NASA Ames Research Center  
Moffett Field, California 94035  
Attn: Technical Librarian | 1 |
| Air Force Rocket Propulsion Laboratory  
Research and Technology Division  
Air Force System Command  
Edwards, California 93523  
Attn: Mr. K. Rimer | 1 | NASA Ames Research Center  
Moffett Field, California 94035  
Attn: Mr. Clarence A. Syvertson | Ltr. Only |
| Air Force Rocket Propulsion Laboratory  
Research and Technology Division  
Air Force System Command  
Edwards, California 93523  
Attn: Capt. Royce/3725 | 1 | NASA Goddard Space Flight Center  
Greenbelt, Maryland 20771  
Attn: Technical Librarian | 1 |
| U. S. Naval Ordnance Test Station  
China Lake, California 93553  
Attn: Mr. Daane Williams | 1 | NASA Goddard Space Flight Center  
Greenbelt, Maryland 20771  
Attn: Mr. Merland L. Moseson, Code 620 | Ltr. Only |
| U. S. Naval Ordnance Test Station  
China Lake, California 93553  
Attn: Mr. James Dale | 1 | NASA Goddard Space Flight Center  
Greenbelt, Maryland 20771  
Attn: Mr. D. Grant | Ltr. Only |
| U. S. Naval Ordnance Test Station  
China Lake, California 93553  
Attn: Mr. David Oliver | 1 | Jet Propulsion Laboratory  
California Institute of Technology  
4800 Oak Grove Drive  
Pasadena, California 91103  
Attn: Mr. Theodore W. Price | 2 |
| Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, California 91103  
Attn: Mr. Theodore W. Price | 10 | Jet Propulsion Laboratory  
California Institute of Technology  
4800 Oak Grove Drive  
Pasadena, California 91103  
Attn: Technical Librarian | Ltr. Only |
| NASA Pasadena Office  
4800 Oak Grove Drive  
Pasadena, California 91103  
Attn: Contracting Officer | 1 | NASA Langley Research Center  
Langley Station  
Hampton, Virginia 23365  
Attn: Technical Librarian | 1 |
| NASA Pasadena Office  
4800 Oak Grove Drive  
Pasadena, California 91103  
Langley Station  
Hampton, Virginia 23365  
Attn: Mr. David Carter | Ltr. Only |
| Scientific & Technical Information Facility  
P. O. Box 5700  
Bethesda, Maryland 20014  
Attn: NASA Rep., Code CRT | 3 | NASA Langley Research Center  
Langley Station  
Hampton, Virginia 23365  
Attn: Dr. Floyd L. Thompson, Dir. | |

18
<table>
<thead>
<tr>
<th>Addresses</th>
<th>Copies</th>
<th>Addresses</th>
<th>Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Langley Research Center</td>
<td>Ltr. Only</td>
<td>Air Force Missile Development Center</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>Langley Station</td>
<td></td>
<td>Holloman Air Force Base, New Mexico 88330</td>
<td></td>
</tr>
<tr>
<td>Hampton, Virginia 23665</td>
<td></td>
<td>Attn: Maj. E. E. Bracken, Code MOQT</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. R. Hook</td>
<td></td>
<td>Air Force Missile Test Center</td>
<td></td>
</tr>
<tr>
<td>NASA Lewis Research Center</td>
<td></td>
<td>Patrick Air Force Base, Florida</td>
<td></td>
</tr>
<tr>
<td>21000 Brookpark Road</td>
<td>Ltr. Only</td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Cleveland, Ohio 44135</td>
<td></td>
<td>Air Force Missile Test Center</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Patrick Air Force Base, Florida</td>
<td></td>
</tr>
<tr>
<td>NASA Lewis Research Center</td>
<td>Ltr. Only</td>
<td>Attn: Mr. L. J. Uillian</td>
<td></td>
</tr>
<tr>
<td>21000 Brookpark Road</td>
<td></td>
<td>Air Force Systems Division</td>
<td></td>
</tr>
<tr>
<td>Cleveland, Ohio 44135</td>
<td></td>
<td>Air Force Unit Post Office</td>
<td></td>
</tr>
<tr>
<td>Attn: Dr. Abe Silverstein, Dir.</td>
<td></td>
<td>Los Angeles 45, California 90045</td>
<td></td>
</tr>
<tr>
<td>NASA Lewis Research Center</td>
<td>Ltr. Only</td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>21000 Brookpark Road</td>
<td></td>
<td>Air Force Systems Division</td>
<td></td>
</tr>
<tr>
<td>Cleveland, Ohio 44135</td>
<td></td>
<td>Air Force Unit Post Office</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. Steve Cohen</td>
<td></td>
<td>Los Angeles 45, California 90045</td>
<td></td>
</tr>
<tr>
<td>NASA Marshall Space Flight Center</td>
<td>Ltr. Only</td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Huntsville, Alabama 35812</td>
<td></td>
<td>Technical Library</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Edwards AFB, California 93523</td>
<td></td>
</tr>
<tr>
<td>NASA Marshall Space Flight Center</td>
<td>Ltr. Only</td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Huntsville, Alabama 35812</td>
<td></td>
<td>Arnold Engineering Development Center</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. Hans G. Paul, Code B-PVHD</td>
<td></td>
<td>Arnold Air Force Station</td>
<td></td>
</tr>
<tr>
<td>NASA Marshall Space Flight Center</td>
<td>Ltr. Only</td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Huntsville, Alabama 35812</td>
<td></td>
<td>Tallahoma, Tennessee 37368</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. Werner Voss, R-PVE-IM</td>
<td></td>
<td>Arnolde Engineering Development Center</td>
<td></td>
</tr>
<tr>
<td>NASA Manned Spacecraft Center</td>
<td>Ltr. Only</td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Houston, Texas 77001</td>
<td></td>
<td>Arnold Air Force Station</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Tallahoma, Tennessee 37368</td>
<td></td>
</tr>
<tr>
<td>NASA Manned Spacecraft Center</td>
<td>Ltr. Only</td>
<td>Attn: Dr. H. K. Doetsch</td>
<td></td>
</tr>
<tr>
<td>Houston, Texas 77001</td>
<td></td>
<td>Bureau of Naval Weapons</td>
<td></td>
</tr>
<tr>
<td>Attn: Dr. Robert R. Gilruth, Dir.</td>
<td></td>
<td>Department of the Navy</td>
<td></td>
</tr>
<tr>
<td>NASA Manned Spacecraft Center</td>
<td>Ltr. Only</td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Houston, Texas 77001</td>
<td></td>
<td>Washington, D. C. 20546</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. H. Pohl</td>
<td></td>
<td>Bureau of Naval Weapons</td>
<td></td>
</tr>
<tr>
<td>NASA John F. Kennedy Space Center</td>
<td>Ltr. Only</td>
<td>Department of the Navy</td>
<td></td>
</tr>
<tr>
<td>Cocoa Beach, Florida 32931</td>
<td></td>
<td>Washington, D. C. 20546</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Attn: Mr. J. Kay, RMS-41</td>
<td></td>
</tr>
<tr>
<td>NASA John F. Kennedy Space Center</td>
<td>Ltr. Only</td>
<td>Defense Documentation Center Headquarters</td>
<td></td>
</tr>
<tr>
<td>Cocoa Beach, Florida 32931</td>
<td></td>
<td>Cameron Station, Building 5</td>
<td></td>
</tr>
<tr>
<td>Attn: Dr. Kurt H. Debus</td>
<td></td>
<td>5010 Duke Street</td>
<td></td>
</tr>
<tr>
<td>NASA Jet Propulsion Laboratory</td>
<td>Ltr. Only</td>
<td>Alexandria, Virginia 22314</td>
<td></td>
</tr>
<tr>
<td>Propulsion Engineering Office</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>White Sands, New Mexico</td>
<td></td>
<td>Defense Documentation Center Headquarters</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Cameron Station, Building 5</td>
<td></td>
</tr>
<tr>
<td>NASA Jet Propulsion Laboratory</td>
<td>Ltr. Only</td>
<td>5010 Duke Street</td>
<td></td>
</tr>
<tr>
<td>Propulsion Engineering Office</td>
<td></td>
<td>Alexandria, Virginia 22314</td>
<td></td>
</tr>
<tr>
<td>White Sands, New Mexico</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. I. D. Smith, Staff Chemist</td>
<td></td>
<td>Defense Documentation Center Headquarters</td>
<td></td>
</tr>
<tr>
<td>Aeronautical Systems Division</td>
<td>Ltr. Only</td>
<td>Cameron Station, Building 5</td>
<td></td>
</tr>
<tr>
<td>Air Force Systems Command</td>
<td></td>
<td>5010 Duke Street</td>
<td></td>
</tr>
<tr>
<td>Wright-Patterson Air Force Base</td>
<td></td>
<td>Alexandria, Virginia 22314</td>
<td></td>
</tr>
<tr>
<td>Dayton, Ohio 45433</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Defense Documentation Center Headquarters</td>
<td></td>
</tr>
<tr>
<td>Air Force Systems Command</td>
<td>Ltr. Only</td>
<td>Cameron Station, Building 5</td>
<td></td>
</tr>
<tr>
<td>Wright-Patterson Air Force Base</td>
<td></td>
<td>5010 Duke Street</td>
<td></td>
</tr>
<tr>
<td>Dayton, Ohio 45433</td>
<td></td>
<td>Alexandria, Virginia 22314</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. D. L. Schmidt, Code ASTRON-2</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Air Force Missile Development Center</td>
<td>Ltr. Only</td>
<td>Picatinny Arsenal</td>
<td></td>
</tr>
<tr>
<td>Holloman Air Force Base, New Mexico 88330</td>
<td>1</td>
<td>Dover, New Jersey 07801</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Picatinny Arsenal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dover, New Jersey 07801</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Attn: Mr. I. Forsten, Chief</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid Propulsion Lab., SNPA-DL</td>
<td></td>
</tr>
<tr>
<td>Address</td>
<td>Copies</td>
<td>Address</td>
<td>Copies</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>--------</td>
<td>------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Air Force Rocket Propulsion Laboratory</td>
<td></td>
<td>Aerodynamic Division</td>
<td></td>
</tr>
<tr>
<td>Research and Technology Division</td>
<td></td>
<td>Philco Corporation</td>
<td></td>
</tr>
<tr>
<td>Air Force Systems Command</td>
<td></td>
<td>Ford Road</td>
<td></td>
</tr>
<tr>
<td>Edwards, California 93523</td>
<td></td>
<td>Newport Beach, California 90663</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Mr. H. Main, HPFR</td>
<td></td>
</tr>
<tr>
<td>Air Force Rocket Propulsion Laboratory</td>
<td></td>
<td>Aerodynamic Division</td>
<td></td>
</tr>
<tr>
<td>Research and Technology Division</td>
<td>Ltr. Only</td>
<td>Philco Corporation</td>
<td></td>
</tr>
<tr>
<td>Air Force Systems Command</td>
<td></td>
<td>Ford Road</td>
<td></td>
</tr>
<tr>
<td>Edwards, California 93523</td>
<td></td>
<td>Newport Beach, California 90663</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. H. Main, HPFR</td>
<td></td>
<td>Mr. E. Stern</td>
<td></td>
</tr>
<tr>
<td>U.S. Atomic Energy Commission</td>
<td></td>
<td>Aerospace Corporation</td>
<td></td>
</tr>
<tr>
<td>Technical Information Services</td>
<td></td>
<td>2400 East El Segundo Boulevard</td>
<td></td>
</tr>
<tr>
<td>Box 62</td>
<td></td>
<td>P. 0. Box 95085</td>
<td></td>
</tr>
<tr>
<td>Oak Ridge, Tennessee 37830</td>
<td></td>
<td>Los Angeles, California 90045</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Mr. J. S. Busel</td>
<td></td>
</tr>
<tr>
<td>Aerospace Corporation</td>
<td></td>
<td>2400 East El Segundo Boulevard</td>
<td></td>
</tr>
<tr>
<td>U.S. Army Missile Command</td>
<td></td>
<td>P. 0. Box 95085</td>
<td></td>
</tr>
<tr>
<td>Redstone Arsenal, Alabama 35809</td>
<td></td>
<td>Los Angeles, California 90045</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Mr. J. Greer, Propulsion Dept.</td>
<td></td>
</tr>
<tr>
<td>U.S. Army Missile Command</td>
<td>Ltr. Only</td>
<td>Arthur D. Little, Incorporated</td>
<td></td>
</tr>
<tr>
<td>Redstone Arsenal, Alabama 35809</td>
<td></td>
<td>20 Acorn Park</td>
<td></td>
</tr>
<tr>
<td>Attn: Dr. Walter Wharton</td>
<td></td>
<td>Cambridge, Massachusetts 02180</td>
<td></td>
</tr>
<tr>
<td>U.S. Naval Ordnance Test Station</td>
<td></td>
<td>Arthur D. Little, Incorporated</td>
<td></td>
</tr>
<tr>
<td>China Lake, California 93357</td>
<td></td>
<td>20 Acorn Park</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Cambridge, Massachusetts 02180</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>U.S. Naval Ordnance Test Station</td>
<td>Ltr. Only</td>
<td>Mr. E. Earl Hestness</td>
<td></td>
</tr>
<tr>
<td>China Lake, California 93357</td>
<td></td>
<td>Abstractor Laboratory</td>
<td></td>
</tr>
<tr>
<td>Attn: Code 4562</td>
<td></td>
<td>Douglas Aircraft Company</td>
<td></td>
</tr>
<tr>
<td>Chief, Missile Propulsion Division</td>
<td></td>
<td>2121 Paulino</td>
<td></td>
</tr>
<tr>
<td>Chemical Propulsion CPIA Information Agency</td>
<td></td>
<td>Newport Beach, California 92663</td>
<td></td>
</tr>
<tr>
<td>Applied Physics Laboratory</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>8621 Georgia Avenue</td>
<td></td>
<td>Autopower Laboratory</td>
<td></td>
</tr>
<tr>
<td>Silver Spring, Maryland 20910</td>
<td></td>
<td>Douglas Aircraft Company</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Newport Beach, California 92663</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>Chemical Propulsion CPIA Information Agency</td>
<td>Ltr. Only</td>
<td>Autosystem International, Incorporated</td>
<td></td>
</tr>
<tr>
<td>Applied Physics Laboratory</td>
<td></td>
<td>1275 Bloomfield Avenue</td>
<td></td>
</tr>
<tr>
<td>8621 Georgia Avenue</td>
<td></td>
<td>Fairfield, New Jersey 07007</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. P. Martin</td>
<td></td>
<td>Autosystem International, Incorporated</td>
<td></td>
</tr>
<tr>
<td>Aerostation-General Corporation</td>
<td></td>
<td>1275 Bloomfield Avenue</td>
<td></td>
</tr>
<tr>
<td>P. 0. Box 296</td>
<td></td>
<td>Fairfield, New Jersey 07007</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>Azusa, California 91703</td>
<td></td>
<td>Atlantic Research Corporation</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>E Hale Road and Shirley Highway, Alexandria, Virginia 2231A</td>
<td></td>
</tr>
<tr>
<td>Aerostation-General Corporation</td>
<td>Ltr. Only</td>
<td>Atlantic Research Corporation</td>
<td></td>
</tr>
<tr>
<td>P. 0. Box 296</td>
<td></td>
<td>E Hale Road and Shirley Highway, Alexandria, Virginia 2231A</td>
<td></td>
</tr>
<tr>
<td>Azusa, California 91703</td>
<td></td>
<td>Attn: Mr. A. Mendonvann</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. L. F. Kohrs</td>
<td></td>
<td>Atlantic Research Corporation</td>
<td></td>
</tr>
<tr>
<td>Aerostation-General Corporation</td>
<td></td>
<td>E Hale Road and Shirley Highway, Alexandria, Virginia 2231A</td>
<td></td>
</tr>
<tr>
<td>P. 0. Box 1947</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Technical Library, Elq. 2015, Dept. 2410</td>
<td></td>
<td>Atlantic Research Corporation</td>
<td></td>
</tr>
<tr>
<td>Sacramento, California 95809</td>
<td></td>
<td>E Hale Road and Shirley Highway, Alexandria, Virginia 2231A</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Attn: Mr. A. Souleys</td>
<td></td>
</tr>
<tr>
<td>Aerostation-General Corporation</td>
<td>Ltr. Only</td>
<td>Beech Aircraft Corporation</td>
<td></td>
</tr>
<tr>
<td>P. 0. Box 1947</td>
<td></td>
<td>Boulder Division</td>
<td></td>
</tr>
<tr>
<td>Sacramento, California 95809</td>
<td></td>
<td>Box 631</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Boulder, Colorado 80302</td>
<td></td>
</tr>
</tbody>
</table>

20
<table>
<thead>
<tr>
<th>Copies</th>
<th>Addresses</th>
<th>Copies</th>
</tr>
</thead>
</table>
| Ltr. Only | Beech Aircraft Corporation  
Boulder Division  
Box 631  
Boulder, Colorado 80302  
Attn: Mr. J. R. Rodgers |
| | | |
| Ltr. Only | Missile and Space Systems Division  
Douglas Aircraft Company, Incorporated  
300 Ocean Park Boulevard  
Santa Monica, California 90406  
Attn: Mr. W. N. Balle, Chief Engineer  
Advanced Space Tech. |
| Ltr. Only | Aircraft Missiles Division  
Fairchild Hiller Corporation  
Hagerstown, Maryland 21740  
Attn: Technical Librarian |
| Ltr. Only | Aircraft Missiles Division  
Fairchild Hiller Corporation  
Hagerstown, Maryland 21740  
Attn: Technical Librarian |
| Ltr. Only | Aircraft Missiles Division  
Fairchild Hiller Corporation  
Hagerstown, Maryland 21740  
Attn: Technical Librarian |
| Ltr. Only | General Dynamics  
Convair Division  
5001 Kearny Villa Road  
P.O. Box 1628  
San Diego, California 92112  
Attn: Mr. W. F. Peterson  
V.P., Research and Eng. |
| Ltr. Only | General Dynamics  
Convair Division  
5001 Kearny Villa Road  
P.O. Box 1628  
San Diego, California 92112  
Attn: Frank Dore |
| Ltr. Only | Missile and Space Systems Center  
Valley Forge Space Technology Center  
P.O. Box 8555  
Philadelphia, Pennsylvania  
Attn: Mr. F. Mezger |
| Ltr. Only | Missile and Space Systems Center  
Valley Forge Space Technology Center  
P.O. Box 8555  
Philadelphia, Pennsylvania  
Attn: Mr. E. B. Emser |
| Ltr. Only | Missile and Space Systems Center  
Valley Forge Space Technology Center  
P.O. Box 8555  
Philadelphia, Pennsylvania  
Attn: Mr. F. Mezger |
| Ltr. Only | Advanced Engine & Technology Department  
General Electric Company  
Cincinnati, Ohio 45215  
Attn: Technical Librarian |
<table>
<thead>
<tr>
<th>Addresser</th>
<th>Copies</th>
<th>Addresser</th>
<th>Copies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Engine &amp; Technology Department</td>
<td></td>
<td>The Marquardt Corporation</td>
<td></td>
</tr>
<tr>
<td>General Electric Company</td>
<td>Ltr. Only</td>
<td>16755 Saricoy Street</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>Cincinnati, Ohio 45215</td>
<td></td>
<td>Van Nuys, California 91409</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. B. Oldham</td>
<td></td>
<td>Attn: Mr. Warren P. Boardman, Jr.</td>
<td></td>
</tr>
<tr>
<td>Gruenman Aircraft Engineering Corporation</td>
<td></td>
<td>The Marquardt Corporation</td>
<td></td>
</tr>
<tr>
<td>Bethpage, Long Island, New York 11714</td>
<td></td>
<td>16755 Saricoy Street</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Van Nuys, California 91409</td>
<td></td>
</tr>
<tr>
<td>Gruenman Aircraft Engineering Corporation</td>
<td></td>
<td>Attn: Mr. D. Suichu</td>
<td></td>
</tr>
<tr>
<td>Bethpage, Long Island, New York 11714</td>
<td>Ltr. Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. Joseph Olin</td>
<td></td>
<td>Baltimore Division</td>
<td></td>
</tr>
<tr>
<td>Hughes Aircraft Company</td>
<td></td>
<td>Martin Marietta Corporation</td>
<td></td>
</tr>
<tr>
<td>Aerospace Group</td>
<td></td>
<td>Baltimore, Maryland 21003</td>
<td></td>
</tr>
<tr>
<td>Centinela and Teale Streets</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Culver City, California</td>
<td>Ltr. Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Baltimore Division</td>
<td></td>
</tr>
<tr>
<td>Hughes Aircraft Company</td>
<td></td>
<td>Martin Marietta Corporation</td>
<td></td>
</tr>
<tr>
<td>Aerospace Group</td>
<td></td>
<td>Baltimore, Maryland 21003</td>
<td></td>
</tr>
<tr>
<td>Centinela and Teale Streets</td>
<td></td>
<td>Attn: Mr. John Calathes (2114)</td>
<td></td>
</tr>
<tr>
<td>Culver City, California</td>
<td>Ltr. Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walter Kidde &amp; Company, Incorporated</td>
<td></td>
<td>Denver Division</td>
<td></td>
</tr>
<tr>
<td>675 Main Street</td>
<td></td>
<td>Martin Marietta Corporation</td>
<td></td>
</tr>
<tr>
<td>Belleville, New Jersey 07109</td>
<td>Ltr. Only</td>
<td>1903</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Denver, Colorado 80201</td>
<td></td>
</tr>
<tr>
<td>Walter Kidde &amp; Company, Incorporated</td>
<td></td>
<td>Attn: Mr. J. D. Goodlette (A-241)</td>
<td></td>
</tr>
<tr>
<td>675 Main Street</td>
<td></td>
<td>Denver Division</td>
<td></td>
</tr>
<tr>
<td>Belleville, New Jersey 07109</td>
<td>Ltr. Only</td>
<td>1903</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>Attn: Mr. K. A. Tranquels</td>
<td></td>
<td>Denver, Colorado 80201</td>
<td></td>
</tr>
<tr>
<td>Ling-Temco-Vought Corporation, Astronautics</td>
<td></td>
<td>Attn: Mr. A. J. Kullis</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 5977</td>
<td></td>
<td>Denver Division</td>
<td></td>
</tr>
<tr>
<td>Dallas, Texas 75222</td>
<td></td>
<td>Martin Marietta Corporation</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td>Ltr. Only</td>
<td>P.O. Box 1979</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>Ling-Temco-Vought Corporation, Astronautics</td>
<td></td>
<td>Orlando, Florida</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 5977</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Dallas, Texas 75222</td>
<td></td>
<td>Orlando, Florida</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. Garanid Whisenhurst</td>
<td>Ltr. Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lockheed Missiles and Space Company</td>
<td></td>
<td>McDonnell Aircraft Corporation</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Information Center</td>
<td></td>
<td>P. O. Box 54</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 504</td>
<td></td>
<td>Municipal Airport</td>
<td></td>
</tr>
<tr>
<td>Sunnyvale, California 9408</td>
<td></td>
<td>St. Louis, Missouri 63166</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Attn: Mr. J. P.</td>
<td></td>
</tr>
<tr>
<td>Lockheed Missiles and Space Company</td>
<td></td>
<td>McDonnell Aircraft Corporation</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Information Center</td>
<td></td>
<td>P. O. Box 54</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 504</td>
<td></td>
<td>Municipal Airport</td>
<td></td>
</tr>
<tr>
<td>Sunnyvale, California 9408</td>
<td></td>
<td>St. Louis, Missouri 63166</td>
<td></td>
</tr>
<tr>
<td>Attn: Y. T. Y. Lee</td>
<td>Ltr. Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lockheed Propulsion Company</td>
<td></td>
<td>McDonnell Aircraft Corporation</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 111</td>
<td></td>
<td>P. O. Box 54</td>
<td></td>
</tr>
<tr>
<td>Redlands, California 92374</td>
<td></td>
<td>Municipal Airport</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>St. Louis, Missouri 63166</td>
<td></td>
</tr>
<tr>
<td>Lockheed Propulsion Company</td>
<td></td>
<td>Attn: Mr. R. A. Hermmark</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 111</td>
<td></td>
<td>McDonnell Aircraft Corporation</td>
<td></td>
</tr>
<tr>
<td>Redlands, California 92374</td>
<td></td>
<td>P. O. Box 54</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. H. L. Thackwell</td>
<td>Ltr. Only</td>
<td>Municipal Airport</td>
<td></td>
</tr>
<tr>
<td>Lockheed Propulsion Company</td>
<td></td>
<td>St. Louis, Missouri 63166</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 111</td>
<td></td>
<td>Attn: Mr. P. Kelley</td>
<td></td>
</tr>
<tr>
<td>Redlands, California 92374</td>
<td></td>
<td>Rocket Research Corporation</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. D. Suichu</td>
<td>Ltr. Only</td>
<td>250 South Portland Street</td>
<td></td>
</tr>
<tr>
<td>Lockheed Propulsion Company</td>
<td></td>
<td>Rocket Research Corporation</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 111</td>
<td>Ltr. Only</td>
<td>98106</td>
<td></td>
</tr>
<tr>
<td>Redlands, California 92374</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. J. Z. Fitzgerald</td>
<td></td>
<td>Rocket Research Corporation</td>
<td></td>
</tr>
<tr>
<td>The Marquardt Corporation</td>
<td></td>
<td>Rocket Research Corporation</td>
<td></td>
</tr>
<tr>
<td>16755 Saricoy Street</td>
<td>Ltr. Only</td>
<td>98106</td>
<td></td>
</tr>
<tr>
<td>Van Nuys, California 91409</td>
<td></td>
<td>Attn: Mr. Foy McCullough, Jr.</td>
<td></td>
</tr>
<tr>
<td>Addressee</td>
<td>Copies</td>
<td>Addressee</td>
<td>Copies</td>
</tr>
<tr>
<td>----------------------------------------------------------------</td>
<td>--------</td>
<td>----------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Florida Research &amp; Development Center</td>
<td></td>
<td>Brooklyn Polytechnic Institute</td>
<td>Ltr. Only</td>
</tr>
<tr>
<td>Pratt &amp; Whitney Aircraft</td>
<td></td>
<td>Department of Chemical Engineering</td>
<td></td>
</tr>
<tr>
<td>United Aircraft Corporation</td>
<td></td>
<td>333 Jay Street</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 2691</td>
<td></td>
<td>Brooklyn, New York</td>
<td></td>
</tr>
<tr>
<td>West Palm Beach, Florida 33402</td>
<td></td>
<td>11201</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Attn: Prof. I. Miller</td>
<td></td>
</tr>
<tr>
<td>Florida Research &amp; Development Center</td>
<td></td>
<td>Vickers Incorporated</td>
<td></td>
</tr>
<tr>
<td>Pratt &amp; Whitney Aircraft</td>
<td></td>
<td>Box 302</td>
<td></td>
</tr>
<tr>
<td>United Aircraft Corporation</td>
<td></td>
<td>Troy, Michigan</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 2691</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>West Palm Beach, Florida 33402</td>
<td></td>
<td>Sunstrand Aviation</td>
<td></td>
</tr>
<tr>
<td>Attn: Mr. R. J. Coar</td>
<td></td>
<td>2421 11th Street</td>
<td></td>
</tr>
<tr>
<td>Florida Research &amp; Development Center</td>
<td></td>
<td>Rockford, Illinois</td>
<td></td>
</tr>
<tr>
<td>Pratt &amp; Whitney Aircraft</td>
<td></td>
<td>61101</td>
<td></td>
</tr>
<tr>
<td>United Aircraft Corporation</td>
<td></td>
<td>Attn: Mr. R. W. Reynolds</td>
<td></td>
</tr>
<tr>
<td>P. O. Box 2691</td>
<td></td>
<td>Hamilton Standard Division</td>
<td></td>
</tr>
<tr>
<td>West Palm Beach, Florida 33402</td>
<td></td>
<td>United Aircraft Corporation</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Windsor Locks, Connecticut</td>
<td></td>
</tr>
<tr>
<td>Sunstrand Aviation</td>
<td></td>
<td>06096</td>
<td></td>
</tr>
<tr>
<td>2421 11th Street</td>
<td></td>
<td>Attn: Mr. B. Hatch</td>
<td></td>
</tr>
<tr>
<td>Rockford, Illinois</td>
<td></td>
<td>Technical Library</td>
<td></td>
</tr>
<tr>
<td>61101</td>
<td></td>
<td>Air Research Manufacturing Company</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Sepulveda Boulevard</td>
<td></td>
</tr>
<tr>
<td>Hamilton Standard Division</td>
<td></td>
<td>Los Angeles, California</td>
<td></td>
</tr>
<tr>
<td>United Aircraft Corporation</td>
<td></td>
<td>90009</td>
<td></td>
</tr>
<tr>
<td>Windsor Locks, Connecticut</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>06096</td>
<td></td>
<td>Air Research Manufacturing Company</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>90009</td>
<td></td>
</tr>
<tr>
<td>Technical Library</td>
<td></td>
<td>Attn: Mr. C. S. Coe</td>
<td></td>
</tr>
<tr>
<td>Air Research Manufacturing Company</td>
<td></td>
<td>Air Research Manufacturing Company</td>
<td></td>
</tr>
<tr>
<td>Sepulveda Boulevard</td>
<td></td>
<td>Sepulveda Boulevard</td>
<td></td>
</tr>
<tr>
<td>Los Angeles, California</td>
<td></td>
<td>Los Angeles, California</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>90009</td>
<td></td>
</tr>
<tr>
<td>Shell Development Company</td>
<td></td>
<td>Attn: Mr. A. C. Standiffe</td>
<td></td>
</tr>
<tr>
<td>1400 53rd Street</td>
<td></td>
<td>Air Research Manufacturing Company</td>
<td></td>
</tr>
<tr>
<td>Emeryville, California</td>
<td></td>
<td>Sepulveda Boulevard</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Los Angeles, California</td>
<td></td>
</tr>
<tr>
<td>94608</td>
<td></td>
<td>Attn: Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Shell Development Company</td>
<td></td>
<td>Shell Development Company</td>
<td></td>
</tr>
<tr>
<td>1400 53rd Street</td>
<td></td>
<td>Sepulveda Boulevard</td>
<td></td>
</tr>
<tr>
<td>Emeryville, California</td>
<td></td>
<td>Dr. H. Voge</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Shell Development Company</td>
<td></td>
</tr>
<tr>
<td>1400 53rd Street</td>
<td></td>
<td>Sepulveda Boulevard</td>
<td></td>
</tr>
<tr>
<td>Emeryville, California</td>
<td></td>
<td>Dr. T. J. Jennings</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Shell Development Company</td>
<td></td>
</tr>
<tr>
<td>1400 53rd Street</td>
<td></td>
<td>Sepulveda Boulevard</td>
<td></td>
</tr>
<tr>
<td>Emeryville, California</td>
<td></td>
<td>Technical Librarian</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>94608</td>
<td></td>
</tr>
<tr>
<td>Brooklyn Polytechnic Institute</td>
<td></td>
<td>Shell Development Company</td>
<td></td>
</tr>
<tr>
<td>Department of Chemical Engineering</td>
<td></td>
<td>Sepulveda Boulevard</td>
<td></td>
</tr>
<tr>
<td>333 Jay Street</td>
<td></td>
<td>Dr. T. J. Jennings</td>
<td></td>
</tr>
<tr>
<td>Brooklyn, New York</td>
<td></td>
<td>Shell Development Company</td>
<td></td>
</tr>
<tr>
<td>11201</td>
<td></td>
<td>Sepulveda Boulevard</td>
<td></td>
</tr>
<tr>
<td>Attn: Technical Librarian</td>
<td></td>
<td>Technical Librarian</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>94608</td>
<td></td>
</tr>
</tbody>
</table>
COMPARISON OF THEORETICAL AND EXPERIMENTAL TRANSIENT TEMPERATURE PROFILES

STEADY-STATE CHAMBER PRESSURE = 200 PSIA
STEADY-STATE MASS FLOW RATE = 6.5 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED #1 (SEE TEXT)
INITIAL BED TEMPERATURE = 530 DEG R
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

(A) AXIAL POSITION = 0.08 FT

(B) AXIAL POSITION = 0.12 FT

(C) AXIAL POSITION = 0.17 FT

(D) AXIAL POSITION = 0.25 FT
TRANSIENT AXIAL PROFILES OF MOLE- FRACTIONS OF HYDRAZINE AND AMMONIA

INITIAL BED TEMPERATURE = 530 DEG R

STEADY-STATE CHAMBER PRESSURE = 200 PSIA
STEADY-STATE MASS FLOW RATE = 6.5 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

![Graphs showing transient axial profiles of mole-fractions of hydrazine and ammonia.](image)
TRANSIENT AXIAL PROFILES OF MOLE-FRACTIONS OF NITROGEN AND HYDROGEN
INITIAL BED TEMPERATURE = 530 DEG R
STEADY-STATE CHAMBER PRESSURE = 200 PSIA
STEADY-STATE MASS FLOW RATE = 6.5 LB/FT^2-SEC
CATALYST BED CONFIGURATION: MIXED BED #1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

MOLE-FRACTION OF HYDROGEN IN INTERTISSIAL PHASE

0.5 0.4 0.3 0.2 0.1
0 0.1 0.2 0.3
AXIAL DISTANCE, z - FT

TIME, t = 3.01 SEC 0.063 SEC 0.002 SEC

MOLE-FRACTION OF NITROGEN IN INTERTISSIAL PHASE

0.5 0.4 0.3 0.2 0.1
0 0.1 0.2 0.3
AXIAL DISTANCE, z - FT

TIME, t = 3.01 SEC 0.063 SEC 0.002 SEC
COMPARISON OF THEORETICAL AND EXPERIMENTAL TRANSIENT TEMPERATURE PROFILES FOR VARIOUS INITIAL BED TEMPERATURES

(A) INITIAL BED TEMPERATURE = 530 DEG R

(B) INITIAL BED TEMPERATURE = 950 DEG R

(C) INITIAL BED TEMPERATURE = 1420 DEG R

AXIAL POSITION = 0.12 FT
STEADY-STATE CHAMBER PRESSURE = 200 PSIA
STEADY-STATE MASS FLOW RATE = 6.5 LB/FT²-SEC
CATALYST BED CONFIGURATION: MIXED BED #1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

TEMPERATURE IN INTERSTITIAL PHASE, T' - DEG R
VARIATION OF INTERSTITIAL TEMPERATURE WITH TIME
AT VARIOUS AXIAL POSITIONS

STEADY-STATE CHAMBER PRESSURE = 260 PSIA
STEADY-STATE MASS FLOW RATE = 5.8 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED #1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

AXIAL POSITION, z =

0.010 FT
0.052 FT
0.140 FT
0.308 FT

TEMPERATURE IN INTERSTITIAL PHASE, Tᵢ - DEG R

TIME, t - MILLISECONDS

0 40 80 120 160 200 240

200 400 600 800 1000 1200 1400 1600 1800 2000
VARIATION OF CATALYST PARTICLE TEMPERATURE WITH TIME AT VARIOUS AXIAL POSITIONS

STEADY-STATE CHAMBER PRESSURE = 260 PSIA

STEADY-STATE MASS FLOW RATE = 5.8 LB/FT$^2$ - SEC

CATALYST BED CONFIGURATION: MIXED BED #1 (SEE TEXT)

SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

![Graph showing variation of catalyst particle temperature with time at various axial positions.](image)

**AXIAL POSITION, z:**
- 0.010 FT
- 0.052 FT
- 0.140 FT
- 0.308 FT

**TIME, t - MILISECONDS:**
- Reactor On
- Reactor Off
- Reactor On

**TEMPERATURE WITHIN CATALYST PARTICLE, T,°C:**
- 0
- 100
- 200
- 300
- 400
- 500
- 600
- 700
- 800
- 900
- 1000
- 1100
- 1200
- 1300
- 1400
- 1500
- 1600
- 1700
- 1800
- 1900
- 2000
- 2100
- 2200
VARIATION OF CHAMBER PRESSURE WITH TIME

STEADY-STATE CHAMBER PRESSURE = 260 PSIA
STEADY-STATE MASS FLOW RATE = 5.8 LB/FT^2 - SEC
CATALYST BED CONFIGURATION: MIXED BED # 1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS
VARIATION OF MOLE-FRACTION OF HYDRAZINE WITH TIME AT VARIOUS AXIAL POSITIONS

STEADY-STATE CHAMBER PRESSURE = 260 PSIA
STEADY-STATE MASS FLOW RATE = 5.8 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED #1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS
VARIATION OF MOLE-FRACTION OF AMMONIA
WITH TIME AT VARIOUS AXIAL POSITIONS

STEADY-STATE CHAMBER PRESSURE = 260 PSIA
STEADY-STATE MASS FLOW RATE = 5.8 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

![Graph showing variation of mole-fraction of ammonia with time at various axial positions.](image-url)
VARIATION OF MOLE-FRACTION OF NITROGEN WITH TIME AT VARIOUS AXIAL POSITIONS

STEADY-STATE CHAMBER PRESSURE = 260 PSIA
STEADY-STATE MASS FLOW RATE = 5.8 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: MIXED BED # 1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS
VARIATION OF MOLE-FRACTION OF HYDROGEN WITH TIME AT VARIOUS AXIAL POSITIONS

STEADY-STATE CHAMBER PRESSURE = 260 PSIA
STEADY-STATE MASS FLOW RATE = 5.8 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: MIXED BED #1 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

MOLE-FRACTION OF HYDROGEN IN INTERSTITIAL PHASE

AXIAL POSITION, $x =$

0.308 FT
0.140 FT
0.052 FT
0.010 FT

0.0 40 80 120 160 200 240
TIME, $t$ - MILISECONDS
TRANSIENT INTERSTITIAL TEMPERATURE PROFILES
FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT^2 SEC
CATALYST BED CONFIGURATION: MIXED BED #2 (SEE TEXT)

SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVES REPRESENT CONTINUOUS OPERATION

TIME, t - SECONDS

TEMPERATURE IN INTERSTITIAL PHASE, T_i - DEG R

0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8

ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF

z = 0.052 FT
0.52 FT
0.100 FT
0.100 FT

TRANSIENT INTERSTITIAL TEMPERATURE PROFILES
FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT^2 SEC
CATALYST BED CONFIGURATION: MIXED BED #2 (SEE TEXT)

SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS
FIG. 13

TRANSIENT PARTICLE TEMPERATURE PROFILES FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

DASHED CURVES REPRESENT CONTINUOUS OPERATION
TRANSIENT CHAMBER PRESSURE PROFILE FOR THE
REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVE REPRESENTS CONTINUOUS OPERATION

CHAMBER PRESSURE, P - PSIA

TIME, t - SECONDS
TRANSIENT PROFILE OF MOLE-FRACTION OF HYDRAZINE FOR
THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVE REPRESENTS
CONTINUOUS OPERATION

AXIAL POSITION, z = 0.052 FT

TIME, t - SECONDS
TRANSIENT PROFILE OF MOLE-FRACTION OF HYDRAZINE FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS
TRANSIENT PROFILE OF MOLE-FRACTION OF AMMONIA FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVE REPRESENTS CONTINUOUS OPERATION

AXIAL POSITION, z = 0.052 FT

TIME, t - SECONDS

MOLE-FRACTION OF AMMONIA IN INTERSTITIAL PHASE

AXIAL POSITION, z = 0.052 FT
TRANSIENT PROFILE OF MOLE-FRACTION OF AMMONIA
FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVE REPRESENTS CONTINUOUS OPERATION
AXIAL POSITION, z = 0.100 FT
TRANSIENT PROFILE OF MOLE–FRACTION OF NITROGEN FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY–STATE MASS FLOW RATE = 5.76 LB/FT² – SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVE REPRESENTS CONTINUOUS OPERATION
AXIAL POSITION, z = 0.052 FT

TIME, t – SECONDS
TRANSIENT PROFILE OF MOLE-FRACTION OF NITROGEN FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED #2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

Reactor Status

ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF

DASHED CURVE REPRESENTS CONTINUOUS OPERATION

AXIAL POSITION, z = 0.100 FT

MOLE-FRACTION OF NITRGEN IN INTERSTITIAL PHASE

0 0.1 0.2 0.3 0.4 0.5 0.6

TIME, t - SECONDS

0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8
TRANSIENT PROFILE OF MOLE-FRACTION OF HYDROGEN FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

AXIAL POSITION, \( z = 0.052 \) FT
DASHED CURVE REPRESENTS CONTINUOUS OPERATION

MOLE-FRACTION OF HYDROGEN IN INTERSTITIAL PHASE

TIME, \( t \) - SECONDS
TRANSIENT PROFILE OF MOLE-FRACTION OF HYDROGEN FOR THE REFERENCE OPERATING CONDITIONS

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

AXIAL POSITION, $z = 0.100$ FT
DASHED CURVED REPRESENTS CONTINUOUS OPERATION

TIME, $t$ - SECONDS
TRANSIENT INTERSTITIAL TEMPERATURE PROFILES
FOR AN INJECTOR PRESSURE OF 500 PSIA

STEADY-STATE MASS FLOW RATE = 5.76 LB/FT$^2$ -SEC

CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)

SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

FIG. 23

DASHED CURVES REPRESENT CONTINUOUS OPERATION
FIG. 24

COMPARISON OF TRANSIENT INTERSTITIAL TEMPERATURE PROFILES FOR TWO INJECTOR PRESSURES IN A CONTINUOUS FLOW SYSTEM

STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC

CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)

SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

AXIAL POSITION = 0.100 FT
TRANSIENT INTERSTITIAL TEMPERATURE PROFILES FOR A STEADY-STATE MASS FLOW RATE OF 1.44 LB/FT²-SEC

INJECTOR PRESSURE = 150 PSIA
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

FIG. 25

REACTOR STATUS

DASHED CURVES REPRESENT CONTINUOUS OPERATION

TEMPERATURE IN INTERSTITIAL PHASE, T₁ - DEG R

TIME, t - SECONDS
TRANSIENT INTERSTITIAL TEMPERATURE PROFILES FOR A STEADY-STATE MASS FLOW RATE OF 14.4 LB/FT² - SEC

INJECTOR PRESSURE = 150 PSIA
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

FIG. 26

REACTOR STATUS

DASHED CURVES REPRESENT CONTINUOUS OPERATION
FIG. 27

COMPARISON OF TRANSIENT INTERSTICIAL TEMPERATURE PROFILES FOR VARIOUS STEADY-STATE MASS FLOW RATES IN A CONTINUOUS FLOW SYSTEM

INJECTOR PRESSURE = 150 PSIA
CATALYST BED CONFIGURATION: MIXED BED #2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

MASS FLOW RATE (LB./FT^2 - SEC) =

14.4
5.76
1.44

AXIAL POSITION, z = 0.100 FT
TRANSIENT INTERSTITIAL TEMPERATURE PROFILE FOR A BURIED INJECTOR CONFIGURATION

INJECTOR PRESSURE = 150 PSIA
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

TEMPERATURE IN INTERSTITIAL PHASE, $T_i$ - DEG R

AXIAL POSITION,
$z = 0.052$ FT

DASHED CURVE REPRESENTS CONTINUOUS OPERATION

TIME, $t$ - SECONDS
TRANSIENT INTERSTITIAL TEMPERATURE PROFILE FOR A BURIED INJECTOR CONFIGURATION

INJECTOR PRESSURE = 150 PSIA
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

TEMPERATURE IN INTERSTITIAL PHASE, T₁, DEG R

AXIAL POSITION, z = 0.100 FT
DASHED CURVE REPRESENTS CONTINUOUS OPERATION

TIME, t – SECONDS
COMPARISON OF TRANSIENT INTERSTITIAL TEMPERATURE PROFILES FOR TWO INJECTION CONFIGURATIONS IN A CONTINUOUS FLOW SYSTEM

INJECTOR PRESSURE = 150 PSIA
CATALYST BED CONFIGURATION: MIXED BED #2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS
FIG. 31

TRANSIENT INTERSTITIAL TEMPERATURE PROFILES FOR A CATALYST BED
PACKED WITH ALL 25–30 MESH PARTICLES

injector pressure = 150 PSIA
steady-state mass flow rate = 5.76 LB/FT² – SEC
see text for additional reactor parameters

Reactor status

Dashed curves represent continuous operation.
Transient interstitial temperature profiles for a catalyst bed packed with all 14-18 mesh particles

Injector pressure = 150 PSIA
Steady-state mass flow rate = 5.76 LB/FT² - SEC
See text for additional reactor parameters

Dashed curves represent continuous operation
TRANSIENT INTERSTITIAL TEMPERATURE PROFILE
FOR THE "MIXED BED #1" CATALYST BED CONFIGURATION

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

AXIAL POSITION, \( x = 0.052 \text{ FT} \)
DASHED CURVE REPRESENTS CONTINUOUS OPERATION

TIME, \( t \) — SECONDS
TRANSIENT INTERSTITIAL TEMPERATURE PROFILE
FOR THE "MIXED BED #1" CATALYST BED CONFIGURATION

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

FIG. 34

REACTOR STATUS
ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF ON OFF

TEMPERATURE IN INTERSTITIAL PHASE, Tᵢ, °F
DASHED CURVE REPRESENTS CONTINUOUS OPERATION
AXIAL POSITION, z = 0.100 FT

TIME, t - SECONDS
COMPARISON OF TRANSIENT INTERSTITIAL TEMPERATURE PROFILES FOR VARIOUS BED CONFIGURATIONS IN A CONTINUOUS FLOW SYSTEM

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/ FT² - SEC
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

CATALYST BED CONFIGURATION

A MIXED BED # 2 * (SEE TEXT)
B ALL 14-18 MESH
C MIXED BED # 1 (SEE TEXT)
D ALL 25-30 MESH

AXIAL POSITION,
z = 0.100 FT
TRANSIENT INTERSTITIAL TEMPERATURE PROFILES
FOR 60 msec/120 msec PULSE DUTY CYCLE

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

DASHED CURVES REPRESENT CONTINUOUS OPERATION

<table>
<thead>
<tr>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
</tr>
</tbody>
</table>

TIME, t - SECONDS

TEMPERATURE IN INTERSTITIAL PHASE, T_r - DEG R

Z = 0.052 FT

0.100 FT
TRANSIENT INTERSTITIAL TEMPERATURE PROFILES
FOR 60 msec/240 msec PULSE DUTY CYCLE

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED #2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

![Graph showing transient interstitial temperature profiles](image-url)

- **Time, t** - Seconds
- **Temperature in interstitial phase, T₁** - Degrees R
- **Reactor Status**
  - ON
  - OFF
- **Distance, z**
  - 0.052 FT
  - 0.100 FT

DASHED CURVES REPRESENT CONTINUOUS OPERATION
COMPARISON OF TRANSIENT INTERSTITIAL TEMPERATURE PROFILES FOR VARIOUS PULSE DUTY CYCLES

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

FIG. 38

(A) CONTINUOUS OPERATION
(B) DUTY CYCLE: 60 msec ON, 60 msec OFF
(C) DUTY CYCLE: 60 msec ON, 120 msec OFF
(D) DUTY CYCLE: 60 msec ON, 240 msec OFF

AXIAL POSITION
z = 0.100 FT

TIME, t - SECONDS

TEMPERATURE IN INTERSTITIAL PHASE, T - DEG R

INJECTOR PRESSURE = 150 PSIA
STEADY-STATE MASS FLOW RATE = 5.76 LB/FT² - SEC
CATALYST BED CONFIGURATION: MIXED BED # 2 (SEE TEXT)
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

AXIAL POSITION
z = 0.100 FT

TIME, t - SECONDS

TEMPERATURE IN INTERSTITIAL PHASE, T - DEG R
FIG. 39

TRANSIENT INTERSTITIAL TEMPERATURE PROFILE FOR A HIGH THRUST ENGINE

INJECTOR PRESSURE = 1405 PSIA
STEADY-STATE MASS FLOW RATE = 40.3 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: ALL 25-30 MESH PARTICLES
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVE REPRESENTS CONTINUOUS OPERATION
AXIAL POSITION, z = 0.084 FT

TIME, t - SECONDS
TRANSIENT PARTICLE TEMPERATURE PROFILE FOR A HIGH THRUST ENGINE

INJECTOR PRESSURE = 1405 PSIA
STEADY-STATE MASS FLOW RATE = 40.3 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: ALL 25-30 MESH PARTICLES
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

TEMPERATURE WITHIN CATALYST PARTICLE, $T_p$ - DEG R

DASHED CURVE REPRESENTS CONTINUOUS OPERATION

AXIAL POSITION, z = 0.084 FT

TIME, t - SECONDS
TRANSIENT CHAMBER PRESSURE PROFILE FOR A HIGH THRUST ENGINE

INJECTOR PRESSURE = 1405 PSIA
STEADY-STATE MASS FLOW RATE = 40.3 LB/FT² - SEC
CATALYST BED CONFIGURATION: ALL 25-30 MESH PARTICLES
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVE REPRESENTS CONTINUOUS OPERATION
AXIAL POSITION, \( z = 0.084 \) FT

CHAMBER PRESSURE, \( p \) - PSIA

TIME, \( t \) - SECONDS
TRANSIENT PROFILE OF MOLE-FRACTION OF HYDRAZINE
FOR A HIGH THRUST ENGINE

INJECTOR PRESSURE = 1405 PSIA
STEADY-STATE MASS FLOW RATE = 40.3 LB/FT² – SEC
CATALYST BED CONFIGURATION: ALL 25-30 MESH PARTICLES
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

DASHED CURVES REPRESENT CONTINUOUS OPERATION
AXIAL POSITION, z = 0.084 FT
TRANSIENT PROFILE OF MOLE-FRACTION OF AMMONIA FOR A HIGH THRUST ENGINE

INJECTOR PRESSURE = 1405 PSIA
STEADY-STATE MASS FLOWRATE = 40.3 LB/FT² - SEC
CATALYST BED CONFIGURATION: ALL 25-30 MESH PARTICLES
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

TIME, t - SECONDS

MOLE FRACTION OF AMMONIA IN INTERSTITIAL PHASE

REACTOR STATUS

DASHED CURVE REPRESENTS CONTINUOUS OPERATION
AXIAL POSITION, z = 0.084 FT
TRANSIENT PROFILE OF MOLE-FRACTION OF NITROGEN FOR A HIGH THRUST ENGINE

INJECTOR PRESSURE = 1405 PSIA
STEADY-STATE MASS FLOW = 40.3 LB/FT$^2$ - SEC
CATALYST BED CONFIGURATION: ALL 25-30 MESH PARTICLES
SEE TEXT FOR ADDITIONAL REACTOR PARAMETERS

REACTOR STATUS

DASHED CURVE REPRESENTS CONTINUOUS OPERATION
AXIAL POSITION, $z = 0.084$ FT

MOLE-FRACTION OF NITROGEN IN INTERSTITIAL PHASE

TIME, $t$ - SECONDS
Figure 45

Transient Profile of Mole-Fraction of Hydrogen for a High Thrust Engine

Injector Pressure = 1405 PSIA
Steady-State Mass Flow Rate = 40.3 LB/FT² - SEC
Catalyst Bed Configuration: All 25-30 Mesh Particles
See text for additional reactor parameters

Reactors Status

[Graph showing reactor status with on and off cycles]

Dashed curve represents continuous operation

Axial Position, z = 0.084 FT

Time, t - Seconds