RM No. SE8H06



NACA

# RESEARCH MEMORANDUM

for the

Bureau of Aeronautics, Department of the Navy

## INVESTIGATION OF X24C-2 10-STAGE AXIAL-FLOW COMPRESSOR

## III - SURGE CHARACTERISTICS

By Howard A. Buckner, Jr. and Richard M. Downing

Flight Propulsion Research Laboratory
Cleveland, Ohio



NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

AUGUST 19 1948

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

for the

Bureau of Aeronautics, Department of the Navy

# INVESTIGATION OF X24C-2 10-STAGE AXIAL-FLOW COMPRESSOR

# III - SURGE CHARACTERISTICS

By Howard A. Buckner, Jr. and Richard M. Downing

## SUMMARY

During the investigation of the X24C-2 axial-flow compressor, the surge characteristics were studied from comparative fluctuations of static pressure behind each stage during surge. Of particular interest were the variation in the surge characteristics from stage to stage and the effects of compressor speed and inlet pressure on the surge characteristics of the compressor.

All stages started surging at approximately the same time and, although the end of surge was not clearly defined, all stages apparently stopped surging at approximately the same time. The amplitude of pressure pulsations decreased from either end of the compressor toward the center, which indicated the possibility of a node near the center. Compressor speed had an appreciable effect on both the amplitude and the frequency of pulsation. Inlet pressure had an appreciable effect on amplitude but little effect on frequency. When adapted to this compressor system, the equation for computing the frequency of pulsation for an equivalent Helmholtz resonator gave a frequency of 2.74 as compared with an observed frequency of 1.97 to 2.58 cycles per second.

## INTRODUCTION

Compressor operation at low air flows for a given speed is limited by unstable flow conditions, commonly called surge. An investigation of surge in centrifugal compressors (reference 1) showed that the pulsation of pressures and velocities occurred when the slope of the compressor characteristic curve was positive and that the magnitude and frequency, as well as the incidence of surge, depended on the capacity and resistance of the total system. Although the theory presented in reference 1 is applicable to axial-flow compressors, little experimental information is available on the surge characteristics of the individual stages of axial-flow compressors, or on the variation of the surge characteristics with operating conditions.

During the investigation to determine the performance of the X24C-2 compressor (references 2 and 3), instrumentation was added to study the surge characteristics and to determine the effect of speed and inlet pressure on the frequency, amplitude, and phase relation of the pressure pulsations behind each stage.

## APPARATUS AND PROCEDURE

Compressor. - The X24C-2 compressor, described in reference 2, was designed for an air weight flow of 54.6 pounds per second and a pressure ratio of 4 at 12,000 rpm with sea-level inlet conditions. The blading consisted of a row of inlet guide vanes, ten rows of rotor blades, nine rows of stator blades, and two rows of outlet guide vanes. The maximum diameter was $23\frac{5}{8}$ inches; the length, $44\frac{1}{8}$ inches; and the constant rotor-blade tip diameter, 18.91 inches. The hub-tip ratio at the inlet and first two stages was approximately 0.5 and gradually increased through succeeding stages to about 0.74 at the exit. The clearance between the rotor-blade tips and the casing was 0.045 inch.

Setup. - The compressor was driven by a 9000-horsepower variable-frequency induction motor through a gearbox with a step-up ratio of 8.974. A floating-spline coupling connected the gearbox to the drive shaft, which was bolted to the compressor rotor.

Air entered the compressor through a submerged adjustable orifice in the inlet duct, a butterfly valve, and a depression tank 6 feet in diameter and 10 feet in length. A series of three screens was fitted into the midsection of the tank to remove any foreign particles and equalize the air distribution. A wooden nozzle between the depression tank and the compressor inlet provided smooth air entry into the compressor. The compressor discharged through a straight annular passage into the collector. Two 20-inch radial ducts diametrically opposite connected the collector to a common 20-inch duct, which in turn was connected to the laboratory altitude exhaust. The outlet pressure was regulated by a butterfly valve in the discharge duct.

Instrumentation. - The instrumentation for determining the air weight flow and over-all compressor performance was that recommended in reference 4. The static pressure at the outer casing was measured immediately downstream of each row of stator blades. Each tap was circumferentially located at the center of the passage between two adjacent stator blades. The taps for the different stages were in approximately the same axial plane. As shown schematically in figure 1, two differential-pressure recorders of five cells each were connected to these static-pressure taps to obtain simultaneous recordings of the pulsations in all stages on two film units. The static-pressure tap was connected directly to one side of the recorder diaphragm and connected through a relatively high-volume, high-resistance damping chamber to the other side of the recorder diaphragm. The diaphragm thus had a fluctuating pressure at one side and a relatively steady pressure at the other during surge, but the average pressure on the two sides was nearly the same. This method of utilizing the pressure recorder eliminated the necessity of providing a mechanical source of pressure for balancing the mean static pressures of the various compressor stages. Because the installations for the ten stages were identical, the amplitudes of the fluctuations for the different stages can be compared when the small variations in calibration among the recorders are taken into account (fig. 2). The absolute values of amplitude, however, are dependent on the dynamic characteristics of the installation rather than being a true indication of the static-pressure fluctuation.

Procedure. - With the compressor operating at constant speed and inlet conditions just outside the surge region, the pressure recorders were started and the outlet throttle was gradually closed until surge was obtained. After the unit had surged for a few seconds, the outlet throttle was opened until surge was stopped; the recorders were then turned off.

Surge traces were obtained at equivalent compressor speeds of 80, 89, and 100 percent of design speed at an inlet pressure of 12 inches of mercury absolute and at 89 and 100 percent of design speed for an inlet pressure of 6 inches of mercury absolute. All runs were made with an inlet temperature of approximately 538° R. Because of accidental plugging of the small orifice holes in the surge chambers and the delicacy of the pressure recorders, considerable difficulty was encountered in getting the recorders to function properly. As a result, complete data for all stages were not obtained for any one run. By repearing runs, however, sufficient data were obtained on all stages for determining the trends desired.

Because film exposure could not simultaneously be within the proper range for all of the pressure recorders, it was necessary to retouch the surge traces to make duplication possible. This retouching consisted in increasing the density of the lines on the film without changing the position or width of the lines.

## RESULTS AND DISCUSSION

Surge characteristics. - The surge traces for 89 percent of design equivalent speed and an inlet pressure of 12 inches of mercury absolute are presented in figure 3 for all the stages except stage 9. In general, all stages began to surge at approximately the same time and, although the end of surge is not clearly defined, all stages apparently stopped surging at the same time. Data from a preliminary run at design equivalent speed are presented in figure 4 for stages 8 and 9 to show that stage 9 exhibited the same general trends as the other stages. Because the sensitivity of the recorders was different for this preliminary run, the calibration curves of figure 2 are inapplicable to these data.

Because of the superimposition of higher harmonics and mechanical vibrations on the pressure fluctuations, it is difficult to determine whether the fluctuations for the different stages are in phase. Stages 1 to 5, where the maxima and minima are well defined and uniformly separated, are in phase (fig. 3(a)), but the time spacing between the maxima and minima for stages 6 to 10 is so small that the phase relations are poorly defined (fig. 3(b)). The fundamental frequencies of all the different stages, however, are approximately equal. The amplitude tended to decrease from either end of the compressor toward the center with the minimum amplitude occurring at approximately the sixth stage. This trend indicates the possibility of a node near the center of the compressor, which may result from the large volumes of the depression tank and the collector at the inlet and outlet of the compressor, respectively. Because of the superimposition of higher harmonics and mechanical vibrations of unknown magnitude on the pressure fluctuations, this phenomenon could not be further investigated by a harmonic analysis.

In reference 1, it was found that a compressor system with a large external volume has a low-frequency, high-amplitude fluctuation during surge, whereas a system with a small volume has a high-frequency, low-amplitude fluctuation. In reference 5 it was found that the frequency of pulsation could be calculated with reasonable accuracy for centrifugal blowers by an adaptation of the Helmholtz resonator equation. In the present case, a slightly different adaptation of the equation was made for computing frequency as follows:

$$f = \frac{c}{2\pi}\sqrt{\frac{s}{LV_o}}$$

where

f frequency of pulsation, cycles per second

s minimum flow area in compressor discharge, 0.900 square foot

L distance between inlet depression tank and exhaust collector, 7.07 feet

$V_o$ total volume of system between inlet and outlet throttles, 556 cubic feet

c velocity of sound in air, feet per second

The solution of this expression gave a frequency of 2.74 cycles per second, whereas the experimental values varied from 1.97 to 2.58. The volume used in the calculation is apparently smaller than the effective volume, which is logical since the inlet and outlet throttles were partly open. This belief is supported by the surge traces where the amplitude generally increased and the frequency decreased as the outlet throttle was opened to bring the unit out of surge.

Effect of speed. - The effect of speed on the surge characteristics can be seen by a comparison of figures 3, 5, and 6. For example, the amplitude for stage 2 increased from 0.80 to 2.20 inches of water with an increase in speed from 80 to 100 percent of design equivalent speed at an inlet pressure of 12 inches of mercury absolute and the trend was similar for the other stages. For centrifugal compressors, compressor speed apparently had little influence on the frequency of pulsation (references 1 and 5) but for axial-flow compressors, speed apparently has an appreciable affect. The frequency decreased as the speed was increased. For example, an increase from 80 to 100 percent of design equivalent speed at an inlet pressure of 12 inches of mercury absolute resulted in a decrease of frequency from 2.58 to 1.97 cycles per second, which may result from the increased pressure and temperature at the compressor outlet caused by the increase in speed.

Effect of inlet pressure. - Comparison of figure 5 with 7 and figure 3 with 8 shows that inlet pressure had little effect on the frequency of pulsation. For 89 percent of design equivalent speed, the frequency varied only from 2.46 to 2.30 for an increase in pressure from 6 to 12 inches of mercury absolute; at 100 percent of design equivalent speed the frequency varied only from 2.15 to 1.97. The amplitude, however, increased appreciably with inlet pressure. For 89 percent of design equivalent speed, the amplitude for stage 2 increased from 0.60 to 0.98 inch of water for an increase in pressure from 6 to 12 inches of mercury; at 100 percent of design equivalent speed, the variation was from 0.98 to 2.20 inches of water. The other stages in general exhibited the same trend.

## SUMMARY OF RESULTS

An investigation of the surge characteristics of the X24C-2 axial-flow compressor produced the following results:

1. All stages started surge at approximately the same time. Although the end of surge was not clearly defined, it appeared that surging also ended at approximately the same time for all stages.

2. The amplitude of the pressure pulsations decreased from either end of the compressor toward the center, which indicated the possibility of a node near the center of the compressor.

3. When adapted to this compressor system, the equation for computing the frequency of pulsation for a Helmholtz resonator gave a frequency of 2.74 as compared with observed frequencies of 1.97 to 2.58 cycles per second.

4. Compressor speed had an appreciable effect on both the amplitude and the frequency of pulsation.

5. Inlet pressure had an appreciable effect on the amplitude but very little effect on the frequency of pulsation.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 6, 1948.

Howard A. Buckner, Jr.,
Aeronautical Research
Scientist.

Richard M. Downing,
Mechanical Engineer.

Approved: Robert O. Bullock,
Aeronautical Research
Scientist.

Oscar W. Schey,
Aeronautical Research
Scientist.

rl

## REFERENCES

1. Bullock, Robert O., Wilcox, Ward W., and Moses, Jason J.: Experimental and Theoretical Studies of Surging in Continuous-Flow Compressors. NACA TN No. 1213, 1947.

2. Schum, Harold J., and Buckner, Howard A., Jr.: Investigation of 10-Stage Axial-Flow X24C-2 Compressor. I - Performance at Inlet Pressure of 21 Inches Mercury Absolute and Inlet Temperature of 538° R. NACA RM No. E7G11, Bur. Aero., 1947.

3. Finger, Harold B., Schum, Harold J., and Buckner, Howard A., Jr.: Investigation of X24C-2 10-Stage Axial-Flow Compressor. II - Effect of Inlet-Air Pressure and Temperature on Performance. NACA RM No. E7H22, Bur. Aero., 1947.

4. NACA Subcommittee on Compressors: Standard Procedures for Rating and Testing Multistage Axial-Flow Compressors. NACA TN No. 1138, 1946.

5. Heath, W. R., and Elliot, W. R.: Control and Prediction of Pulsation Frequency in a Duct System. Journal of Applied Mechanics, vol. 13, no. 4, Dec. 1946, pp. A-291 - A-293.

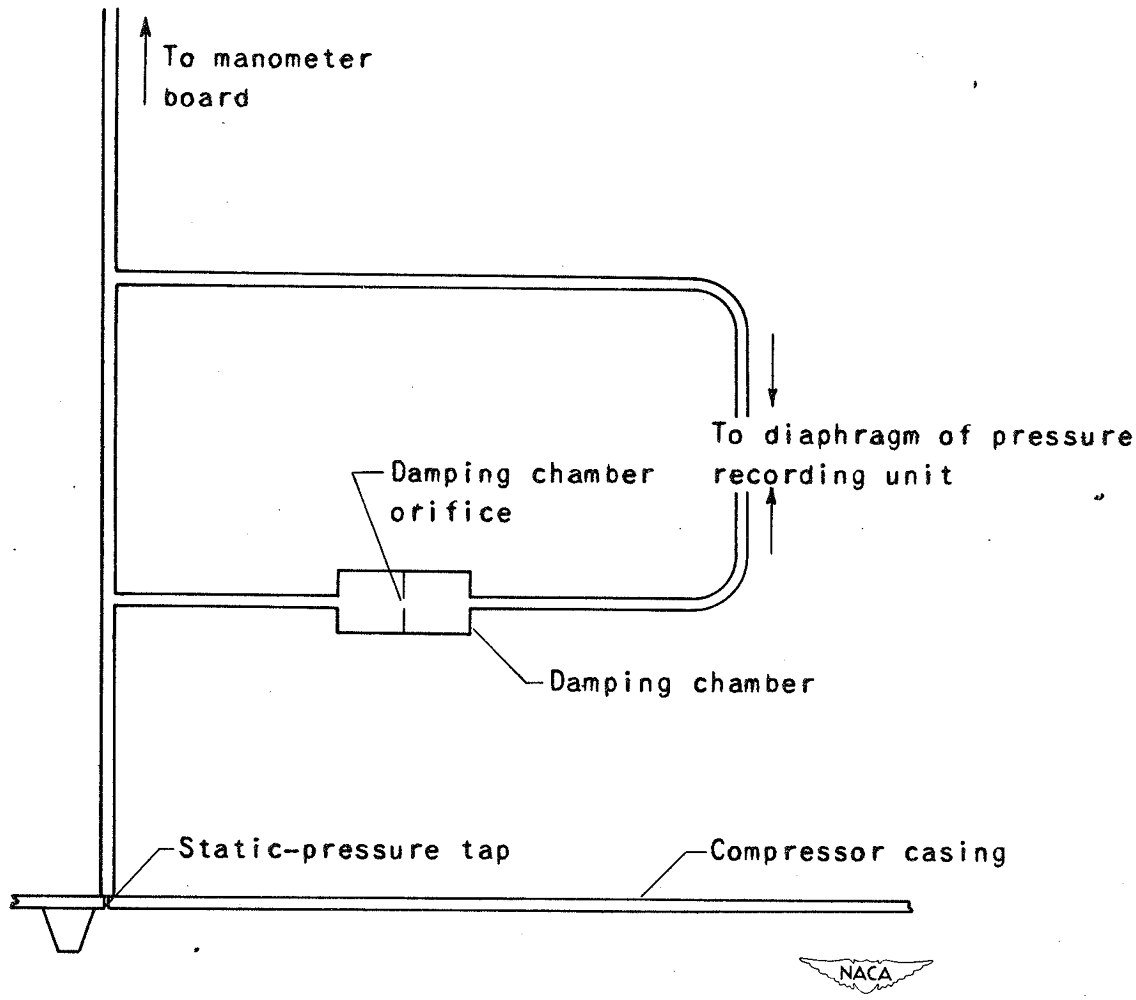



Figure 1. - Schematic diagram of differential-pressure recording unit.

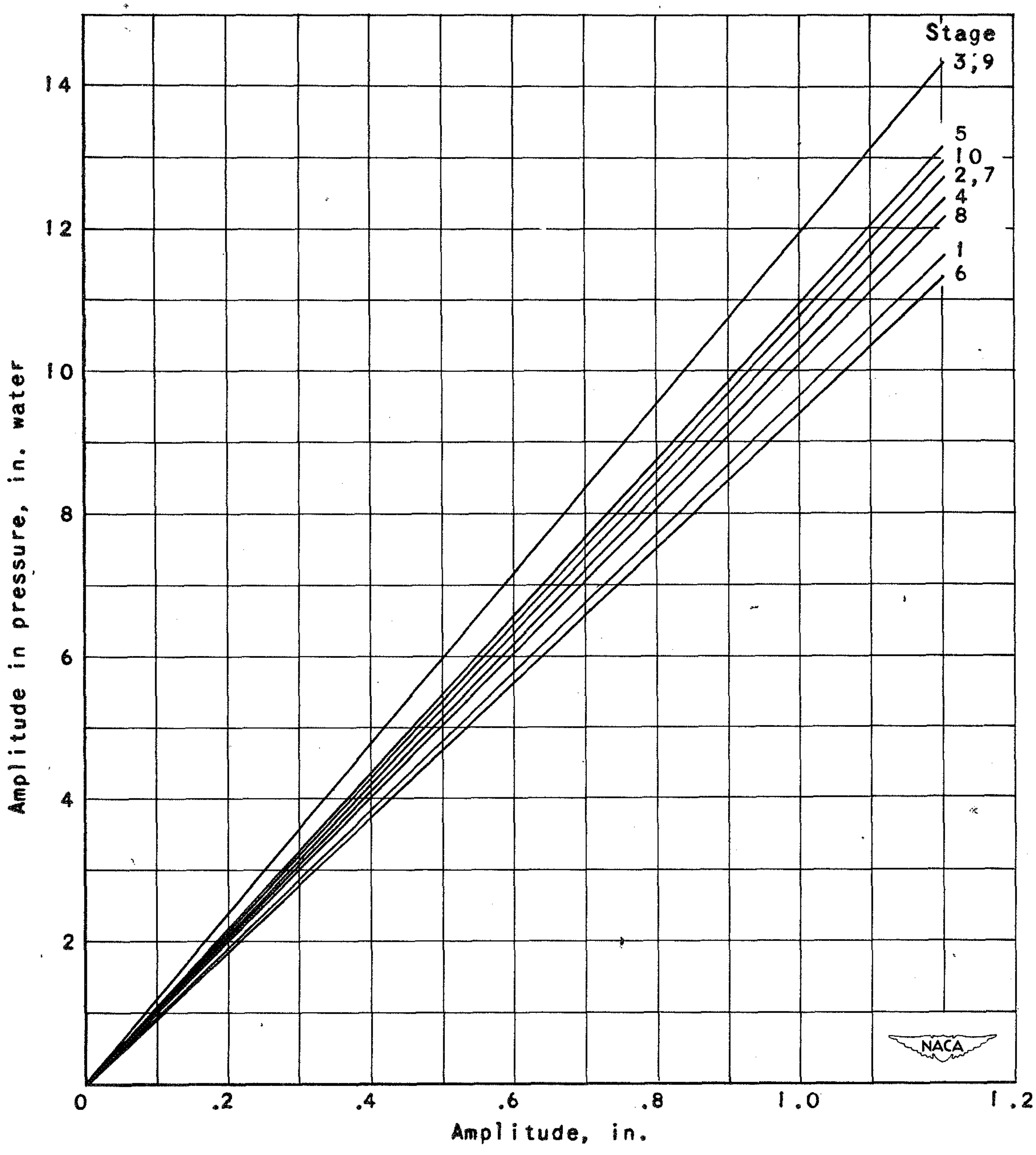
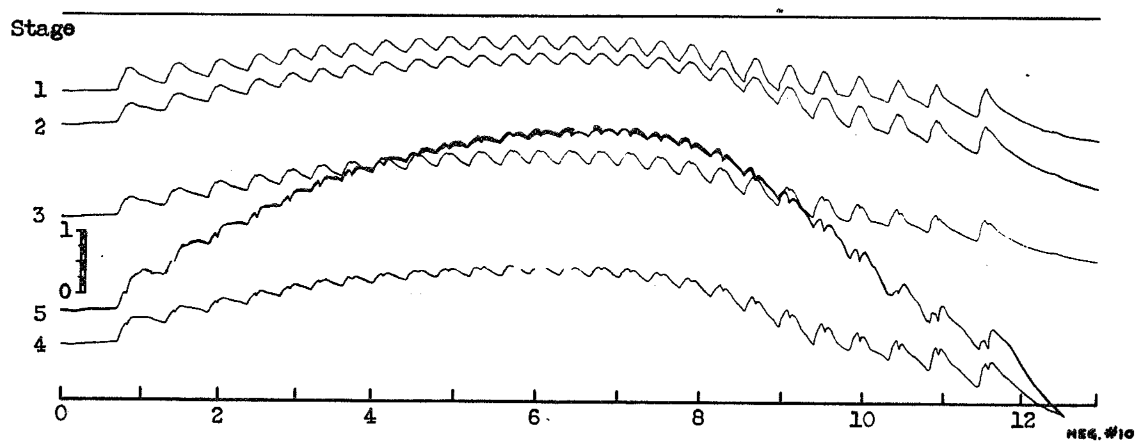
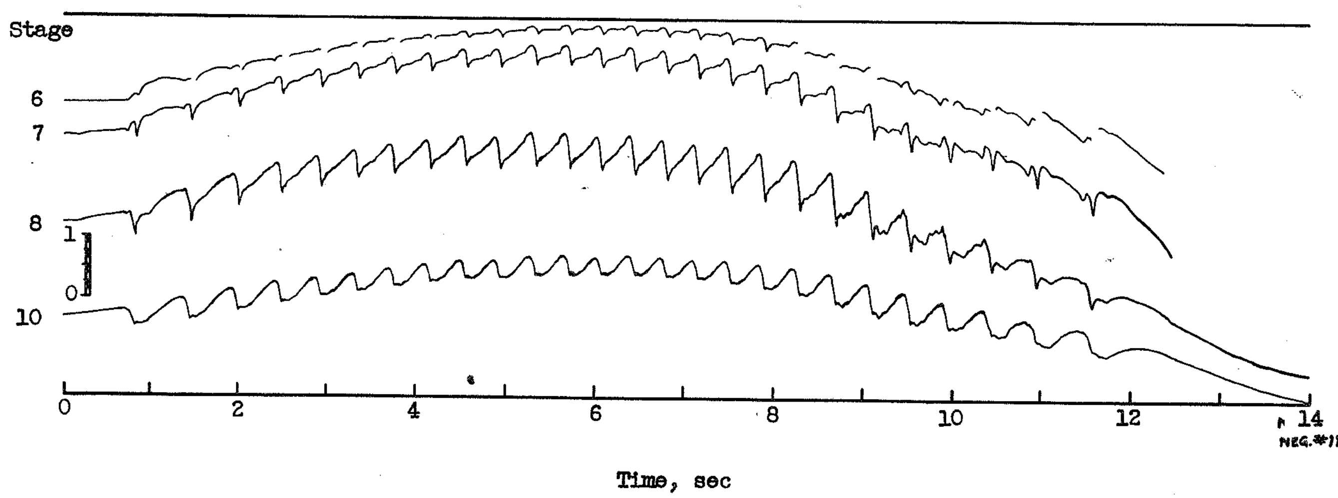



Figure 2. - Calibration of differential-pressure recorders.




(a) Stages 1 to 5.




(b) Stages 6 to 10.

Figure 3. - Surge traces for 89 percent of design equivalent speed, inlet pressure of 12 inches mercury absolute, and inlet temperature of 538° R.

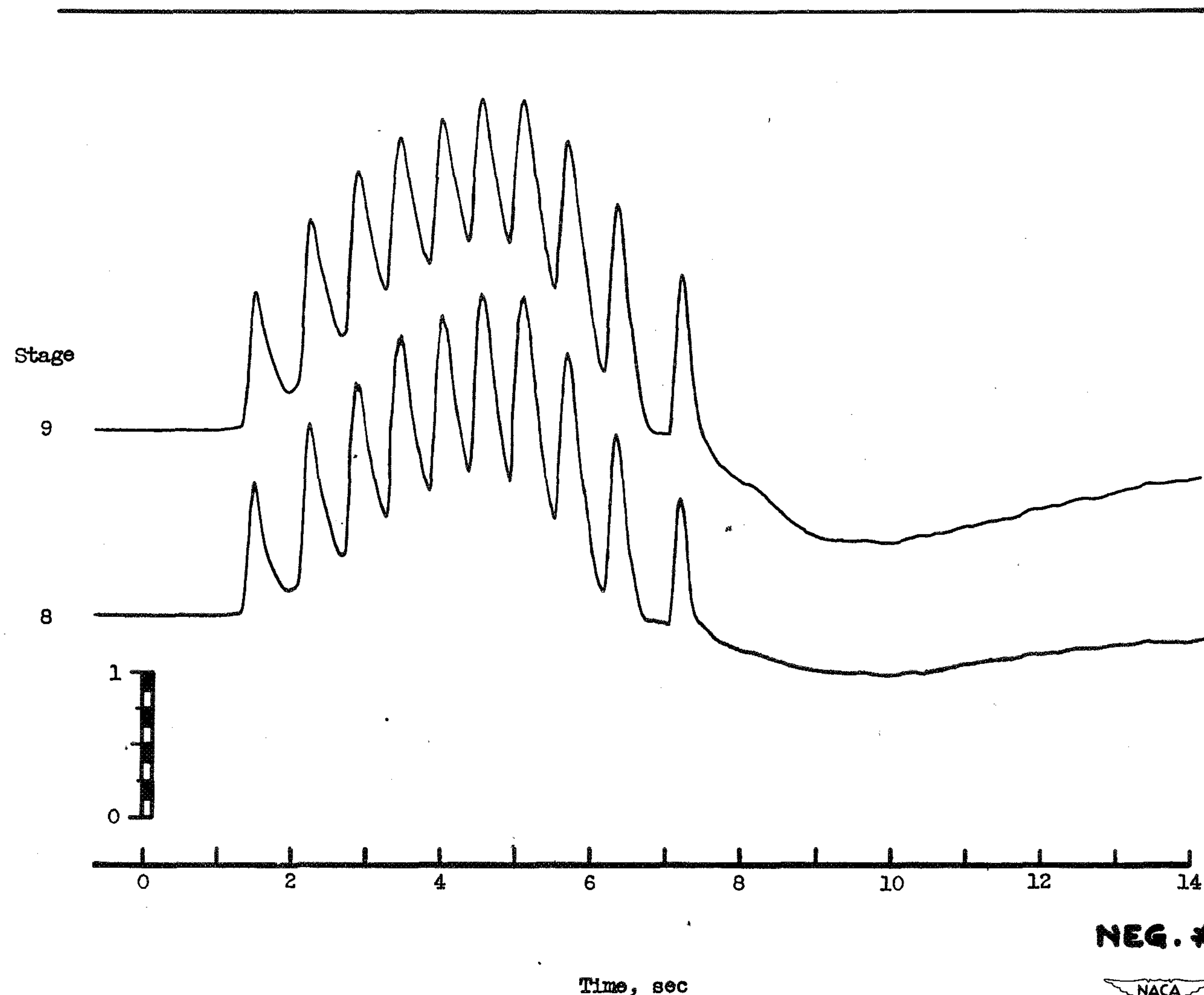
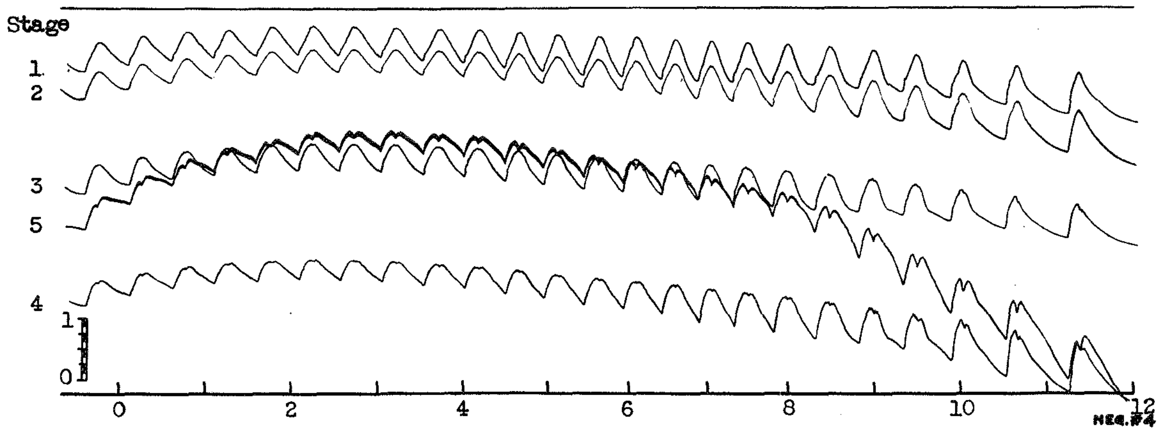
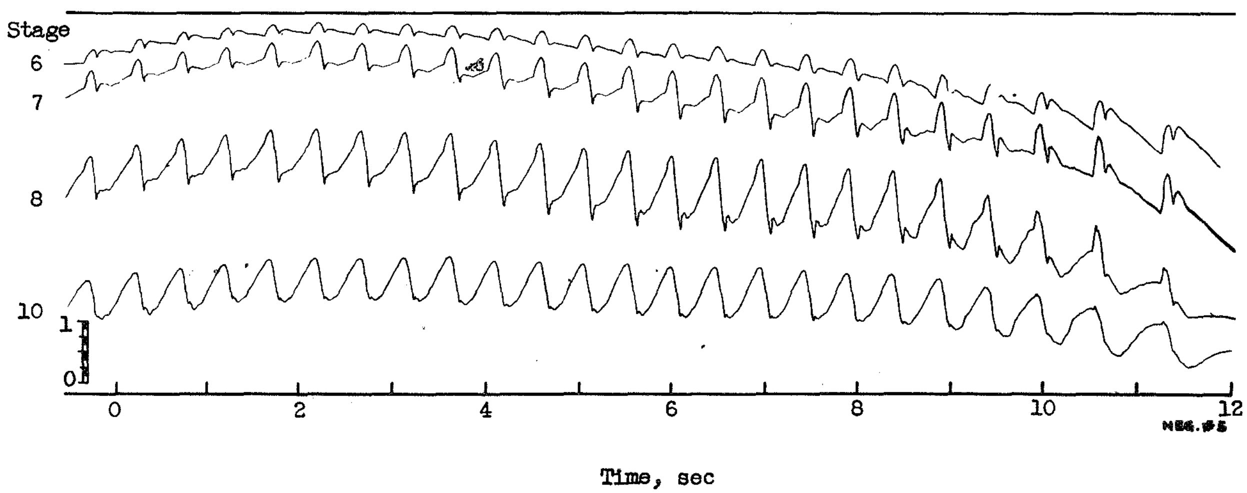



Figure 4. - Surge traces for stages 8 and 9 for 100 percent of design speed, inlet pressure of 12 inches mercury absolute and inlet temperature of 538° R. (Calibration curves of fig. 2 inapplicable.)



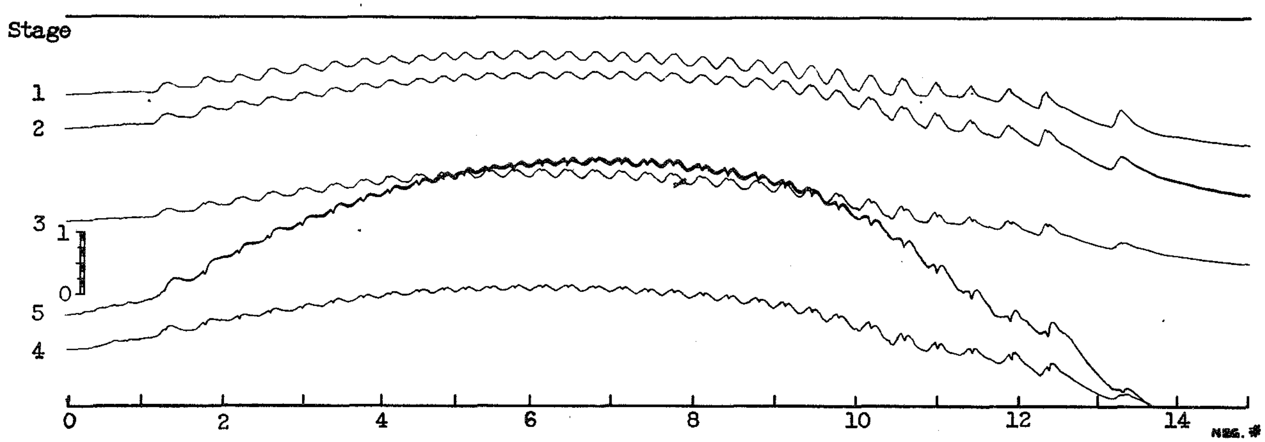

(a) Stages 1 to 5.



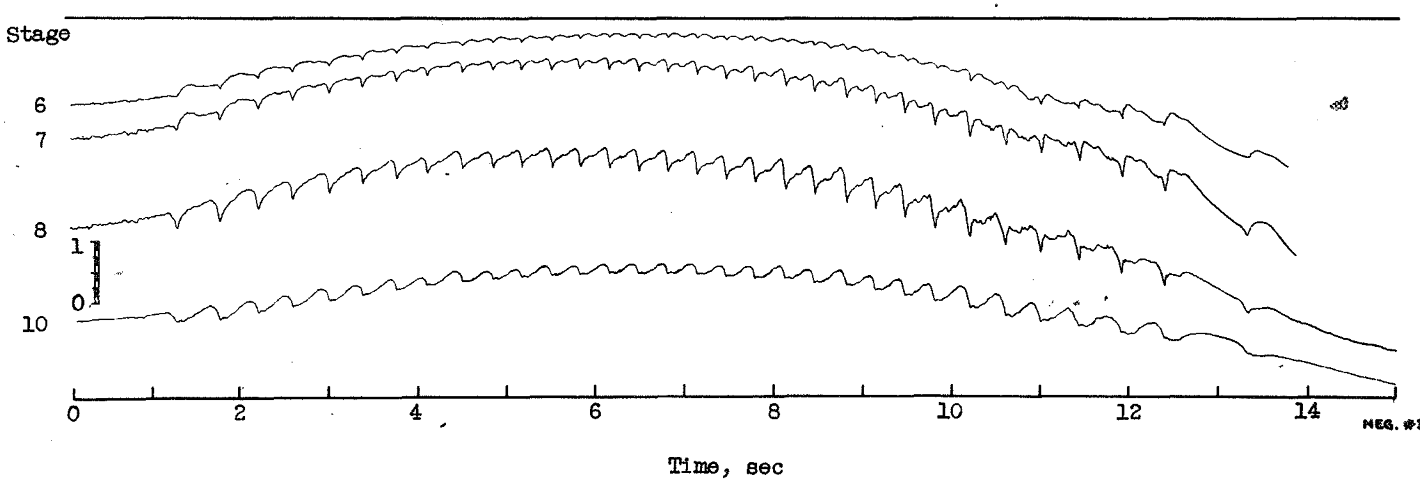

(b) Stages 6 to 10.

Figure 5. - Surge traces for 100 percent of design equivalent speed, inlet pressure of 12 inches mercury absolute, and inlet temperature of 538° R.

CONFIDENTIAL



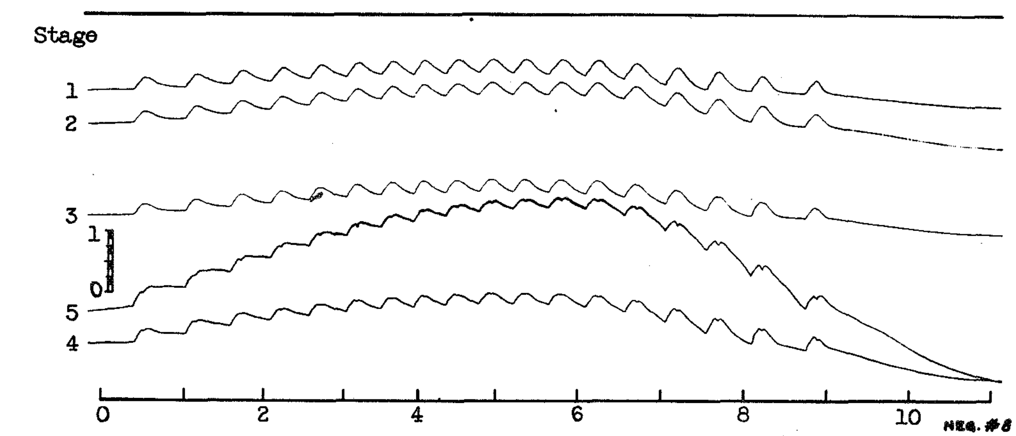

(a) Stages 1 to 5.



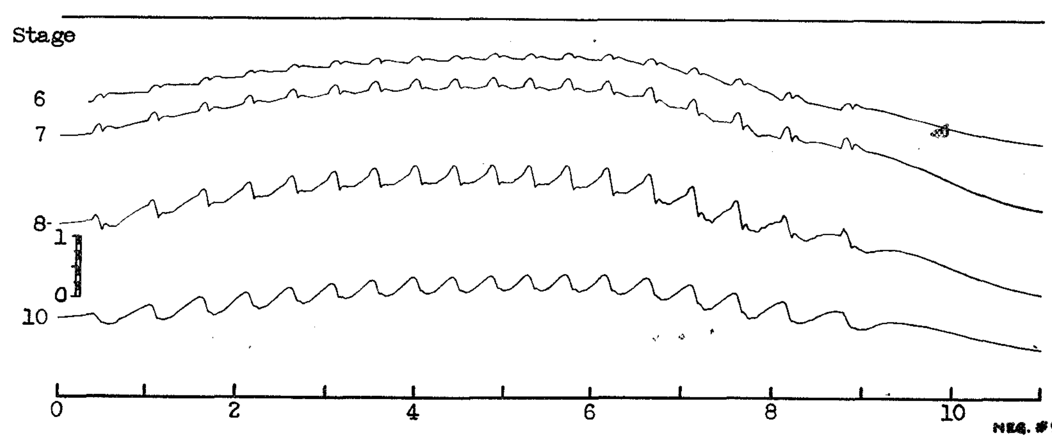

(b) Stages 6 to 10.

Figure 6. - Surge traces for 80 percent of design equivalent speed, inlet pressure of 12 inches mercury absolute, and inlet temperature of 538° R.

CONFIDENTIAL



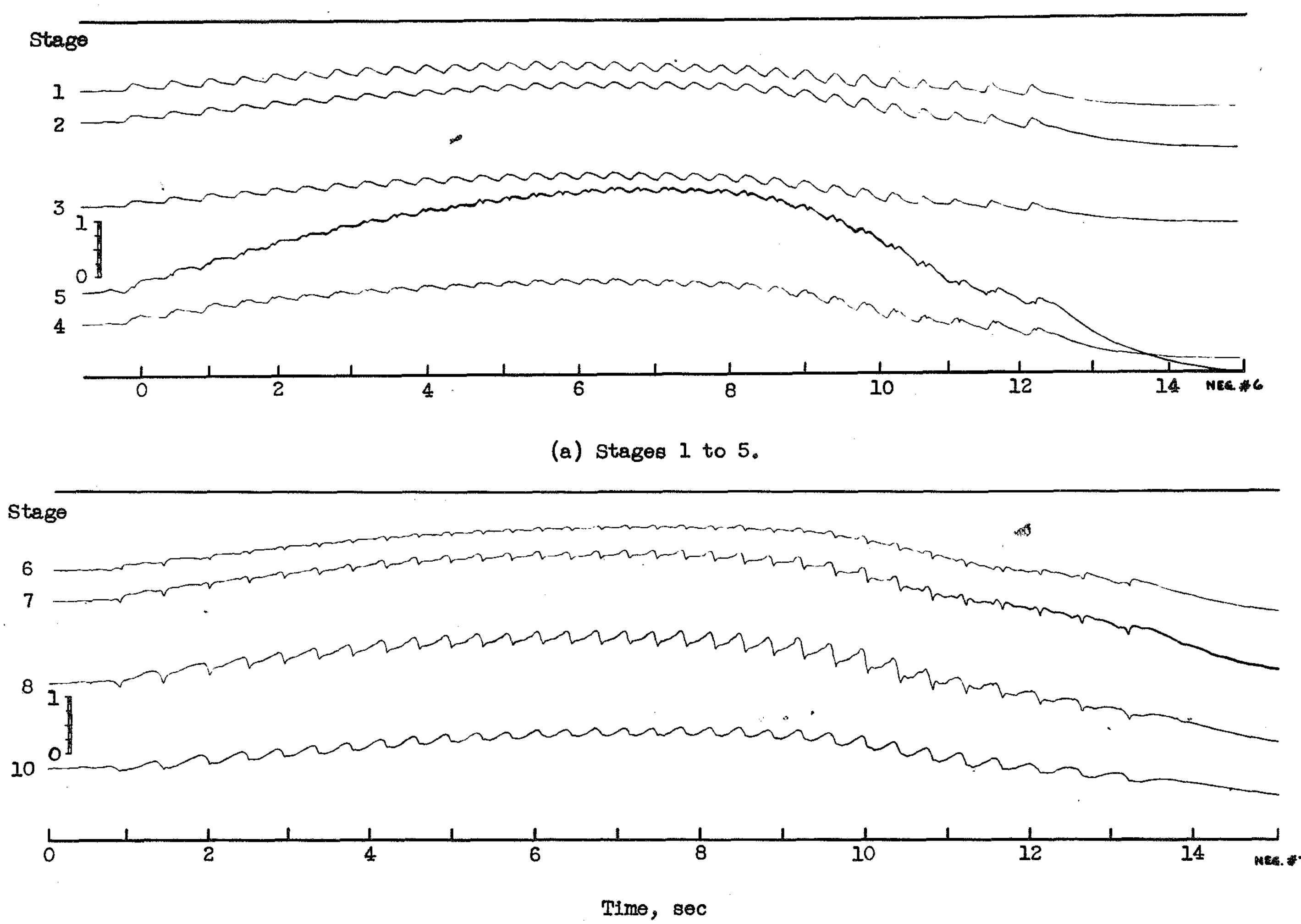

(a) Stages 1 to 5.




(b) Stages 6 to 10.

Figure 7. - Surge traces for 100 percent of design equivalent speed, inlet pressure of 6 inches mercury absolute, and inlet temperature of 538° R.

CONFIDENTIAL




(a) Stages 1 to 5.

(b) Stages 6 to 10.

NACA

Figure 8. - Surge traces for 89 percent of design equivalent speed, inlet pressure of 6 inches mercury absolute, and inlet temperature of 538° R.