

LAUNCH VEHICLE AND SPACECRAFT DYNAMICS

NASA Langley Research Center
Langley Station, Hampton, Va.

Presented at Field Inspection of Advanced Research and Technology

Hampton, Virginia
May 18-22, 1964

DYNAMICS RESEARCH LABORATORY

This is the Dynamics Research Laboratory where we conduct advanced research on dynamics of launch vehicles and spacecraft. Our discussion will emphasize the nature of the problems, the phenomena involved, and the research facilities used.

During launch and flight through the atmosphere, the vehicle is subjected to many types of pulsating forces such as engine starting shocks, noise pressures, fluctuations in engine thrust, and forces from the sloshing propellants and winds aloft. These forces cause the vehicle to vibrate. An essential task is to reduce these vibrations or design the vehicle to withstand the loads. To do this we must know the forces and the physical characteristics of the structure. We must also develop the necessary analytical and experimental techniques to predict the vehicle motions.

Thus to advance the state of the art, we must deal with a variety of problems. We begin with a discussion of steady and unsteady winds blowing past the vehicle while it is still on the launch pad. These winds produce stresses in the vehicle and tie-down mechanism, and in some cases actually dictate the design of some vehicle structures. The principal phenomenon involved is a vortex shedding in the wake, and you may recall that even bridges and smoke stacks must be designed to allow for these effects. This movie illustrates the problem. This is an overhead view of a 14-foot model of the Saturn I-B launch vehicle mounted in a wind tunnel. Even though the wind is steady, it causes the vehicle to vibrate from side to side. We have chosen a rather extreme case to demonstrate the motions. This is a view looking into the wind. Such vibrations interfere with launch operations, and the vehicles must be properly designed to avoid catastrophic failures such as shown by this model. Gusts, which always occur in natural winds, make the problem even more difficult.

That red and white model over there with its umbilical tower is a model of the Saturn V vehicle which was used for similar studies in the same wind tunnel.

As you may note during this movie which shows the first phases of a Saturn flight, the ignition of the engines is a very violent transient or shock phenomenon which has about the same effect on the vehicle instrumentation as dropping a fine watch on the floor. The instrumentation has to be able to take the shock loads. On lift-off, the noise from the engines is reflected from the ground and the associated pressure fluctuations produce vibrations which are damaging to the vehicle structure and payload. This noise is also transmitted through the air and ground, and the high sound-pressure levels, which may reach 170 decibels near the launch pad, will damage conventional buildings at distances up to several miles. Consequently, launch sites must be separated from population centers.

As the size of the launch vehicle is increased, most of the acoustic energy occurs at lower frequencies and a substantial part of the noise is below the audible range. One may feel the pressure pulses but may not hear much of the sound. This is a subject of much interest to NASA and a unique facility, shown

in the next slide, has recently been constructed at Langley to study the effects of low-frequency noise on the vehicle, the payload, the surrounding structure, and on man himself.

This facility permits us to produce and study controlled high-intensity noise pressures in the frequency range from 1 to 50 cycles per second. The large chamber is adequate for investigation of the response of payloads as large as the Apollo Command Module, or the Lunar Excursion Module. The noise generator is a 14-foot-diameter woofer or loudspeaker which is driven by a 20,000-pound hydraulic shaker.

In addition to the vibrations of the vehicle excited by the acoustic pressure pulses, an unsteady component of engine thrust also exists which is directly transmitted to the structure and may cause it to vibrate severely.

As the vehicle continues its ascent through the atmosphere, strong and variable winds are often encountered, particularly at the jet stream altitudes of about 30,000 feet. The vehicle feels these winds as a series of fluctuating forces. These unsteady forces represent severe dynamic loading conditions which must be coped with for successful design of both the structure and the control system of the vehicle.

The nature of the winds above launch sites has been investigated by a smoke-trail technique developed at Langley for research evaluation of more routine methods. This technique has been shown to be very accurate and is indicated in the following movie. A solid-propellant rocket motor is fitted with a nose cone which contains about 150 pounds of smoke producing chemical. The first shot was in real time and this one is in slow motion. The rocket is launched on a near vertical trajectory and the chemical is ejected during flight to produce a continuous and highly reflective smoke trail to altitudes of about 75,000 feet. The smoke is blown by the winds and the trail outlines very clearly the complete wind profile. Photographs from ground-based camera stations then permit detailed determination of the wind speeds and directions. These upper winds are currently under study in a Langley program at Wallops and a cooperative Langley-Marshall program at Cape Kennedy.

A complex interaction of structure and control system takes place as a launch vehicle ascends through winds while maneuvering to stay on the correct flight path. The model shown in the next movie demonstrates these interactions. Notice that the vehicle responds as a flexible structure - not as a rigid body. The flexibility is exaggerated here for illustration. On the model an accelerometer is used as a sensor to simulate a control-system gyroscope which senses vehicle motion. The control system compares the motion measured by the gyro with the desired motion, then commands the vehicle's rocket motors to gimbal to keep it on course. The gyro sees both the bending motions and the rigid-body motions, and under certain conditions, when the vehicle is disturbed, it will continue to oscillate. Such oscillations can be destructive and a continued and alert research effort is necessary to develop means to avoid them.

Throughout these intermediate regions of the flight trajectory, the sloshing of fuel, as shown in the next movie, may become a problem unless proper precautions are taken during design. As the vehicle moves in response to the motions

of the control systems, the massive quantities of free-surface propellants also move and generate forces on the vehicle. These forces are minimized by damping the fluid motions with various types of baffles. For example, baffles shaped like this are being used in the Saturn V tanks. The forces are also minimized by designing the control system to minimize its reaction to the sloshing forces. As you probably noticed, both swinging and swirling motions are possible.

Thus, in this intermediate range of flight, in particular, we must concern ourselves with the overall motions of the vehicle, propellants, and controls as a system. Of particular importance is a detailed understanding of the natural frequencies, mode shapes, and damping of the structure since these are fundamental. We have demonstrated that an economic and efficient way to obtain this information is to construct and test dynamic models. Such models have been and continue to be widely used in the development of all types of aircraft. That model of a rigid rotor helicopter and that model of the F-105 are typical examples. Other examples include dynamic studies of the propeller whirl of the Modified Electra and flutter studies of the C-141 jet cargo transport and the TFX. The same basic principles and techniques are applicable to dynamic models of space vehicles. They provide a substantial lead time and readily facilitate investigation of the effects of modifications in payload, propellant conditions, and structure. The 1/5-scale model of the Saturn I which you see on the balcony contributed to the success of the Saturn flights. We are currently working with the Air Force and the Martin Company on a study of the dynamics of Titan III - the vehicle which you see mounted on the backstop to your left. We expect that the tests of this 1/5-scale model will provide a sounder basis for future analytical studies and eliminate the need for costly full-scale tests. This is a 1/40-scale model of the Apollo launch vehicle - the Saturn V. In about a month, we will begin an investigation of a larger 1/10-scale model of this vehicle on the far side of the backstop. The results of our studies of these two dynamic models will provide needed information for future Saturn V payloads, as well as for Apollo.

As the velocity of the vehicle increases to about the speed of sound, it may encounter large oscillatory pressure forces, which we call buffet forces and which are caused by flow separation or wake impingement. The next movie shows schlieren photographs of a Mercury-Atlas vehicle model being subjected to a buffeting flow in a wind tunnel. The flow direction is from right to left and the speed is gradually increasing from just below to just above the speed of sound. Randomly fluctuating flows such as shown here can produce high-frequency local vibrations of the vehicle structure.

In addition to local vibrations, buffeting flows can also produce low-frequency response of the entire vehicle. Such response is illustrated by these shots of an aeroelastic Apollo-Saturn model. The primary vibration shown in these scenes corresponds to a full-scale bending frequency of about 2 cycles per second.

These buffeting pressures also produce undesirable vibrations of structural panels and payloads. The best way to minimize these problems is to reduce the fluctuating pressures associated with buffeting and aerodynamic noise. Other possibilities, also under study, include the use of damping materials and isolation techniques - techniques quite similar to those used in designing a good

ride in your automobile, although the application of the technique is much more difficult.

On numerous flights of liquid-propellant launch vehicles a severe longitudinal instability has occurred which is widely referred to as Pogo oscillations. This instability essentially involves an interaction of all components of the system, and results in large low-frequency oscillations throughout the vehicle which are particularly troublesome for delicate payloads - including astronauts. For some time this problem was very critical on Titan II, the Gemini vehicle. It has since been solved by modifications to the propellant system.

Considerable research is now in progress to obtain a better understanding and solution to this problem. For example, a full-scale Thor-Agena vehicle, which has also exhibited the problem, is now being readied for tests this summer on the far side of the backstop, and one of the primary objectives is a study of the coupling of the structure and propellant systems in the Pogo mode.

A recent problem of considerable concern is fuel-dome impact. In the event that the thrust is terminated while the vehicle is accelerating through the atmosphere, the aerodynamic drag forces act in such a fashion as to reverse the direction of the acceleration and cause the remaining propellants to move forward relative to their container and impact on the dome. The forces imposed on the dome, when superimposed on existing forces, may cause the domes in the tanks to burst, posing substantial dangers.

Our research in this area is illustrated by these movie clips which show you the basic fuel motions. Two cases are shown. The first involves the fuel starting from an undisturbed condition. In this case you will note that the fuel moves essentially straight up and impacts on the dome. The second starts with the fuel sloshing from side to side and you will note that the fuel moves up one side across the dome and down the other side. Both situations are possible. We are measuring the forces and pressures on the tank dome for such models and scaling the results in order to predict full-scale loads.

The next problem area is one of separation of the spent first stage from the remaining stages. The basic problem here is the shock loads imposed by separation devices which invariably involve the use of explosives such as shaped charges, primer cords, or explosive bolts. Highly transient loads are imparted to the upper stages and payload and research objectives include reduction of the separation forces and proper design of the upper stages and payload attachments to withstand these forces.

During this brief review of the launch phase, we have tried to describe some aspects of vehicle dynamics and some of the research facilities and techniques being employed to obtain solutions to the many problems which may arise.

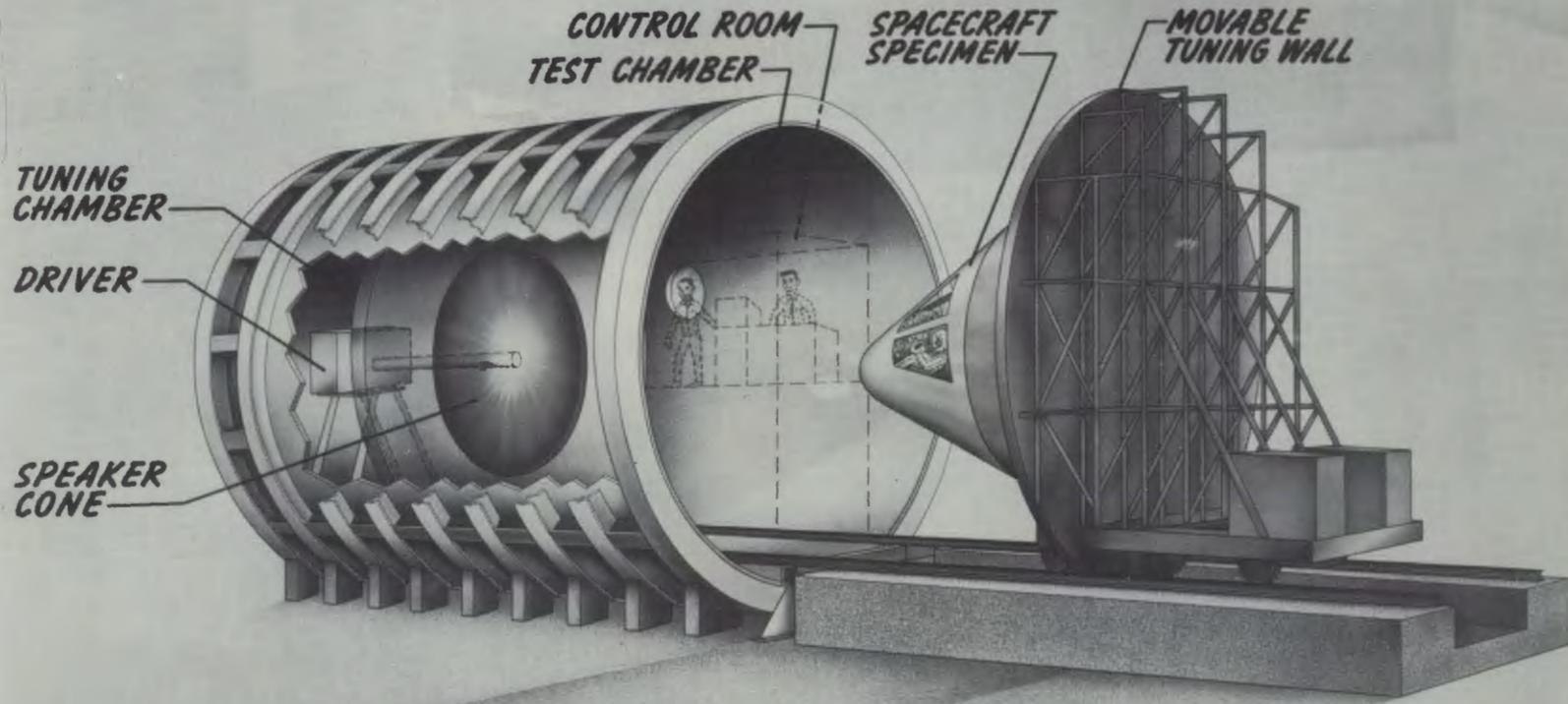
As the payload moves through the launch phase and continues on into orbit, in space, or to the moon or planets, it is subjected to the space environment including radiation, micrometeoroids, and vacuum. The most general environment for all space missions is vacuum, and the effect of this environment on spacecraft is simulated by testing in vacuum chambers. One such chamber is described

in the next slide. We are going to take you through the chamber but first I'd like to describe it briefly. It is 55 feet in diameter and 68 feet tall. It has a large launch acceleration table mounted below the removable floor where payloads can be subjected to combined environmental conditions of acceleration, vibration, and vacuum. It contains an air lock, viewing ports, and a 20-foot-square access door.

The next slide shows the environmental capabilities of the chamber. Altitudes up to 70 miles can be simulated and very large payloads can be installed and tested under variable environments. The air lock and the emergency pressurization system provide the capability for man-rating the chamber. The next slide shows some of the potential uses of the chamber. Among these are the inflation and erection of space structures such as the Echo balloons and space stations, research on highly accelerated vehicles such as anti-missile missiles, and problems associated with highly expanded nozzle flows.

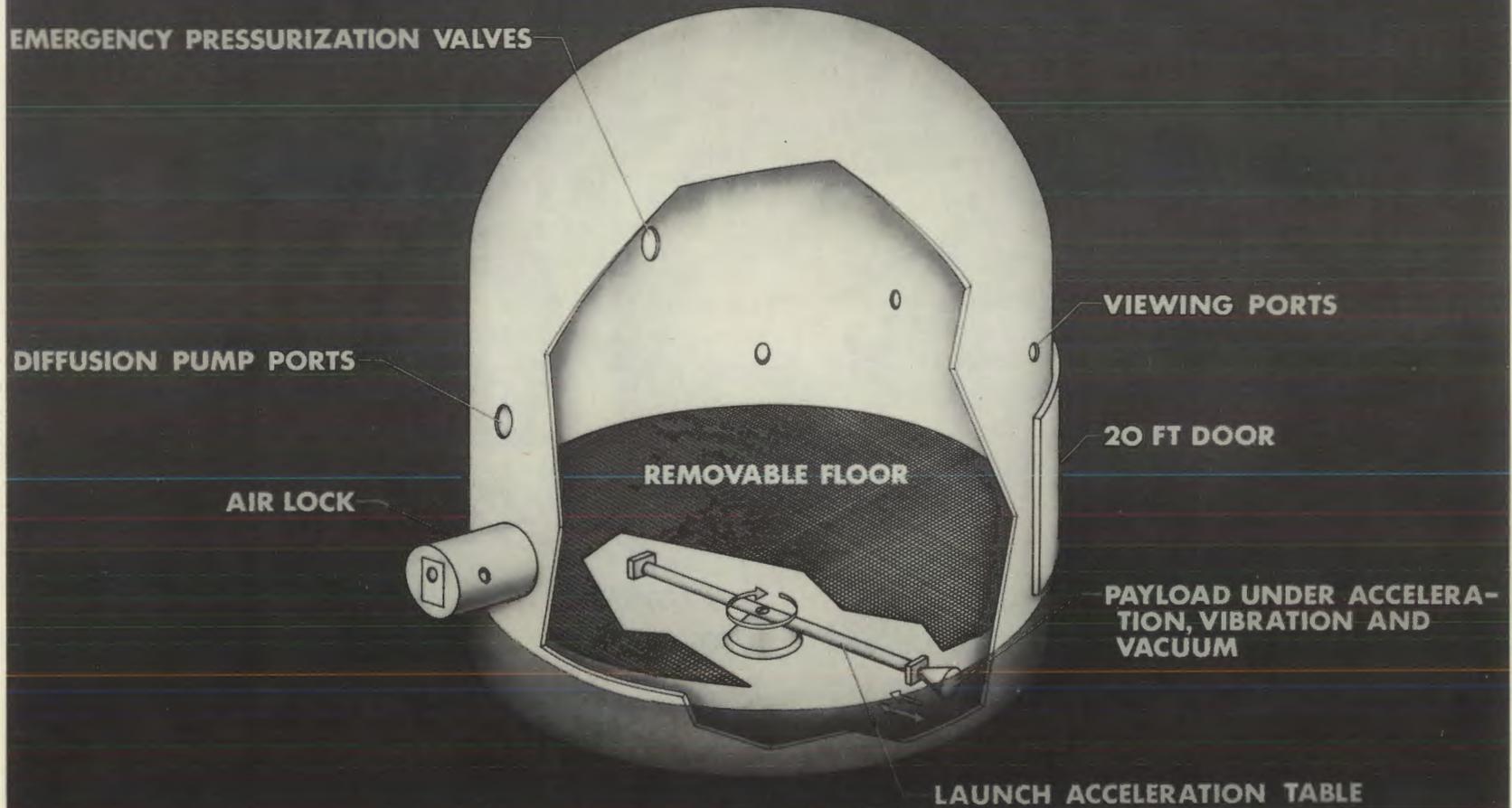
The subject of highly expanded flows is of particular interest in connection with rockets for use in lunar landing and outer space. You will see some of the apparatus used to study erosion of craters by rocket jet impinging on dust-like surfaces, and some of the nozzles used in a study of instability of rocket nozzles when you enter the chamber.

LANGLEY LOW FREQUENCY NOISE FACILITY



55-FOOT VACUUM CYLINDER

GENERAL DESCRIPTION



55-FOOT VACUUM CYLINDER

ENVIRONMENTAL CAPABILITIES

EMERGENCY PRESSURIZATION:
1/3 ATMOSPHERE IN 10 SEC
1 ATMOSPHERE IN 30 SEC

PRESSURE ALTITUDE:
50 MI - MECHANICAL PUMPS
70 MI - DIFFUSION PUMPS

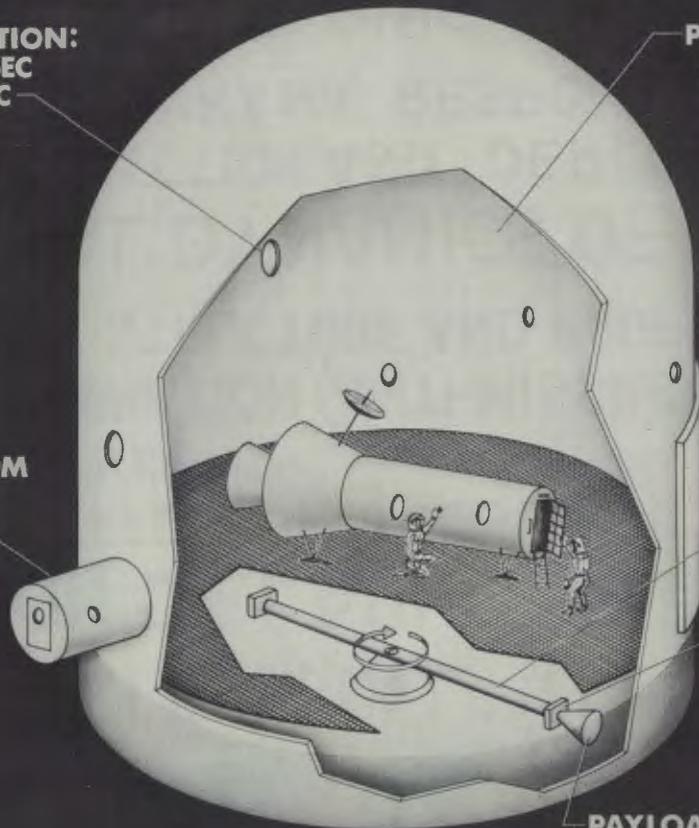
**PRESSURE VARIABLE FROM
ATMOSPHERIC TO
CHAMBER PRESSURE**

PAYLOAD ACCESS:
20 FT SQUARE

ACCELERATION:
100 EARTH GRAVITY UNITS
50,000 LB FORCE

VIBRATION:
3,000 LB FORCE
600 CYCLES/SEC

PAYLOAD VOLUME:
500 CU FT

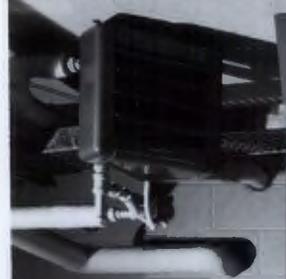


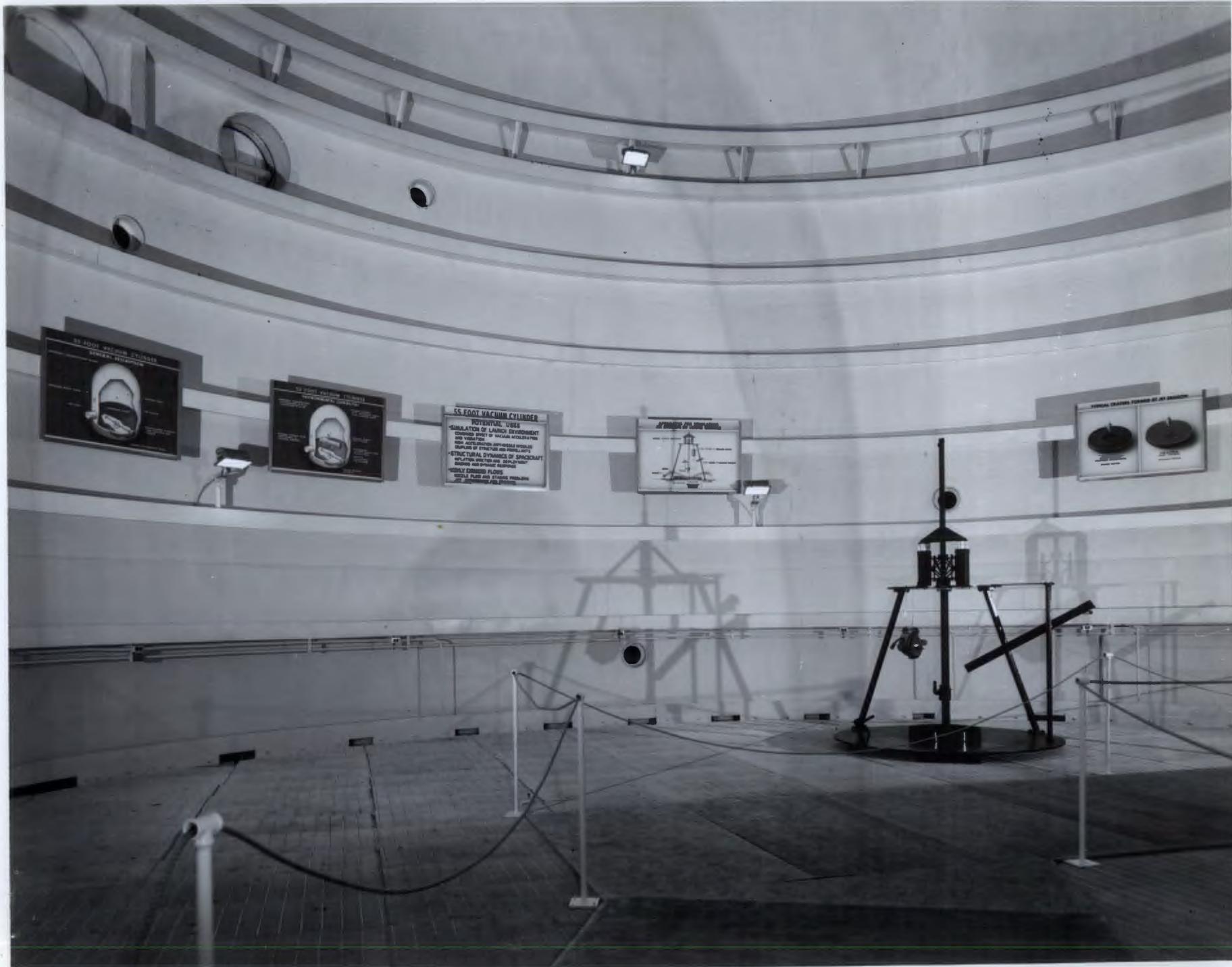
55 FOOT VACUUM CYLINDER

POTENTIAL USES

- **SIMULATION OF LAUNCH ENVIRONMENT**
COMBINED EFFECT OF VACUUM, ACCELERATION
AND VIBRATION
HIGH ACCELERATION (ANTI-MISSILE MISSILES)
COUPLING OF STRUCTURE AND PROPELLANTS
- **STRUCTURAL DYNAMICS OF SPACECRAFT**
INFLATION, ERECTION AND DEPLOYMENT
DAMPING AND DYNAMIC RESPONSE
- **HIGHLY EXPANDED FLOWS**
NOZZLE FLOW AND STAGING PROBLEMS
JET IMPINGEMENT AND EROSION

LAUNCH VEHICLE AND SPACECRAFT DYNAMICS





55 FOOT VACUUM CYLINDER
GENERAL INFORMATION

55 FOOT VACUUM CYLINDER
GENERAL INFORMATION

55 FOOT VACUUM CYLINDER
POTENTIAL USES
- SIMULATION OF LAUNCH ENVIRONMENT
- CONTROL OF VIBRATION ACCELERATION
- HIGH ACCURACY POSITIONING
- STUDY OF STRUCTURAL AND MATERIALS
- STRUCTURAL DYNAMICS OF SPACECRAFT
- RESEARCH AND DEVELOPMENT
- MODEL EXPOSED FLOWS
- WIND TUNNEL AND OTHER RESEARCH
- TEST FACILITY FOR SPACECRAFT

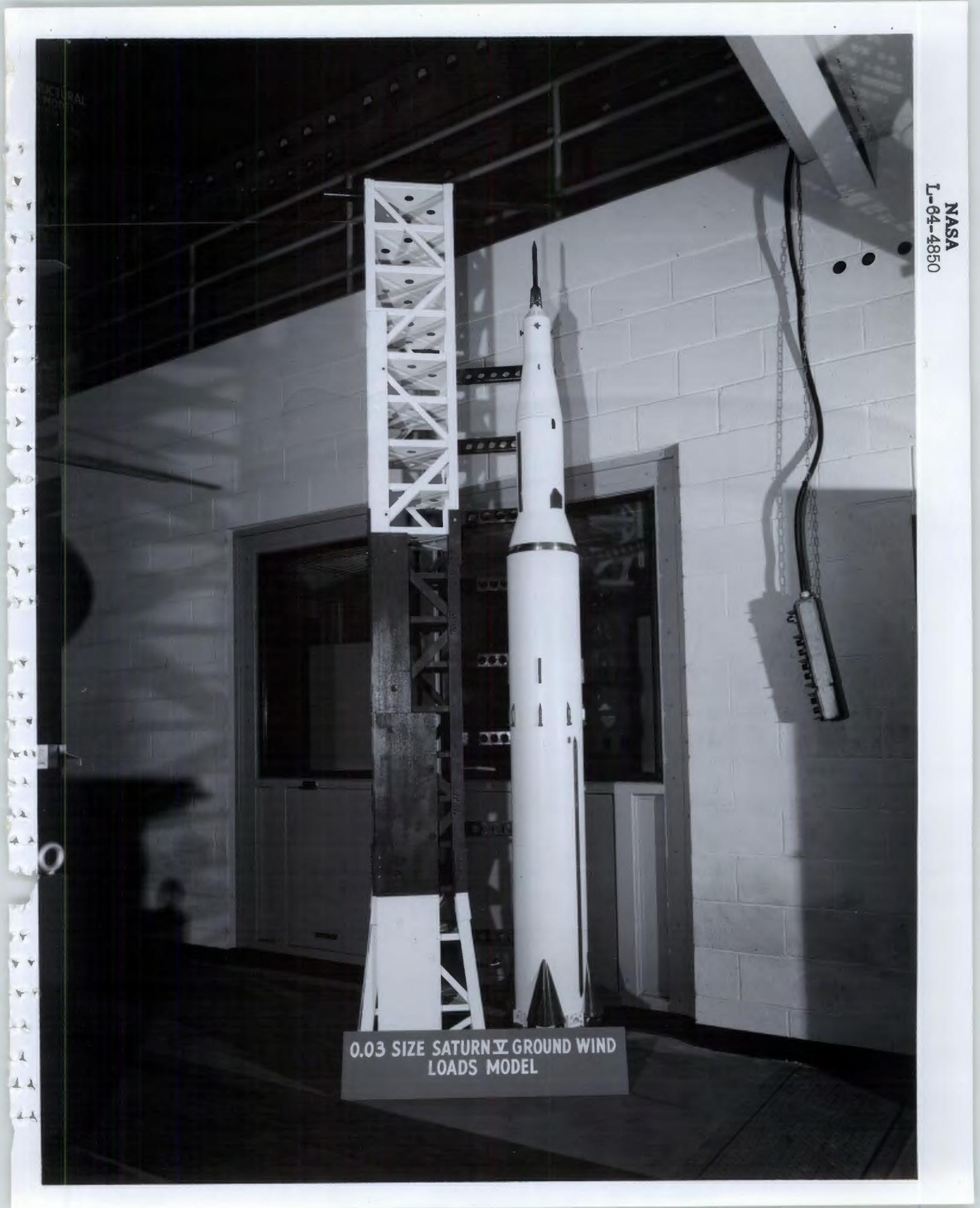
FLIGHT DYNAMICS

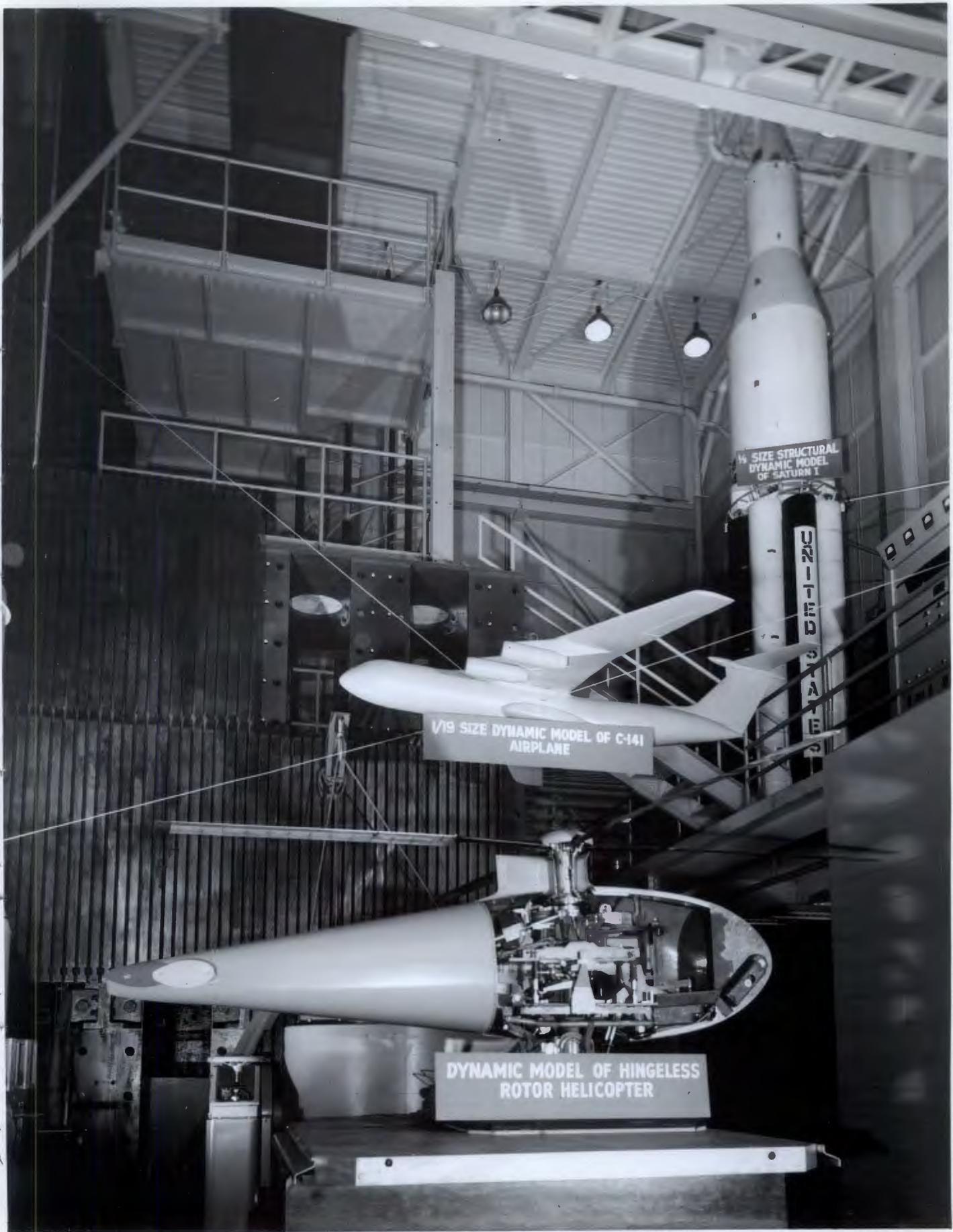
FORMAL CHAIRS FORMED BY AIR STREAMS

STRUCTURAL
MODEL

NASA
I-64-4850

0.03 SIZE SATURN V GROUND WIND
LOADS MODEL





1/19 SIZE DYNAMIC MODEL OF C-141 AIRPLANE

DYNAMIC MODEL OF HINGELESS ROTOR HELICOPTER

1/4 SIZE STRUCTURAL DYNAMIC MODEL OF SATURN I

UNITED STATES

LAUNCH VEHICLE AND SPACECRAFT DYNAMICS



A central display area featuring a large whiteboard. To the left of the whiteboard are three small rectangular panels stacked vertically. Several markers are scattered around the whiteboard and panels, some pointing towards the whiteboard.



1/40 SIZE STRUCTURAL DYNAMICS
MODEL OF SATURN V