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Thermal–Structural Test Facilities at NASA Dryden

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THERMAL–STRUCTURAL TEST FACILITIES AT NASA DRYDEN

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Abstract

The National Aero-Space Plane (NASP) has renewed interest in hypersonic flight and hot-structures technology development for both the airframe and engine. The NASA Dryden Thermostructures Research Facility is a unique national facility that has been designed to conduct thermal-mechanical tests on aircraft and aircraft components by simulating the flight thermal environment in the laboratory. The layout of the facility is presented, which includes descriptions of the high-bay test area, the instrumentation laboratories, the mechanical loading systems, and the state-of-the-art closed-loop thermal control system. The hot-structures test capability of the facility is emphasized by the Mach-3 thermal simulation conducted on the YF-12 airplane. The Liquid-Hydrogen Structural Test Facility, which is presently in the design phase, will provide the capability of thermally testing structures containing hydrogen.

Introduction

A renewed interest in hypersonic flight, as evidenced by the National Aero-Space Plane (NASP), has refocused attention on the two government-owned national hot-structures test facilities. One facility is the Hot Structures Laboratory (Building 65) located at the Wright Laboratories, Wright-Patterson Air Force Base, Ohio.[1] The other is the Thermostructures Research Facility (TRF) located at NASA Dryden Flight Research Facility, Edwards, California. This paper describes the test capabilities of the TRF with focus on the hot-structures test capability.

The principal mission of NASA Dryden is to conduct flight research on high-performance aircraft. Historically, the X-15 flight research aircraft program was one of the most significant, and it was also the driver in developing and implementing a hot-structures test capability at NASA Dryden. Thermal stress-related operational problems on the X-15, such as the inadvertent deployment of the main landing gear and nose landing gear during high-speed flight and a concern over the possible overloading of the cockpit canopy hooks at high speeds, required extensive laboratory thermostructural testing both to qualify design modifications and to certify the aircraft for flight at higher Mach numbers.

An important element in thermostructural testing is the thermal control system. A description of the closed-loop digital data acquisition and adaptive control system, along with a discussion of the state of the art in hot-structures measurement systems, vital to conducting successful thermal–mechanical tests, is presented. An overview of the YF-12A flight loads program featuring the laboratory thermal simulation of a Mach-3 flight profile illustrates the role that the TRF plays in support of flight testing hypersonic aircraft.

The paper will conclude with a description of the Liquid Hydrogen Structural Test Facility (LHSTF), which is currently in the design phase and is targeted to become operational in 1995. This facility will expand the hot-structures test capability of the TRF to thermal testing structures containing liquid hydrogen.

The Building

The TRF was constructed at Dryden in 1966 to provide the capability for combined loading and heating tests of structures ranging in size from components to complete flight vehicles, and for calibration and evaluation of flight loads instrumentation under the conditions expected in flight. Figure 1 is a photograph of the front view of the TRF showing the main entrance to the high-bay test area and the adjacent office areas and instrumentation laboratories.

Figure 2 is a diagram of the layout of the facility. The TRF consists of a large, high-bay test area with adjacent laboratories, offices, and storage area. The 120-ft-by-150-ft reinforced concrete floor contains tie-down slots to anchor test setups and is accessed from the entry ramp by a 136-ft-by-40-ft door. A 5-ton rail crane services the entire test area floor. Systems for mechanical, thermal, and vibration testing of structures, as well as for data acquisition and test control, are incorporated in the facility. The data acquisition and test control room is located on the second floor overlooking the main test area. Instrumentation and electronic support laboratories are also provided. Flame–plasma spray equipment is located in the storage area; and the universal load frame machines are housed in an area separate from the high-bay test area.

Mechanical Loading Systems

The TRF has three closed-loop electrohydraulic universal testing machines, each with a digital engineering unit display and an X-Y recorder. The maximum load capacities of the three machines are 10,000, 100,000, and 220,000 lb. The machines are used for static loadings of coupons and structural components at ambient and elevated temperatures. Figure 3 is a photograph of the 220,000-lb machine applying a compression load to a 2-ft-by-2-ft titanium metal matrix composite buckling-critical panel.

For mechanical loads tests on large structural components and for applying loads to aircraft, the TRF has a 40-channel electrohydraulic closed-loop system. Figure 4 shows a schematic diagram of the closed-loop system. An inventory of hydraulic actuators, with capacities up to 60,000-lb tension and 80,000-lb compression, and load cells with up to 50,000-lb capacity, is available.

Heating Systems

Several ovens with programmable control are available in the TRF for heating coupons and panels up to 2 ft by 2 ft in size. One oven has a temperature range of −100 to 600 °F with liquid nitrogen as the cooling medium. Two microprocessor-controlled ovens, with interior dimensions of approximately 2 ft by 2 ft by 2 ft, are also available for conducting apparent strain tests to temperatures up to 2000 °F. One of these two ovens has been modified so that its atmosphere can be purged using nitrogen or helium gas. A third temperature rate-controlled oven is used to test coupons over a temperature range of −320 to 600 °F. Six ovens are the noncyclic type and are manually set to maintain temperature. Maximum temperatures available with these ovens range from 650 to 1300 °F.

Custom-contoured radiant heaters using quartz lamps are used to heat the larger structural components. Figure 5 is a photograph of the YF-12 forebody custom-contoured heater system. Quartz lamp heaters can achieve heat fluxes up to 100 Btu/ft^2-sec, temperature rates up to 150 °F/sec, and maximum temperatures of 3000 °F. The TRF data acquisition and control system (DACS) and the control of these custom heater systems will be discussed in the next section.

Data Acquisition and Control System

The TRF DACS is a state-of-the-art system that has an addressable, gain programmable, self-calibrating, 1280-channel data acquisition capability.[2] The system has built-in redundancy and can handle three simultaneous test activities while recording and displaying real-time data. Data may be replayed after the test and displayed in a variety of graphic and alphanumeric formats. All test setup data entry and system checkout functions are designed to be user-friendly.

The DACS primary function is to provide the means to conduct real-time simulations of thermal and mechanical loads on full-scale aircraft and aircraft components. The real-time system resources may be dedicated to a single test or may be shared among as many as three independent test activities conducted simultaneously. The system provides the capability to acquire data from analog transducers such as accelerometers, flowmeters, heat flux meters, load cells, potentiometers, pressure gages, resistance temperature devices, strain gages, and thermocouples.

Figure 6 shows a schematic diagram of the DACS, including an illustration of the closed-loop thermal control technique for heating a test specimen. The DACS has a distributed processing architecture that uses five classes of computers:

1. The host or central computing facility, located in the control room, for database management and test operation and monitoring.

2. Small mobile or "satellite" computers, located either near the test specimen in the high-bay test area or at a remote site, for small independent test operation and for input-output control in a larger test.

3. An analysis computer, located in the control room, for test scenario definition, real-time data analysis and display, and extended data reduction and analysis functions.

4. A power control computer to perform thermal output functions and to distribute the thermal power loads.

5. A function generator computer to provide mechanical output functions (fig. 4).

The DACS has two basic operating modes — independent test and combined test. In the independent test mode, a test is run on one of three satellite computers that are physically connected to the host computer. The test may be controlled and monitored either from the high-bay test area using the satellite computer or from the control room using the host computer. In this independent test mode, channel capacities include 512 data, 100 thermal control, and 12 mechanical control channels.

In the combined test mode, the host computer and one to three satellite computers are used. The test may be monitored and controlled only by the host computer in the control room. In this mode, the channel capacities are a function of the number of satellite computers used and are shown in the table below.

Channel capacities for combined test mode.

No. of satellites	Data channels	Thermal control channels	Mechanical control channels
1	512	256	22
2	1024	512	40
3	1280	512	40

During a given test, all data channels are sampled at the same rate. The sampling rate must be an integer multiple of 4 samples/sec/channel, e.g., 4, 8, 12, 16, 20, 24. Thus a satellite in the independent test mode, with the capacity to acquire 5120 samples/sec, is able to acquire 20 samples/sec from 256 channels or 16 samples/sec from 320 channels. The maximum single-channel sampling rate that the DACS will support is 1280 samples/sec.

Temperature profiles for up to 512 thermal outputs are entered into the satellite computer systems during test scenario definition, before test initiation. Adaptive control algorithms are used to determine the output levels required to conform to the supplied profiles within allowable error limits. A power distribution algorithm is used to minimize power peaks. During thermal control, the silicon-controlled rectifier (SCR) power controller sends verification signals to the thermal loads control subsystem (power control computer, satellite computer, and host computer) after the SCR has received each thermal power output command. These verification indicators are available every 0.25 sec. They signify either a successful or unsuccessful power output for that channel during the alternating current cycle. A successful output means that either a requested firing occurred or no firing occurred because none was requested.

The test operator interactively controls the application of the thermal loads defined in the profiles. The capability to start, hold, and stop thermal loading is provided. For static temperature control (in which a thermal control subsystem is in a hold status), the measured temperatures are within ±0.5 percent or ±5 °F, whichever is greater, of the desired temperature over the range from −300 to 2500 °F. For dynamic temperature control, the measured temperature error is dependent on the temperature change rate, as shown in figure 7.

The DACS includes seven interactive workstations with high-resolution, color-graphic displays. Thermal control deviation displays and a choice of custom data displays are available to the user in windows. Three color printers for hard copies of information displayed in windows on the display workstations are provided.

Instrumentation Laboratory

An important aspect of all research programs is obtaining high-quality experimental data. The TRF instrumentation laboratory is vital to obtaining high-quality structural test data.

The instrumentation laboratory has two principal functions. The first is an applications function that provides for the installation of a variety of instrumentation on aircraft and structural test articles for laboratory and flight testing. This includes state-of-the-art bonded foil gages, weldable gages, and capacitive gages applied to materials such as aluminum, titanium, organic composites, and several of the nickel-based super alloys.

The second function is conducting R&D with focus on the development of strain measurement techniques at extreme temperatures (cryogenic to 2000 °F) on advanced state-of-the-art materials including metal matrix composites and carbon-carbon composites. The R&D instrumentation laboratory is equipped with a high-temperature strain-gage evaluation system (figure 8) with both resistance heating and a Marshall furnace to characterize strain gages on various materials at temperatures up to 2000 °F. Characterizing strain gages involves tests for apparent strain, gage factor definition and stability, drift, lead wire attachment and lead wire resistance, strain transfer, etc. Plasma–flame spray equipment is used to attach the high-temperature strain sensors. Signal conditioning and data recording systems, custom tailored for the instrumentation laboratory, are used for test control and data recording and analysis.

YF-12 Flight Research Program Highlights

The largest, if not most complex, heating test conducted in the TRF was the Mach-3 thermal simulation test of the YF-12 airplane. The comprehensive YF-12 flight loads research program, conducted during the late 1960's and early 1970's, was the first attempt at applying a thermal loads calibration technique to a flight vehicle.[3] Specific program objectives included extending strain-gage load measurement to high-performance aircraft, developing and demonstrating laboratory thermal simulation techniques, and evaluating state-of-the-art structural analysis computer programs. There were five distinct phases to the program: instrumentation, static loads tests, flight test, laboratory heating tests, and flight data and analysis correlation.

An objective of the instrumentation phase was to design and develop a measurement system to provide temperature and loads measurement in both the flight environment and laboratory ground tests. Figures 9(a) and (b) illustrate the YF-12 instrumentation system. Figure 9(a) shows some of the 101 strain gage bridges that were installed at three span locations in the left-hand wing. Additional loads measurement locations included three fuselage stations and all control surface actuators for measuring hinge moment. A satisfactory method for bonding thermocouples to titanium with a conductive adhesive was developed in the TRF instrumentation laboratory. For flight measurements, 561 thermocouples and 499 additional thermocouples for laboratory heating tests were installed. Figure 9(b) shows the skin thermocouple locations for flight on the upper surface of the left-hand wing.

Fifty-seven mechanically applied load conditions were used to calibrate the strain gages installed on the airplane. Figure 10 is a photograph of the airplane in the TRF being subjected to one of the loading conditions. The airplane was supported on its landing gear throughout the calibration. As calibration loads were applied, the static load in the main gear was held nearly constant by seven reactive loads applied through contoured pads resting on the centerline of the upper fuselage at various bulkhead locations. Equations for the measurement of shear, bending moment, and torque were derived for each wing station by using single-point loads.

Having instrumented the airplane and calibrated the strain-gage instrumentation for loads measurement, the flight test phase of the program was undertaken. Symmetrical pitch maneuvers were performed at each flight condition at eight different Mach numbers. At each Mach number, a maximum and minimum dynamic pressure was flown and a maximum and minimum weight. Temperatures were measured at 449 skin and 112 substructure locations. Figure 11 shows the surface temperatures and isotherms at a high Mach number cruise condition. From the figure it can be seen that a complex ground heating system is needed to simulate not only the heating rate but also the temperature distribution over the surface of the airplane. Flight data showed that the skin temperatures were at radiation equilibrium temperature during cruise and that the wing spars adjacent to the engine nacelle were hotter than the skin. Since the spars were instrumented with strain gages, it was imperative that the engine heating effects be simulated during the ground heating tests.

After the flight test phase, the airplane was prepared for the laboratory heating tests. Figure 12 illustrates the heater panel configuration used to encapsulate and heat the 5000 ft^2 of surface area of the airplane. There were two fore-body heaters, four center-body heaters, and one large aft-body heater. In addition, a 42-in. diameter cylindrical heater heated an area of 230 ft^2 on the interior of the left-hand engine nacelle. Figure 13 is a photograph of the aft section of the YF-12 with the aft heater removed and the "draw bridge" center-body heaters raised. The tip of the engine nacelle heater can be seen. The ventral fins were removed and were not part of the heating tests. More than 16,000 quartz lamps divided into 470 thermal control zones were used to simulate Mach-2.5, -2.75, and -3.0 flight profile heating tests. The lead wire for some of the 470 control thermocouples installed on the external skin of the airplane is visible. Figure 14 is a photograph of the YF-12 airplane enclosed in the quartz lamp heaters in preparation for a heating test.

Figure 15 is a rear-view photograph of the YF-12 airplane during a Mach-3 thermal simulation test. The bright glow at the left engine is caused by the engine nacelle heater. Only the left-engine heat was simulated because all of the strain-gage instrumentation was concentrated in the left wing, and none was installed in the right wing. The maximum power used during any of the tests was 3.5 MW. The YF-12 airplane was heated to high Mach number aerodynamic heating conditions more than 20 times with only minor problems. After the laboratory heating, the airplane was returned to flight status and made numerous research flights without any problems related to the heating tests.

The YF-12 Flight Loads Research Program made unprecedented contributions in the area of hot-structures technology. These include the first Mach-3 thermal simulation of a complete aircraft that incorporated major advances in digital heating control and real-time data displays, a demonstration and validation of a thermal loads calibration technique, an application of structures instrumentation in an elevated-temperature flight environment, an evaluation of state-of-the-art analytical codes, and an extensive documentation of the entire program in a NASA report. Finally, the YF-12 flight research program demonstrated the important role that the TRF plays in flight testing a high-performance airplane subjected to significant aerodynamic heating.

Liquid Hydrogen Structural Test Facility

Current hypersonic aircraft concepts, such as the NASP, will require the use of hydrogen as a fuel. This dictates the development of new structural concepts including reusable horizontal cryogenic fuel tanks and actively cooled panels using the high-pressure hydrogen fuel as the cooling medium. The integration of actively cooled panels into the airframe will present unprecedented challenges in removing heat from the structure, conditioning the hydrogen before burning it in the engine, and the onboard flight control system monitoring of the health and performance of the panels as a function of the flight environment.

Development of these new structural concepts requires new facilities with new test capabilities. NASA Dryden is building the LHSTF, that will initially focus on providing a test capability for reusable liquid-hydrogen fuel tanks. Figure 16 is a site perspective of the LHSTF showing the major elements of the test complex. The test control center and operations support building are located approximately 1200 ft from the test cell area. The test cell area includes the test cell, a data acquisition and power control building, a high-pressure nitrogen and helium gas storage area, the liquid-hydrogen storage area, and a 20-MW power substation.

Figure 17 is conceptual view of the LHSTF test cell with a 2000-gal liquid hydrogen tank. The test cell interior is 40 ft wide, 60 ft long, and 40 ft high. The test cell will have a nitrogen purged atmosphere to preclude a fire or explosion should the test article rupture during a test. Roof vents allow expanding hydrogen gas to escape should a tank fail in a catastrophic manner. The test cell will accommodate a 40,000-gal liquid hydrogen tank. The thermal and mechanical loading systems will be similar to those in the TRF. Initially, 20 MW power through 256 thermal control channels, 1000 data-recording channels, and 4 mechanical load control channels will be available. The LHSTF project is currently in the design phase. It is expected to be operational at the beginning of fiscal year 1996.

Concluding Remarks

The Thermostructures Research Facility is a unique national facility. It provides a test capability to develop the techniques needed to perform ground-based laboratory structural tests that simulate the flight environment. This environment includes flight profiles in which aerodynamic heating is significant. Important aspects of the Thermostructures Research Facility are its closed-loop control of heating and loading and its high-temperature instrumentation development laboratory.

The YF-12 flight loads program provided a means to demonstrate the thermal loads calibration technique for flight loads measurement and serves as an example of the role the Thermostructures Research Facility plays in flight testing aircraft subjected to aerodynamic heating.

The National Aero-Space Plane program has both generated a renewed interest in hypersonic flight and identified the need for new structural concepts that include actively cooled structures and reusable cryogenic fuel tanks. The Thermostructures Research Facility is playing a major role in developing conventional hot structural concepts for this class of vehicle. The Liquid Hydrogen Structural Test Facility will play a major role in developing reusable liquid hydrogen fuel tanks and hydrogen-cooled structures.

References

[1] Boggs, Bernard C., "The History of Static Test and Air Force Structures Testing," Technical Report AFFDL-TR-79-3071, June 1979. Available from Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433.

[2] Zamanzadeh, Behzad, Trover, William F., and Anderson, Karl F., "DACS II - A Distributed Thermal/Mechanical Loads Data Acquisition and Control System," International Telemetring Conference '87, Instrument Society of America, San Diego, California, July 15, 1987.

[3] *NASA YF-12 Flight Loads Program*, NASA TM X-3061, 1974.

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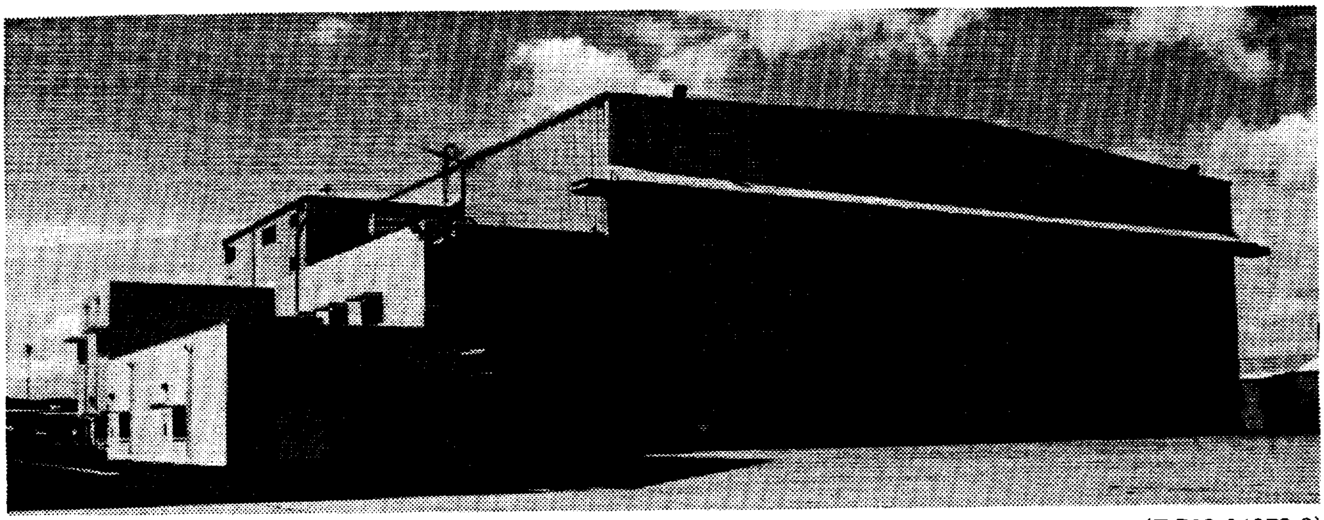


(EC92 04073-3)

Fig. 1. The front view of the Thermostructures Research Facility.

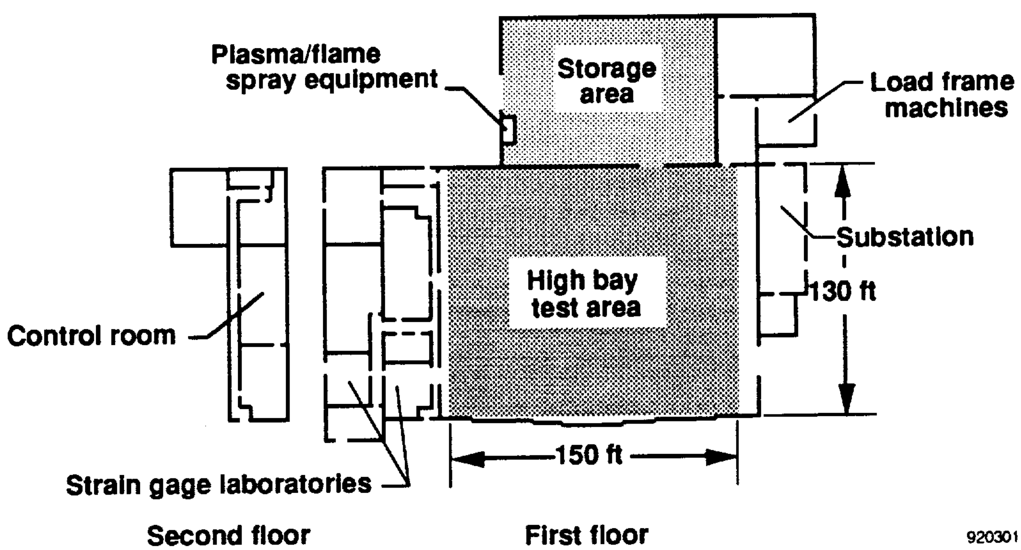
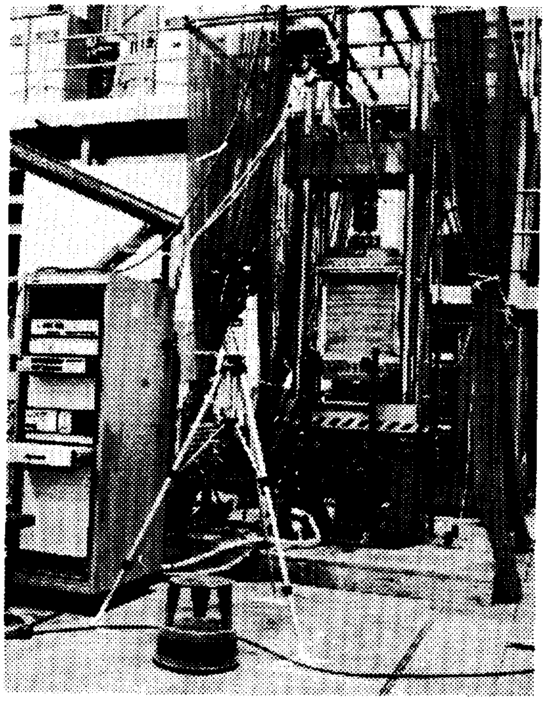


Fig. 2. The layout of the Thermostructures Research Facility.



(EC89 0099-001)
Fig. 3. The 220,000-lb load machine.

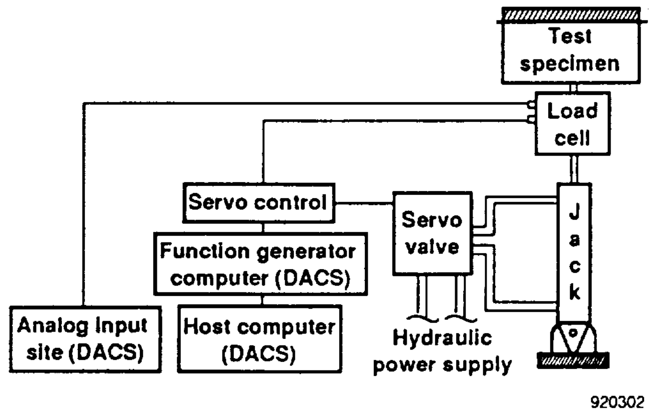


Fig. 4. The closed-loop mechanical load control system.

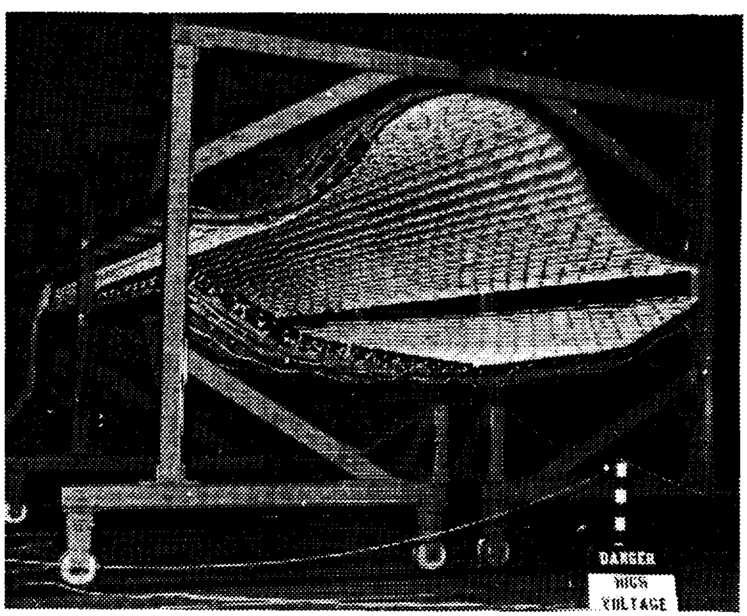


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Fig. 5. The YF-12 forebody custom-contoured heater system.

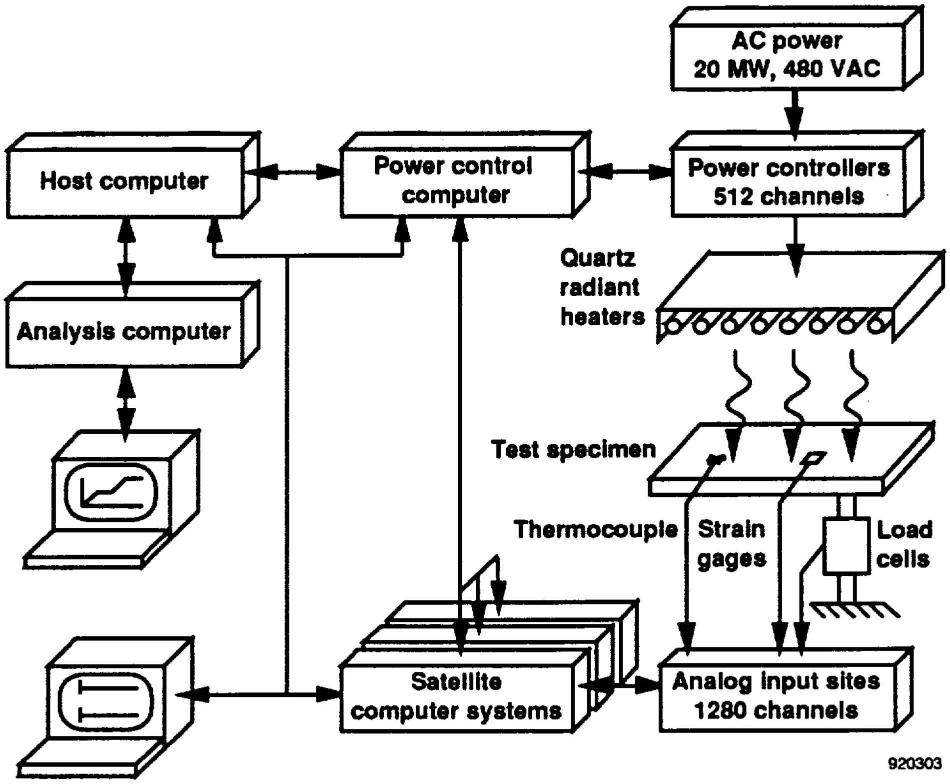

Fig. 6. The data acquisition and control system.

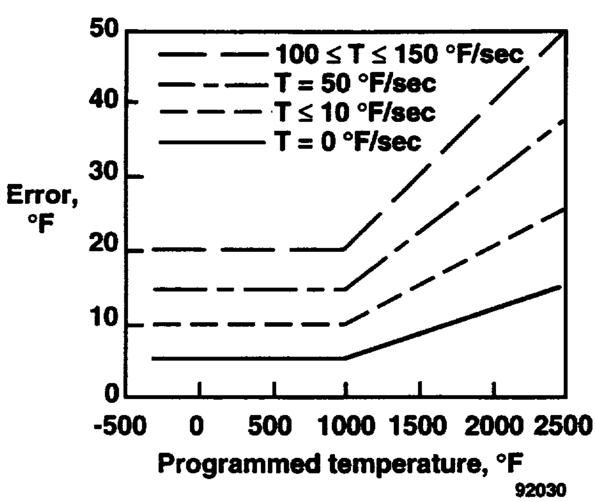

Fig. 7. Control performance of DACS.

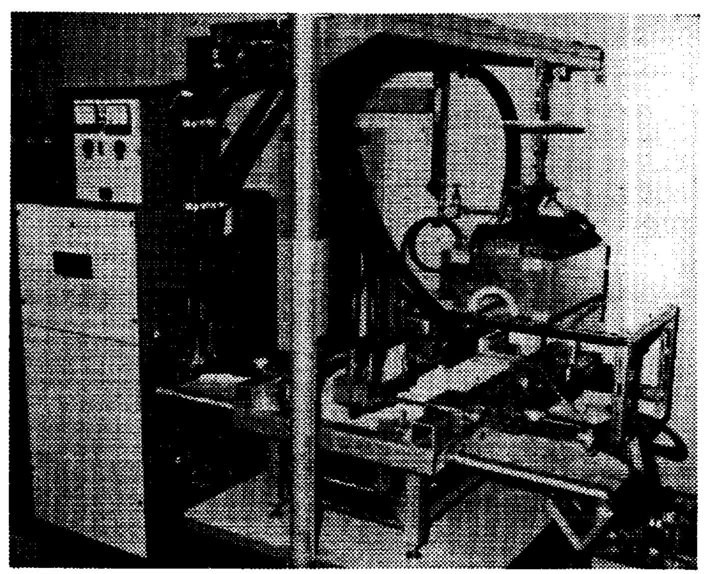

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Fig. 8. High-temperature strain gage evaluation system.

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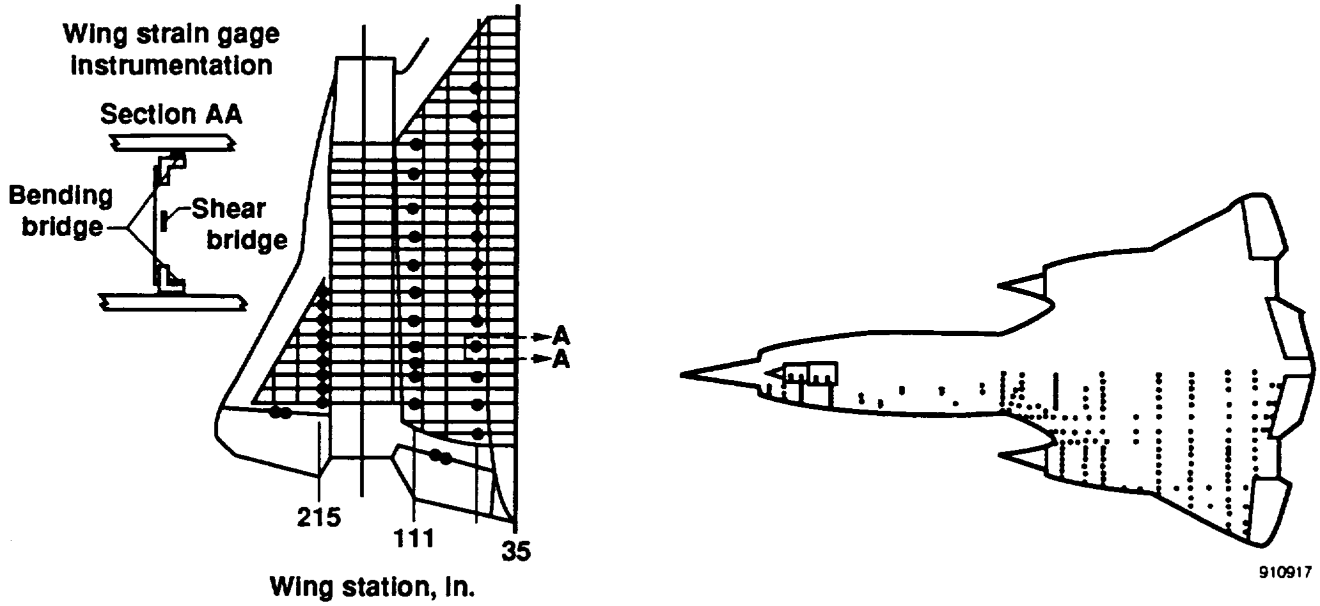
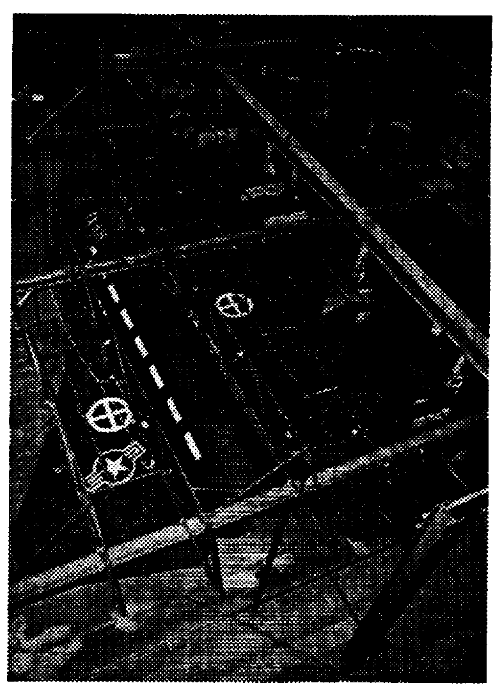


(a) Wing strain-gage bridges.

(b) Skin thermocouples.

Fig. 9. YF-12 instrumentation.



(EC 22237)

Fig. 10. Test setup for YF-12 strain-gage loads calibration.

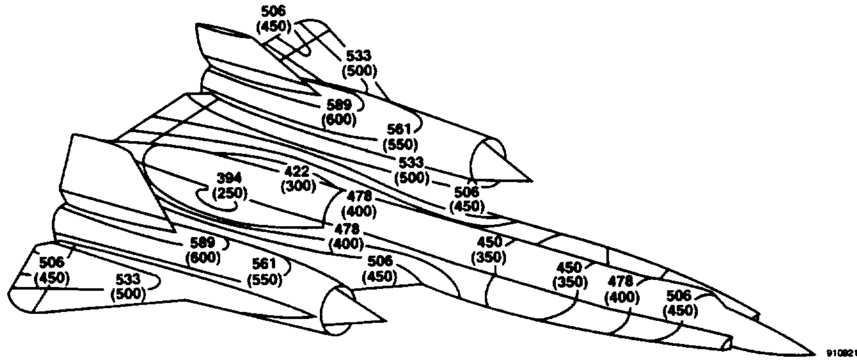


Fig. 11. Surface temperatures for the YF-12 at a high Mach number cruise condition. Temperatures are in degrees Kelvin (degrees Fahrenheit).

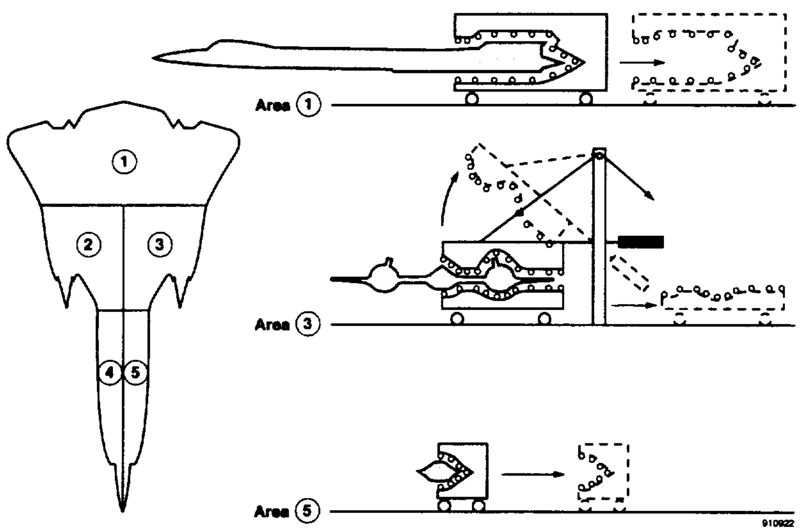
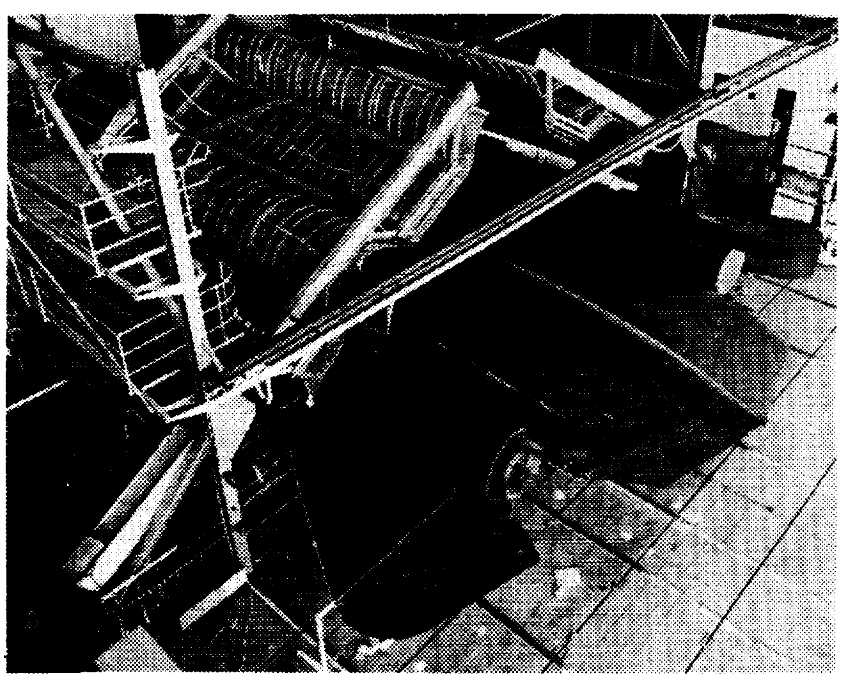
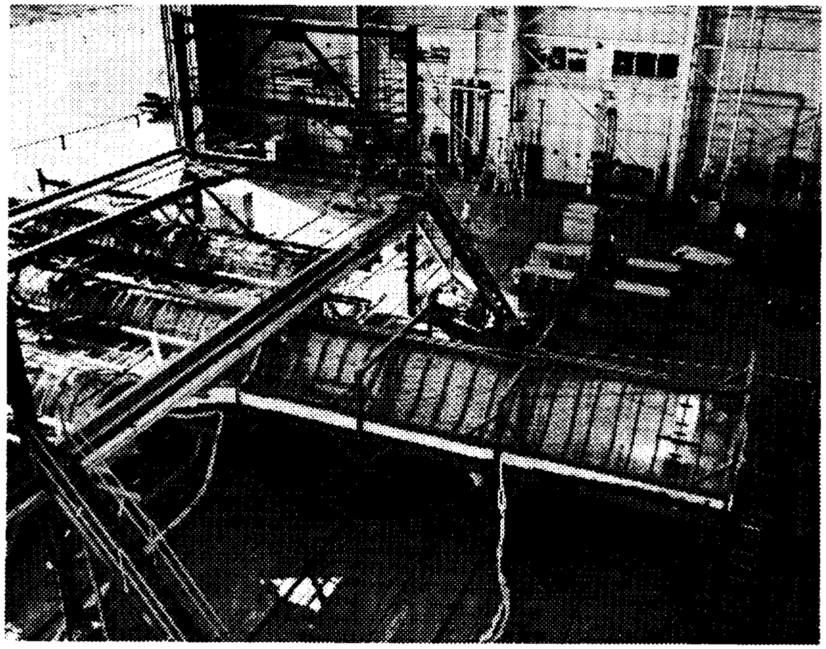


Fig. 12. Heater panel configuration for the YF-12.



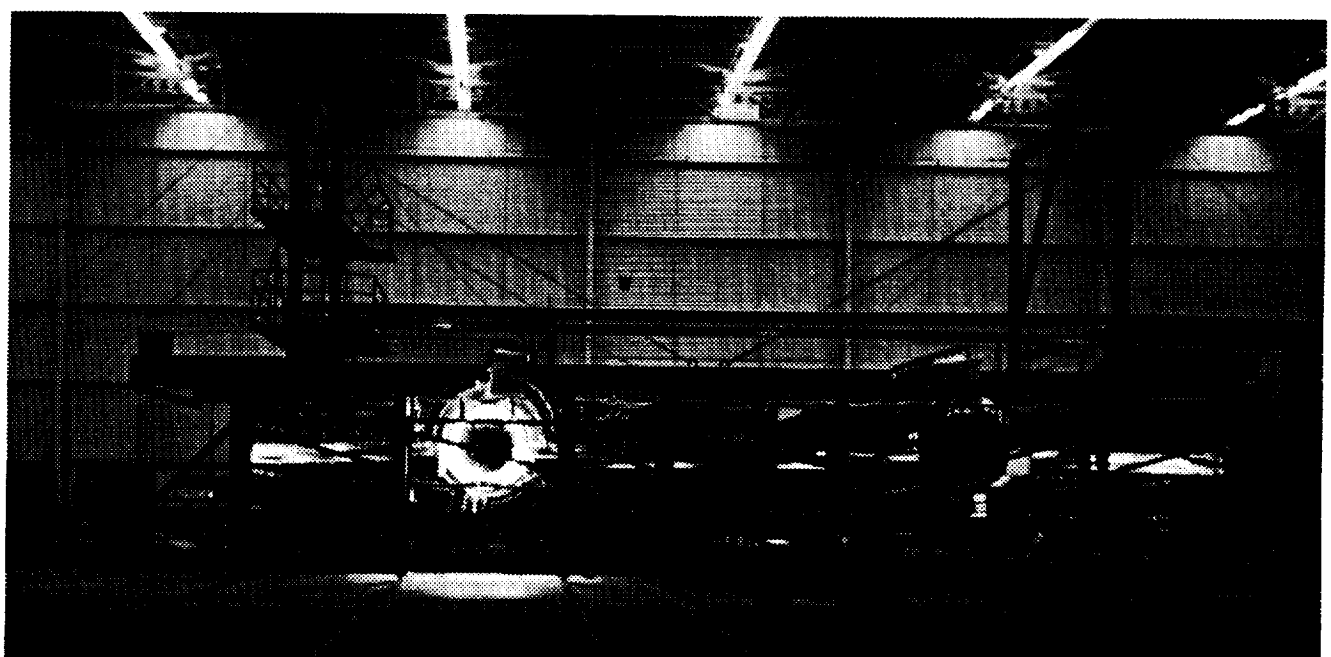
(E 25426)

Fig. 13. The aft section of the YF-12.



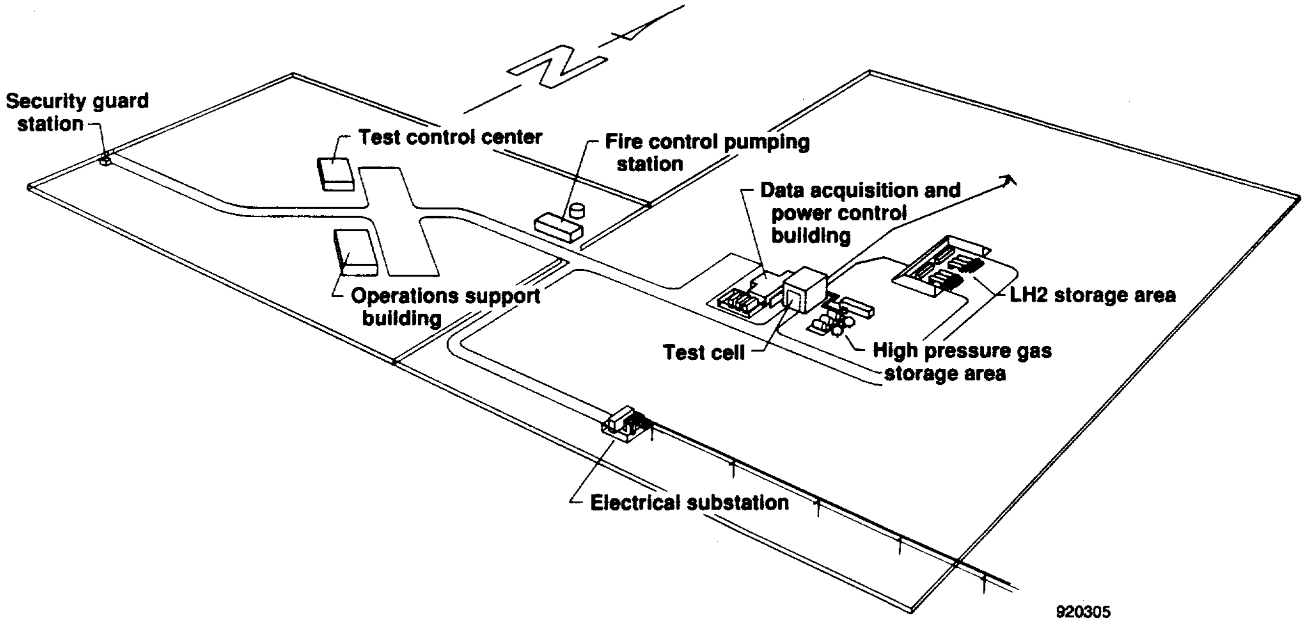
(E 25418)

Fig. 14. The YF-12 enclosed by heaters in preparation for heating test.

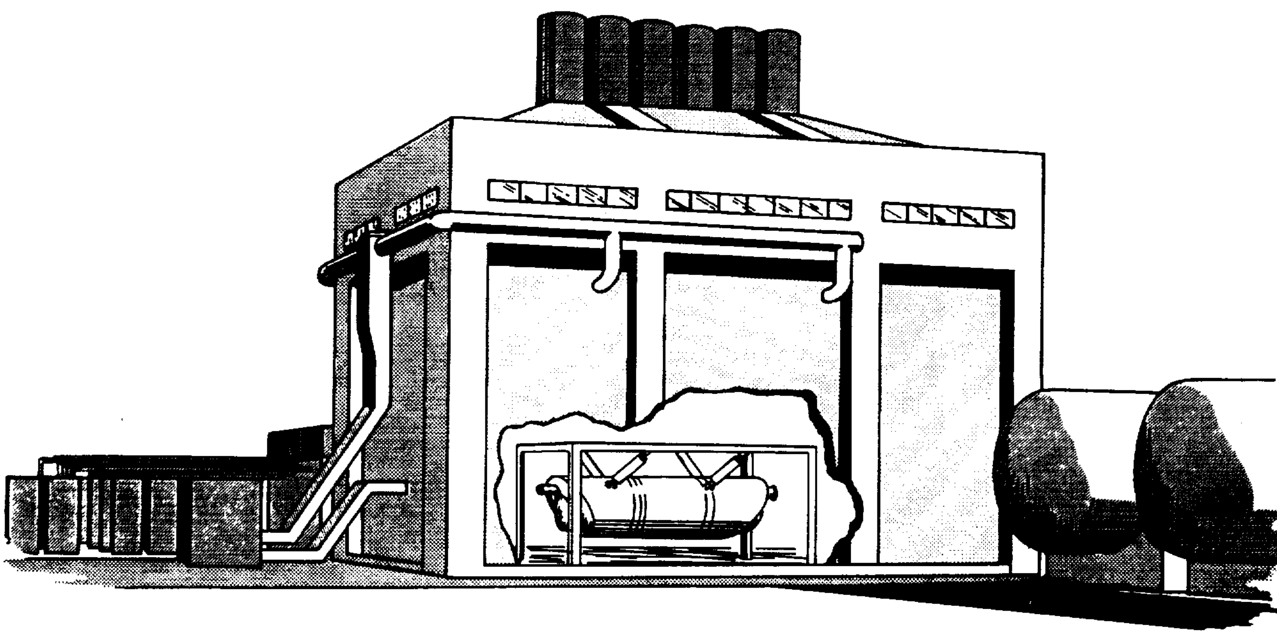


(ECN 3708)

Fig. 15. The YF-12 Mach-3 heating test.



(a) Site perspective.



(b) Test cell.

Fig. 16. The Liquid Hydrogen Structural Test Facility.

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