N72-29896

THIRD FREDERICK J. PLANTEMA MEMORIAL LECTURE

THE PHILOSOPHY WHICH UNDERLIES THE STRUCTURAL TESTS OF A SUPERSONIC TRANSPORT AIRCRAFT WITH PARTICULAR ATTENTION TO THE THERMAL CYCLE

By E. L. Ripley
Royal Aircraft Establishment
Farnborough, Hampshire, United Kingdom

CONTENTS

Page

THE PHILOSOPHY WHICH UNDERLIES THE STRUCTURAL TESTS OF A SUPERSONIC TRANSPORT AIRCRAFT WITH PARTICULAR ATTENTION TO THE THERMAL CYCLE

By E. L. Ripley
Royal Aircraft Establishment
Farnborough, Hampshire, United Kingdom

SUMMARY

The supersonic transport aircraft has brought a new challenge to the structural test engineer. Over the years he has developed skills in representing in the laboratory the conditions that occur in flight and in devising techniques to apply these to the structure. Supersonic flight has introduced important new features into the test programme, particularly for supersonic transport aircraft. Of these new features the most significant is probably the prolonged heating and then cooling of the structure during each flight. Much basic research has been necessary to understand the effects of such a thermal cycle on the structure, and novel engineering techniques have been developed to simulate the cycle in the test laboratory.

The information presented in this paper is based on data obtained from the Concorde. Much of this data also applies to other supersonic transport aircraft. The design and development of the Concorde is a joint effort of the British and French, and the structural test programme is shared, as are all the other activities. Vast numbers of small specimens have been tested to determine the behaviour of the materials used in the aircraft. Major components of the aircraft structure, totalling almost a complete aircraft, have been made and are being tested to help the constructors in each country in the design and development of the structure. Tests on two complete airframes will give information for the certification of the aircraft. A static test was conducted in France and a fatigue test in the United Kingdom. Fail-safe tests are being made to demonstrate the crack-propagation characteristics of the structure and its residual strength.

The paper describes these aspects of the structural test programme in some detail, dealing particularly with the problems associated with the thermal cycle. The biggest of these problems is the setting up of the fatigue test on the complete airframe; therefore, this is covered more extensively with a discussion about how the test time can be shortened and with a description of the practical aspects of the test.

INTRODUCTION

Background

In 1967 a paper entitled "Design Philosophy and Fatigue Testing of the Concorde" was presented at the Fifth Symposium of the International Committee on Aeronautical Fatigue (ICAF) at Melbourne, Australia. (See ref. 1.) Four years later, the basic subject of the structural testing of a supersonic transport aircraft is to be considered again by the ICAF, this time at the Sixth Symposium at Miami Beach, Florida, U.S.A. In the meantime, some updating of the subject was given in a paper to the Eleventh Anglo-American Conference at the Royal Aeronautical Society, London, in 1969 (ref. 2). The present paper brings the story up to date and in doing so incorporates an appreciable amount of the basic information from the other papers for completeness.

The state of the art in structural-strength testing is now well advanced, and the purpose of the present paper is to examine the way this state has to be further developed to meet the needs of the supersonic transport aircraft. The supersonic transport aircraft will be subjected to all the familiar patterns of ground and flight loads, and these patterns must be represented in the structural tests using the techniques which have been developed and proven over many years. What is new is the thermal cycle which produces prolonged heating and then cooling during each flight. The thermal cycle sets up thermal stresses which are in themselves another loading action. Prolonged time at elevated temperature introduces creep and overageing. Further consideration of interaction effects which the thermal cycle may have on the static and fatigue strengths of the aircraft is necessary.

The data presented in this paper were obtained from structural tests on the Concorde, and illustrations are given of what has been done on that aircraft. The principles underlying this work are believed to be equally applicable to other supersonic transport aircraft. The design and development of the Concorde (fig. 1) are a joint effort of the British and the French, and the structural test programme is shared, as are all the other activities. Throughout the programme the aim has been to employ wherever possible test techniques which have been well established and proven throughout the years. Much new research has, however, been necessary to understand the effects of the thermal cycle on the structure, and novel engineering techniques have been developed to simulate it in the test laboratory.

Vast numbers of small specimens have been tested to determine the behaviour of the materials used in the aircraft. Major components of the aircraft structure, totalling almost a complete aircraft, have been tested to help the constructors in each country in the design and development of the structure. Two complete airframes will be tested to give information for the certification of the aircraft. A static test will be made in France and a fatigue test in the United Kingdom. Fail-safe tests are being made to demonstrate the crack-propagation characteristics of the structure and its residual strength. Drop, static, and fatigue tests are being made on the nose and main undercarriages. Acoustic fatigue tests are being made to investigate the effects on the structure of engine noise and various pressure-fluctuation effects in the airflow. Dynamic response in the structural loads is being measured on the structure in ground tests and in flight tests. The measurements and tests are most comprehensive, and the Concorde will certainly be one of the most thoroughly tested aircraft ever flown.

It is not possible in this paper to cover all these aspects in full detail, and preference is given to the strength-test programme with particular reference to the problems associated with the thermal cycle. The biggest problem has been the setting up of the fatigue test on the complete airframe, and some of the practical aspects of this are dealt with hereinafter.

Physical quantities used in this paper, their basic unit, and pertinent conversion factors are listed in table I.

Structural-Load Environment

A typical flight profile of the Concorde is that after take-off the aircraft will climb subsonically to a suitable altitude and then, still climbing, accelerate to its cruising speed of about a Mach number M of 2.0. After the cruise phase has been completed, the aircraft will decelerate to subsonic speed at altitude and then descend to its destination. (See fig. 2.) In the initial climb at subsonic speeds, the external surfaces of the aircraft will cool a little and then heat up in the acceleration phase to a temperature of about 100° C, which will be maintained during cruise. (See fig. 3.) During deceleration and descent, the external structural temperature will drop to about -20° C and rise again to ambient temperature on landing. (See fig. 4.)

The Concorde will be subjected to all the normal aircraft loads – taxying loads, ground-air-ground cycle, gust and manoeuvre loads, cabin pressurisation, etc. Almost all of these will occur while the aircraft is on the ground or flying subsonically; that is, while the structure is at ambient temperature before the acceleration phase or is approaching ambient temperature after the deceleration phase. The exception is any turbulence which may be encountered while the aircraft is flying supersonically and the structure is hot.

One of the most important of the thermal effects is the thermal stress which develops because the temperature of the internal structure lags behind that of the surface structure as a result of the time it takes for heat to be conducted to it. Thus on the climb the external structure will be hotter than the internal structure, and this will set up thermal stresses due to the different amount of expansion. During the cruise the temperature of the internal structure will gradually approach that of the external structure and the thermal stresses will decay. The reverse effect takes place during descent and recovery on the ground; thus, thermal stresses of opposite sign are produced. Such a stress situation has a significant effect on fatigue life. If the structure is deep, these stresses are about one-half the maximum stress permissible for the required life.

Two other thermal effects which need to be considered are overageing and creep. When a material is being manufactured, it is often subjected to heat treatment to "age" it in order to obtain its desired strength. If subsequently it is subjected to long periods at elevated temperature, it will "overage," and its strength will fall slightly. If the material is subjected to long periods at elevated temperature while under load, it will "creep" which means it will remain extended or deformed even after the load and temperature are removed. It is necessary to ensure that the amount of creep occurring is limited so that unacceptable deformation of the structure is prevented. An upper limit of 0.1-percent total plastic strain after 20 000 hours was chosen as a reasonable criterion, based mainly on structural experience in which a 0.1-percent tensile-proof condition has been used for design purposes for many years.

Thus the structure is subjected to the normal loading environment interspersed with periods at elevated temperature and a thermal-stress cycle each supersonic flight. This environment is further complicated by the presence of fuel tanks acting as heat sinks, with their changing levels of fuel during flight and with fuel transfer from tank to tank to preserve aircraft balance for subsonic and supersonic flight. The task of the designer and test engineer is indeed complex since he must understand and interpret all of these effects and their interactions.

Acknowledgements

The author gratefully acknowledges the able and willing assistance of his colleagues in the Royal Aircraft Establishment (R.A.E.), especially those in the Structures Department, who helped with all the many details necessary for the preparation of the paper and made valuable contributions to its content. Grateful acknowledgements are also made to the British Aircraft Corporation, Aerospatiale (S.N.I.A.S.), Centre d'Essais Aéronautique de Toulouse (C.E.A.T.), and Sulzer Brothers (London) Limited for their help with some of the illustrations.

RESEARCH ON THERMAL-CYCLE EFFECTS

Broad Pattern of Research

One of the first engineering tasks was to evaluate a suitable material for the aircraft structure. Aluminium alloy was a desirable choice since its aircraft production capabilities were well understood and it would be able to withstand the thermal effects over almost all the airframe. In a few areas where the temperatures were greater, such as near the engines, steel, titanium, or nickel alloys could be used. The task was therefore to choose a suitable aluminium alloy to give the best overall performance. Several were evaluated and the present Concorde material was evolved from an aluminium alloy which originally was developed to withstand the rigours of use in an aircraft engine. An important criterion in the choice of this material was its creep behaviour, which is superior to that of other aluminium alloys currently being used in subsonic aircraft. In parallel with the work on metallic materials, a similar programme was conducted on nonmetallic materials.

It is not possible within the scope of this paper to tell the story of all the research and development work. A tremendous amount of work has been done in both countries, is being continued, and will be continued right through the certification test programme to provide the necessary backup knowledge for planning and interpreting that programme.

Quite early, two things became apparent from the work on the Concorde aluminium alloy:

(1) Overall creep distortion was unlikely to be a hazard; that is, creep distortion at stresses to be used in the design would not reach the 0.1-percent limit set to avoid unacceptable distortion of the aircraft;

(2) Overageing had little effect on static strength; that is, the reduction in static strength due to prolonged time at elevated temperature was small and could easily be contained by a small factor in the allowable design stresses.

The next step was to see whether exposure to heat, with or without load, affected the fatigue performance of the material in structural configurations and to find out if stresses arising from temperature differences across the structure (thermal stresses) could be regarded simply as equivalent in effect to the same stresses arising from externally applied loads in accumulation of fatigue damage. Clearly at this stage in design, it would not have been practical to await results of tests in real time and temperature conditions; therefore, much of the early work was conducted under accelerated conditions on the basis of Fisher's parameter which gives a relationship of the form

$$\log \frac{t_1}{t_2} = C \frac{T_2 - T_1}{T_1 T_2}$$

where t_1 and T_1 are, respectively, the exposure time and absolute temperature in the real environment, t_2 and T_2 are the corresponding times and temperatures in accelerated conditions, and C is a constant (approximately 8200° K for the material concerned). On this basis the anticipated service environment was represented in much of the early work for Concorde by exposure times of 1000 hours at 150° C, which gives an equivalence of 30 000 hours at 120° C or 400 000 hours at 100° C. At the same time as the accelerated test programmes were initiated, tests were begun using temperature and time exposures close to real service conditions; such tests span several years, and it is only recently that results have started to accrue.

In planning the research programmes, it was also borne in mind that both under the special conditions of the full-scale fatigue test and under the actual service environment, there would be considerable deviations at different points in the structure from the nominal stress and temperature conditions. To meet this situation, the general policy was to concentrate the more detailed investigations on the nominal conditions and to explore deviations to either side with a comparatively light coverage of test conditions. This approach would give sufficient information to enable correction factors to be derived under such deviating conditions, and these correction factors would be of vital importance in interpreting any failures occurring during the full-scale tests.

In the majority of the early programmes, attention was centred primarily on the effect of heat exposure on cycles (or "flights") to failure, but as the research and development programmes built up, increasing attention was paid to examining the effects of heat exposure on the crack-nucleation phase of damage growth and on the subsequent crack-propagation phase since there was no presupposed reason to assume that both phases of damage growth would be equally affected. This aspect had to be explored both under accelerated and real-time conditions so that, for example, crack-initiation times observed during the full-scale fatigue test could be interpreted in terms of true environment.

An enormous programme of work has been done and is continuing to obtain information on the foregoing problems; many types of specimens are being used, ranging from simple notched and riveted-joint coupon specimens to large structural components. Loading and environmental conditions have varied from simple sinusoids with a block of heat representing the total service exposure introduced at some point in the fatigue test to elaborate representations of a flight cycle of mechanical loads with appropriate heating and cooling conditions to induce representative thermal stresses.

All this work is giving an empirical understanding of the behaviour of the structure under the thermal environment. More fundamental work is also being done to try to understand the metallurgical phenomena involved.

Examples of Research

It is beyond the scope of this paper to attempt full presentation of the results obtained so far, but some results are outlined subsequently. These serve to illustrate the kind of work that has been done and the nature of the answers that have been obtained. Three examples have been chosen. They show how this work has given understanding and data for design, and also, particularly in the context of this paper, how this work provides essential information for planning and interpretation of the full-scale fatigue test.

Effect of repeated application of heat on fatigue life.- This first example shows the trends which have emerged from fatigue-heat interaction tests on Concorde material. The variation in the ratio of life with heat exposure to life cold with temperature during heat exposure and the creep stress is illustrated in figure 5. The results on which these trends are based were mainly obtained from tests in which periods of heat, with or without mean stress application, were applied periodically during the fatigue life; the mechanical loading patterns included a simple representation of the gust loading and the ground-air-ground cycles. It is considered unlikely that significant thermal stresses were induced in any of the specimen types. It should also be borne in mind that in grouping these data, results were put together from tests having considerable detail variations in loading patterns and numbers of heat interspersions during life. Nevertheless, the trends give a qualitative indication of behaviour, and the following conclusions may be drawn:

(1) Performance reduces as the temperature rises from 120° to 180° C.

(2) Performance is better with tensile creep stress than with zero creep stress, though the improvement is seen to be falling off for the riveted joints at the higher creep stresses.

(3) Performance appears to improve in moving from the simple notched specimen to the riveted-joint specimen and, again, to the relatively complex fabricated box; reasons why this may be so are discussed subsequently.

Effect of heat on nucleation and crack-propagation phases of fatigue life.- This example has been chosen to illustrate one of the more fundamental research studies. The work was undertaken to obtain an understanding of the modifying effects of heat on the growth of fatigue damage at different stages in the life of a specimen under test. In all the tests, fatigue cycling was carried out at room temperature under fluctuating tensile loading. After a mean (nominal) life to failure was established, a single application of heat was introduced at a certain percentage of nominal life; the fatigue cycling was stopped during this period, and the mean load was adjusted to give tensile, zero, or compressive creep. After cooling, the fatigue cycling was then resumed, and from consideration of the total fatigue life to failure, the damaging or beneficial effect of the heat exposure was assessed. In the majority of the tests, the heat exposure was 150° C for 1000 hours, but the work also included a small number of long-term tests in which the exposure was 120° C for 20 000 hours. The tests were carried out on notched, pinned-lug, and clamped-lug specimens. Some of the results for the notched and pinned-lug specimens are shown in figure 6. It is evident from the results of the tests on the notched specimen that

(1) Exposure to heat without load during the first half of the fatigue life has a detrimental effect on fatigue performance.

(2) This detrimental effect is to some extent alleviated by tensile creep, and conversely.

(3) Compressive creep increases the damaging effect of heat alone.

(4) Exposure to heat during the crack-propagation phase has a relatively small effect.

The foregoing test results, supported by examination of the fracture surfaces, have led to a general explanation of the effects of heat and creep on the growth of fatigue damage. The effect of heat alone is to speed up the development of fatigue damage nuclei and hence to reduce the crack-initiation period; a marked reduction in scatter in endurance has been noted after heat exposure, which is in keeping with this explanation. Until comparatively recently, the more rapid appearance of damage nuclei was explained in terms of the relaxing effect of the period of heat on beneficial residual compressive stresses which are often inadvertently introduced at the notch surfaces during manufacture. Recent metallurgical studies have shown that another, and perhaps more important, change takes place in the surface material at the notch during heating.

It has been found that machining leaves behind a work-affected zone some 50 μm deep having a hardness approximately twice that of the interior material. In "as received" specimens, fatigue cracks, in fact, initiated below this zone. The heat exposure was found to reduce the surface hardness to that of the interior material, and cracks then developed from the surface. This phenomenon, combined with some relaxation of residual manufacturing stresses, is believed to explain the observed reduction in crack-initiation time; the biggest reductions, of course, were observed when heat preceded fatigue cycling. When load is applied during heating, plastic deformation of the material in the vicinity of the notch will be encouraged; that is, tensile loading will tend to induce compressive residual stresses at the notch so that after the heating period, the local mean stress will be reduced with consequent improvement in fatigue life relative to the heat-without-load condition. The reverse will be true with compressive load with heating.

It may be noted that results for the notched specimen under long exposure times at lower temperatures, 20 000 hours at 120° C, which have recently become available from tests for heat without load, confirm the appropriate pattern of behaviour. The results of tests on the pinned-lug specimens correspond to anticipated results, bearing in mind that the crack-initiation period is a much smaller percentage of the fatigue life in this type of specimen because fretting promotes early formation of surface cracks. As would therefore be anticipated, the effects of heat are considerably less in such specimens than in simple notched specimens. The general patterns of behaviour observed in the foregoing fundamental studies have been shown also to apply to the observed behaviour of more complex specimens such as fabricated box beams containing riveted joints, cutouts, and so on. This basic understanding will be of great help in the full-scale fatigue test, both in indicating areas of structure where heat is likely to promote relatively early initiation of damage and in assessing the significance of failures that may develop.

Acceleration of tests under combined thermal and mechanical cycles.- The third type of investigation chosen to illustrate backup research and development work is concerned with the problem of accelerating the full-scale fatigue test, in which both thermal fatigue stresses and stresses arising from external loading actions contribute to the growth of fatigue damage. In order to keep the laboratory testing ahead of aircraft in service, the full-scale fatigue test must be accelerated to accumulate fatigue damage more rapidly than the real-time flight experience. This would present no problem if the loading actions were associated solely with externally applied mechanical loads because the frequency of application of such loads could easily be speeded up relative to real-time experience. It is the speeding up of the thermal-stress loading action that presents a problem since hot and cold soak times, for example, are controlled by the heat-transfer characteristics of the structure and cannot be hastened simply. This problem is discussed in more detail subsequently.

Some results of tests to give an assessment of one approach to this acceleration problem are shown in figure 7. The acceleration technique explored in this case was to conduct the accelerated test using a wider temperature range than used in the "real-time" test. The aim of this test was to attain the condition in which the increased range of the thermal-stress cycle would give twice the normal amount of fatigue damage in each test cycle. The accelerated test cycle included twice the number of mechanical loads experienced in one flight. Thus, each accelerated test cycle should give damage appropriate to two flights. The results given were obtained from tests on box beams (figs. 8 and 9) which were tested in four-point bending. The loading action applied resulted in mechanical and thermal stress conditions in the tension-compression surface of the specimen corresponding to those in certain areas of the pressure cabin to which gust loadings, cabin pressurisation, the ground-to-air cycle, and thermal-gradients contribute. It should be noted that in this exploratory work the severity of all the loadings was scaled up somewhat so that answers both in "real time" and accelerated conditions could be obtained in months rather than years. It will be seen from figure 7 that encouraging results were obtained. Damage rate, assessed on the basis of the time to first crack, was accelerated by a factor close to 2.

Though only two specimens were tested in each condition at this stage, the indications were that scatter was low, and therefore the results could be treated with considerable confidence. Low scatter has been found to be a characteristic of much of the background research and development work entailing heat application. This preliminary work is being followed up in a major programme of tests on box beams of similar dimensions but of detail design representing much more closely the Concorde structure. The tests are being run in conditions corresponding closely to those envisaged both in service and in the full-scale test. In addition to providing information on acceleration conditions, analysis of the results also provides understanding of the equivalence of thermal and mechanical stresses in cumulative damage.

DESIGN DEVELOPMENT TESTS

Large Component Specimens

Quite early in the design of an aircraft, it is prudent to build representative sections of the structure to see how ideas work out in practice. This is particularly necessary for the supersonic transport aircraft with all the implications of the interaction of thermal and mechanical effects. Therefore, two sections of fuselage were built initially for the Concorde. Each had about a 15-foot length of representative structure. One was tested in France and the other in the United Kingdom (specimens 2.1 and 2.2 of fig. 10).

As the design took shape, actual components of the aircraft, such as parts of the wing and fuselage, have been made and are being tested to assist in design development. These specimens make almost a complete aircraft. (See fig. 10.) Again, these tests are being shared with the French. A wide range of tests are being done on these component specimens. They include the exploration of temperature and stress distributions under various design conditions, static tests to demonstrate the strength of the structure under extreme conditions, fatigue tests to show its behaviour under the recurring loads in service, and fail-safe tests to show that the structure is capable of withstanding safely damage or failures in service.

For this paper, two tests have been picked as examples of the work which has been covered on the large component specimens.

Centre Wing and Fuselage Specimen at C.E.A.T.

Specimen 2.8B (figs. 10 and 11) is a large section of the centre wing and fuselage and contains the important cutouts for the main undercarriage. It is an early prototype standard and has completed its test programme at the Centre d'Essais Aéronautique de Toulouse (C.E.A.T.). It has been used to check the static strength of the aircraft and has given useful experience in preparation for the static test of the complete airframe, which is now being tested in the same laboratory.

The specimen weighed about 15 tons fully equipped and was approximately 35 feet long with a span of 44 feet. Kinetic heating effects were simulated by the use of 5000 radiant heaters, and cooling was simulated by ambient air and air cooled by liquid nitrogen drawn over the specimen at low speed by extractor fans. (See fig. 12.) The specimen was equipped with 1500 strain-gauge points and 2000 thermocouples. The effect of fuel in the tanks was simulated by using Gilotherm, a fluid which has similar characteristics to kerosene but is noninflammable. The mechanical loading was done with hydraulic jacks.

One of the earliest tests was to measure the influence coefficients across the specimen. Thence followed a thorough investigation of the strain and temperature distribution throughout the structure under typical loading conditions. A number of design cases were taken to limit load. The residual strength of the structure was demonstrated by removing members and unbolting joints to simulate fatigue and other damage. Finally in this group of tests, the wing was taken to ultimate load in a flight case. To see how far cracks propagated, the simulated fuselage was pressurised and struck with a guillotine blade; the impact sites were such that the skin was cut between frames, or both the skin and a frame were cut.

Forward-Fuselage Specimen at R.A.E.

Specimen 2.4/2.5 (figs. 10 and 13) is the forward part of the fuselage and is being tested at the Royal Aircraft Establishment (R.A.E.). It is about 70 feet long and comprises the flight deck and forward part of the passenger cabin. The droop nose is included and also a dummy nose undercarriage. The specimen is made to preproduction standards. The rig provides facilities for static, fatigue, and fail-safe tests and gives experience for the fatigue test on the complete airframe which will use many of the same test techniques.

The specimen is cantilever mounted in the test frame at its aft end and is loaded by 19 hydraulic jacks. It weighs about 8 tons fully equipped. Kinetic heating and cooling effects are simulated by convective means. Hot air is blown over the specimen to heat it for the climb and cruise conditions, and cold air is blown over it to cool it for the descent and recovery conditions. The specimen is enclosed in a duct with about a 4-inch annular gap. The duct is articulated in sections on gimbals to allow for specimen movement. Normally, the specimen and duct are in a closed circuit in which the air can be heated by electrical resistance heaters in the airflow or cooled by the injection of liquid nitrogen. (See fig. 14.) The circuit can however be opened to allow the specimen to be cooled initially with ambient air which has sufficient cooling potential for the first part of the descent.

This method of convective heating and cooling was developed specially by the R.A.E. for the component specimen tests and will be used for the major fatigue test. It provides a very simple testing technique, and one which is inherently safe since rapid and dangerous temperature runaways are impossible. The principle used is that the heat-transfer conditions which are set up on the aircraft at high speed in the rarefied air at altitude can be reproduced in the laboratory by blowing the denser air at ground level at slower speeds and heating or cooling it to the required temperature. In this test a specimen temperature range of 150° C to -35° C can be achieved, and the maximum air speed required is about 170 ft/sec. Control therefore is extremely simple; all that is necessary is to regulate the air speed and the air temperature. Good representation along and around the specimen is obtained.

The cabin is pressurised and air-conditioned to represent the conditions in flight. Additional electrical heaters are provided in the cabin to simulate the heat input from the electronic equipment in the aircraft. The whole test is controlled by an interesting development of on-line computer control. Two KDF7 computers are used. The first controls the test, by giving the instructions for mechanical loading, temperature, airflow, and so forth, against the required test programme; the second monitors the test by reproducing the same programme and comparing the results achieved by the first computer. Two levels of discrepancy are identified. Those differences below the lower level are within the acceptable test tolerances and are ignored. Those between the lower and upper levels are printed out so that the test control staff is informed. Any discrepancies above the upper level automatically cause the test to stop. By this method the test programme can be agreed upon, internationally, before it is commenced. High reliability is achieved because of the built-in checking systems and because elaborate recording with subsequent analysis is avoided.

The specimen is fitted with about 1400 strain-gauge points and 500 thermocouples. The initial tests investigated the strain and temperature distributions throughout the structure under typical loading cases. As a quick check on its integrity, the cabin structure was pressurised 5000 times. The specimen was then rigged for a fatigue test under the full mechanical and thermal environment. The test was done on a flight-by-flight basis, but each test cycle was made slightly more severe and shorter than aircraft flight conditions in order to shorten the testing time for a given amount of fatigue damage. The problems associated with this are discussed more fully for the major fatigue test later in this paper.

These tests were interrupted to obtain early design development information on the fail-safe behaviour of machined skin panels. Soon the specimen is to be modified to bring it up to production standards, and then it will be used for the certification fail-safe tests on this part of the structure. In these tests, natural cracks or artificially induced cracks (or damage) will be propagated under the full environmental conditions for a given period, and then the specimen will be loaded to limit load to check its residual strength.

CERTIFICATION TESTS

Outline of Programme

When the aircraft has reached its production design standard, the aircraft must be shown to merit a Certificate of Airworthiness. Each country has its own certifying authority, in the United Kingdom it is the Air Registration Board, and each country must be satisfied that its particular regulations for this type of aircraft are met.

In the early days of the Concorde project, the French and British Governments agreed that the Concorde aircraft must qualify for both French and British Certificates of Airworthiness. The two airworthiness authorities therefore agreed jointly to produce new airworthiness requirements for supersonic transport aircraft which are now known as TSS standards. These contain the parts of the French and British national requirements which were applicable and such new requirements as were necessary to meet the special conditions arising for a supersonic transport aircraft. These TSS standards thus became the basis for the design of the Concorde.

The United States Federal Aviation Administration (FAA) has also produced a new document entitled "Tentative Airworthiness Standards for Supersonic Transports" (ref. 3). These standards have also been taken into account in the Concorde design and test programme.

Certification of the aircraft will be based partly on calculation, but most emphasis will be placed on the major acceptance tests. Thus static, fatigue, and fail-safe tests are to be done on the whole airframe. The tests in more detail are

(1) The major static test on a complete airframe less the nacelles at C.E.A.T. (France)

(2) The major fatigue test on a complete airframe less the nacelles at R.A.E. (U.K.)

(3) Static and fatigue tests on the nacelles at the British Aircraft Corporation (U.K.)

(4) Drop tests, static, and fatigue tests on the nose and main undercarriages at C.E.A.T. (France)

(5) Fail-safe tests on component specimens in the country of manufacture

In planning the acceptance test programme, it was necessary to select appropriate airframes from the manufacturing sequence. The first two airframes to be made were used for the two prototypes, 001 and 002. The third airframe was chosen for the major static test so that the test results would be available in time for the certification of the aircraft. The airframe is to preproduction standard, and it was agreed that the test results would be reinterpreted to take account of any differences between preproduction and production aircraft. The next two airframes to be made are being used for the preproduction flight aircraft, 01 and 02. The sixth airframe was chosen for the major fatigue test so that it should be closely representative of production standard and yet should be available sufficiently early for the test to have started before the certification of the aircraft.

The following paragraphs discuss the techniques and facilities used for the major static and major fatigue tests. Although the nacelle tests are not described in detail, the procedures used to reproduce air pressure loading and convective heating and cooling are similar to those used for the major fatigue test. Finally, some comment is given on the fail-safe test programme, as Concorde will probably be the first aircraft to satisfy the new FAA requirements for supersonic transport aircraft.

Major Static Test

The purpose of the static test is to show that the structure is capable of withstanding extreme conditions which might arise in service and has an adequate margin of strength as laid down by the airworthiness authorities. A range of test cases has been selected to cover all the loading patterns which the aircraft will experience in service. The tests have been grouped so that those without heating are done first. Currently, the specimen is being rigged ready for the commencement of the hot tests.

The programme commenced with fuselage pressurisation tests and tests to check fuel-tank pressurisation and sealing. Then a number of tests were made to cover the take-off and landing conditions. Two flight cases at the beginning of the climb – the steady pullout case and the checked manoeuvre case – were also made. These tests were followed by a number of partial tests on local parts of the specimen covering various conditions arising from the nose undercarriage, tail bumper, engine loads, fin, flight controls, and the main undercarriage doors. In the next phase, the whole specimen will be subjected to the cases which are critical with the thermal cycle, such as a manoeuvre at the end of the climb, a pull-out at the end of the cruise, and gusts during the descent.

This large and comprehensive test is being made at C.E.A.T. in a test facility built for the Concorde tests. (See fig. 15.) The main test hall has a strong floor with underfloor ducts for cables, hydraulic pipes, and so forth. Portal frames provide support for the overhead and side loading. The loads are applied by hydraulic jacks, servocontrolled by Moog valves from a computer. Forty-eight separately controlled loading channels are available, and each can control more than one jack if required. Double-bridge load cells are used to control and monitor the loads.

The kinetic heating effect will be simulated by radiant heaters supplied by thyratron regulators controlled by the computer. One hundred and fifty channels are available, some of 200 kVA and some of 50 kVA capability. Air will be blown over the specimen at about 20 ft/sec during the heating phase, and increased to about 50 ft/sec in the cooling phase. Cooling will be obtained by the injection of liquid nitrogen into the airstream. The cabin will be pressurised, air conditioned, and filled with polyurethane foam blocks to reduce the explosive risk.

The digital computer controls the sequencing of the whole test and also records the test data. Some 2000 strain gauges and 1500 thermocouples are installed on the specimen, and about 2000 selected inputs can be recorded and processed by the computer in real time. The transducer data are printed every 10 seconds to detect any transducers which may be outside of expected limits.

The load in each test case is built up in a series of steps in the usual way, and full use is made of the computer to examine strains and deflections at each step and to compare them with expected values. It is hoped by this means to be able to detect the onset of failure and to stop the test before catastrophic damage occurs. The inclusion of kinetic heating and cooling in the static tests produces problems of sequencing. For example, it would not be satisfactory to hold the specimen at a high load for a long period while the thermal cycle was applied. It would also be very time consuming to perform a thermal cycle for every load level in every case. Thus an optimum sequence is being worked out for conducting the tests. Care has been taken to install in the specimen strain gauges and thermocouples at corresponding points to those on the flight-test aircraft so that full comparison can be made of conditions measured in flight and reproduced in the test laboratory.

The test will be completed before certification of the aircraft. All the important static design conditions will have been covered, and the tests will demonstrate that the airframe is capable of withstanding extreme conditions which might arise in service.

Major Fatigue Test

The purpose of the fatigue test is to subject the specimen to the whole structural load environment the aircraft would experience in service. The specimen is taken through a series of flight sequences in the laboratory and subjected to the environmental conditions it would encounter in typical flights. These conditions include the external loading actions, such as taxying loads, take-off loads, gust loads, kinetic heating and cooling, and the internal loading actions, such as cabin pressurisation, air-conditioning, and fuel handling. These loading actions must be applied to the specimen flight after flight to build up in the specimens all the fatigue structural experience which the aircraft will accumulate in service.

By their very nature, fatigue tests must take a long time. However, for subsonic aircraft, it has always been possible to compress the loading actions so that a test cycle in the laboratory was considerably shorter than the flight it represented. The problem is very much more difficult for a supersonic transport aircraft, since the effects of the thermal cycle are time dependent. Nonetheless, it is essential to find a way to shorten the test time so that the tests may keep ahead of aircraft in service with an adequate safety margin. The fatigue lives of nominally identical structures are often quite different. Consequently, the Concorde tests are designed so that the specimen will always have at least three times as much fatigue damage (or three times the equivalent loads and thermal cycles) as any aircraft in service. In order to do this, the test must be accelerated, that is, it must represent the aircraft conditions in a shorter time. The test will be run 24 hours per day, 7 days per week, but there will need to be pauses to inspect the specimen and to maintain it, for the essence of this test is to find the fatigue damage while it is still very small so that early preventive measures can be applied to the aircraft in service.

In this part of the paper, broad details only are given of the test techniques and procedures. These are amplified considerably and the practical problems discussed subsequently. The test is being done in the structural test laboratories at R.A.E. (See figs. 16, 17, and 18.) Mechanical loading is being applied by hydraulic jacks. Convective heating and cooling is being used to simulate the external thermal conditions. Because of the need to shorten the time of the test, additional forced heating and cooling systems are needed for the internal structure and the fuel. All this requires a considerable amount of plant to provide the heat and the cold. The test itself and the plant are controlled by two process computers and one monitor computer with a data logging and display system.

Currently the construction of the specimen in the test frame is about complete, and the test rig is being installed. When all this has been completed, the assembly will be calibrated initially by running a number of flight cycles in real time and comparing the achieved strains and temperatures with those measured in corresponding positions in flight. The problem then of accelerating the test will be tackled by shortening the test cycle and by making each test cycle represent more than one flight. This acceleration will be taken in steps, working down from the real-time cycle to ensure that the accelerated test cycle is meaningful. The chosen aim is to do each test cycle in 60 minutes and to make it represent two supersonic flights. Interspersed in the pattern of hot test cycles will be some without the thermal cycle to represent the subsonic flights which are expected to total about 20 percent of the service experience. The use of computer control ensures overall flexibility in the test, and advantage will be taken of this to vary the test cycles as appropriate to represent flight in different degrees of turbulence, at different gross weights, and with different flight patterns.

The engineering tasks involved in this test are considerable. The specimen weighs about 40 tons and the fuel about twice this amount. This entire mass has to be heated and cooled through the appropriate temperature range of each test cycle. Two major plants are required, one for external heating and cooling and the other for internal heating and cooling with all the special forcing systems included. The duct over the specimen is itself a major piece of engineering design. Then there is the mechanical loading system which must be capable of applying a multiple range of loads in a relatively short time.

Finally, the overall control system for the test must itself have high integrity and be able to control and monitor all functions so that the test as a whole achieves high reliability with safety.

Special attention has been paid to the need for extreme reliability of all parts of the rig, and wherever possible, well proven designs and techniques have been used. The tests will be continued for many years over many thousands of cycles to represent the service life of the aircraft with adequate margins. It is imperative therefore that the rig should be trouble free so that the only interruptions in the testing programme are for inspection and repair of the specimen.

While the equipment for the test is impressive, the technical judgement which lies behind it is more significant. The test must be meaningful. It must be possible to interpret the failures and apply preventive measures to aircraft in service. Much is being learned now from the research and development programme to give the necessary basis for this technical judgement. It is planned that the test will start before certification of the aircraft. The test specimen will then keep well ahead of the aircraft in service and will give practical demonstration that the airframe is capable of withstanding the recurring loads which make up its service experience.

Fail-Safe Tests

The Anglo-French TSS standards (ref. 4) call for analysis and substantiating tests to demonstrate the fail-safe characteristics of the structure. The tests are to be taken to limit load in combination with appropriate temperature effects and normal cabin operating pressure, if applicable.

The American FAA standards (ref. 3) go a little further than this. They require that all primary structure shall be designed fail-safe and that it shall be shown that adequate residual strength is provided to ensure that any partial failure will be detected before a hazardous condition develops. This involves showing that the structure remains capable of supporting the expected repeated loading and temperature spectrum and critical design limit loads without catastrophic results during the period after any fatigue failure or partial failure has progressed to obvious proportions and prior to detection by inspection. The intention is to cover the situation in which cracks or accidental damage might occur immediately following an inspection and then remain undetected in service until the next inspection, during which period they might be subjected to limit load. Thus, in a fail-safe test, it is necessary to cut the structure to simulate damage or to grow a crack, then to subject it to fatigue loads under the full environmental conditions for the equivalent of an inspection period, during which the damage may propagate, and then to show that it will withstand limit load. The results of these tests are required for type certification.

This fail-safe testing involves quite a large test programme to cover all aspects of the structure. The tests too are complex and time consuming because fatigue testing under full environmental conditions is required. For Concorde, it is planned to do these tests on the major component specimens, supplemented where necessary by tests on smaller specimens to cover design changes made since these specimens were made. Thus results will be available for type certification. In addition, check tests will be made on the major fatigue test specimen towards the end of its programme. These check tests, of course, will be made after the initial Certificate of Airworthiness tests are completed, but it is not thought practical to mix fail-safe tests with the major fatigue test, as the applications of limit load to check residual strength, necessary for the fail-safe tests, could affect crack initiation in the fatigue test.

THERMAL CYCLE IN MAJOR FATIGUE TEST

Important Thermal Effects in Fatigue Test

Before going into the practical details of how this test is to be done for the Concorde, an examination of why a fatigue test is to be done at all and what the main parameters are which dictate its complexity is appropriate.

A fatigue test is a firm requirement of the British and French certifying authorities. They specifically state in the TSS standards (ref. 4) that "A full scale complete airframe fatigue test programme shall be carried out under representative loading, pressure, heating, and cooling conditions." There is good reason for this. Experience, over many years, has shown that the fatigue test can reveal unexpected weaknesses and enable corrective action to be taken early, thus preserving safety. In safe-life designs, the fatigue test can reveal failures which would not have been found by inspection until they had become catastrophic. In fail-safe designs, the fatigue test shows where to make the inspections and gives guidance on their frequency, based on the rate of crack propagation. It has even been known to show that some structures designed to be fail-safe had unexpected weaknesses with safe-life characteristics. Thus it is extremely desirable for a fail-safe structure to be fatigue tested for its full life with an adequate factor to cover the possibility of unexpected safe-life failures. As well as the safety aspect, the early knowledge of possible fatigue damage in service has important warranty considerations.

Having established that a fatigue test shall be done, there is no doubt that the best and most up-to-date methods of simulation of the mechanical loads must be used, and this is no real difficulty with modern servo-hydraulic loading systems and on-line computer control. The major question, which governs the complexity of the test, is the manner in which it is necessary to include the thermal effects in order to do a meaningful test. There are a number of significant thermal effects including

(1) The thermal stress loading cycle produced by the thermal cycle, that is, heating and cooling each flight

(2) Creep arising from prolonged time at temperature under load

(3) Overageing arising from prolonged time at temperature and giving a reduction of static strength

(4) The interaction of all these thermal effects on each other and on the fatigue behaviour of the structure under mechanical loads.

Of these, the first is of overriding importance in determining if or how the thermal effects should be included in the test. Also intermittent heating is probably important because of its interaction effect on fatigue behaviour under mechanical loads.

It was shown previously that the difference in internal and external structural temperatures arising from the supersonic climb to altitude produced a thermal stress, which died away as the structural temperature equalised during the cruise. The process was repeated during the descent, giving rise to a thermal stress of the opposite sign. These thermal stresses are likely to be characteristic of all supersonic transport aircraft having a long range and to be an important part of the fatigue-loading environment. For the Concorde they are of comparable magnitude to the direct stress. They cannot therefore be ignored in a fatigue test. They might be simulated by mechanical means, but although this may be feasible in simple specimens, it is not thought to be practicable in the complex structure of a complete airframe. By their very nature, thermal stresses arise from the differential expansion or contraction of adjacent structure and have a varying pattern throughout the structure depending upon the temperature differences set up with time. It therefore is regarded as essential that the thermal stresses should be obtained in the fatigue test by the application of the thermal cycles.

The other thermal effects then need to be fitted into the test cycle. Not all of these necessarily involve intermittent heating and cooling for adequate representation. But they should be included in the test somehow, and can be included more easily if the thermal cycle is applied in the test. More details about thermal effects are given in the following sections where the problem of accelerating the test is considered.

Accelerating the Test

Concorde is being designed to have a service life of 45 000 hours. The maximum utilisation for any particular aircraft is expected to be between 3000 and 4000 hours per year. Now, as mentioned previously, the aim is to run the fatigue test so that the specimen will always have achieved at least three times the fatigue life of any aircraft in service. This factor of three allows for the scatter in fatigue performance between nominally identical structures, and allows for the variation between the test specimen and service aircraft. Hence, as much as 12 000 hours of flying may need to be represented in a year.

However, there are only 8760 hours in a year, and even by testing 24 hours per day, 7 days a week, it is unlikely that more than 4000 hours of actual test running can be achieved as time must be allowed for inspection of the specimen, maintenance, and so forth. Thus, the test has to be accelerated by a factor of approximately three, and it would be prudent to achieve rather better than this to allow provision for long delays which would inevitably occur if a major failure took place in the test.

Normally, it is quite a simple matter to accelerate a fatigue test as the mechanical load effects are amenable to grouping and can be represented in a much shorter time in the test than in a flight. This grouping has become a well-established technique, although some workers have slight doubts whether it would not be better to include more dwell periods between loading than is currently done. It is much more difficult to accelerate a test cycle including thermal effects because most of these effects are time dependent. The present plan is to accelerate the hot test cycle in two ways:

(1) By making each thermal cycle as fatigue damaging as two supersonic flights

(2) By shortening the thermal cycle to as near 60 minutes as practicable.

In planning the fatigue test, it has been assumed that

(1) The average length of a supersonic flight is 2.5 hours.

(2) The average length of a subsonic flight is 1.0 hour.

(3) On the average the ratio of supersonic flights to subsonic flights is 4 to 1.

The current plan is to run the fatigue test in a sequence of two hot test cycles and one cold test cycle. The hot test cycle will represent two supersonic flights and will contain one accelerated thermal cycle equivalent to two supersonic flights and two groups of mechical loads each equivalent to one flight. The cold test cycle will contain all the mechanical loads equivalent to one flight. The aim is to do the hot cycle in 60 minutes and the cold cycle in 15 minutes. If this is achieved then the sequence of two hot cycles and one cold cycle will take 2.25 hours and represent four supersonic flights plus one subsonic flight taking 11 hours. Thus, the time has been compressed by a factor of almost five.

Within this broad format, the individual test cycles will take account of flights in different degrees of turbulence, at different gross weights, and for different flight patterns. No test, however complicated, can provide a perfect representation for all aircraft in service, and a means of interpretation is necessary to relate the test results to service as previously mentioned.

Shortening the hot cycle brings a number of tricky problems to fit all the mechanical loadings into the time available, especially as each of these cycles is to represent two flights. Basically, the plan is to associate one set of mechanical loadings with their appropriate place in the test cycle and then to add another set towards the end of the cycle while the specimen is recovering temperature equilibrium ready for the next test cycle. (See fig. 19.) The alternative plan would have been to have put in one set of mechanical loadings, but at a higher level to take account of the acceleration. This plan was rejected however, mainly because of the possible unrepresentative effect on crack propagation.

The time available for mechanical loading thus becomes critical in the shortened cycle; and therefore, great care needs to be taken in choosing the levels of loads to be used, particularly within the taxi and gust load spectra. Especially, it is necessary to ensure that sufficient small loads are applied to reproduce the effects of fretting, even though these small loads take a disproportionate testing time compared with their direct contribution to the fatigue damage. The computer-controlled hydraulic servo-loading system gives great freedom of choice of loading levels, and full advantage can be taken of this to pick an optimum combination of frequencies and levels.

Another advantage arising from this flexibility is that random loading can be used if desired. Random loading, of course, more nearly represents what happens in service, and its use reduces the number of assumptions necessary in setting up the test programme. A possible disadvantage is that it might make it more difficult to trace the progress of failures on the fracture surfaces. Some work is currently in hand to investigate this in laboratory specimens and also the possibility of arranging the random loading to include marker loads which could be found on the subsequent fracture. Certainly, it is an advantage to be able to trace the progress of a fracture, but experience shows that this is often not possible except in simple loading cases and advantages of random loading may well outweigh the disadvantage which might arise in this particular aspect.

Accelerated Thermal Cycle

As previously mentioned the thermal cycle is to be accelerated by making it represent more than one flight and by shortening it. The most important part of the thermal cycle is the representation of the thermal stress, although the effects of creep and overageing and of their interactions are not to be ignored. The thermal stress arises from differential expansion due to the temperature difference between the skin and the internal structure. This stress is proportional to the temperature difference, and hence by increasing this difference a corresponding increase in thermal stress is obtained. This increase, in turn, is related to life through the appropriate S-N relationship, and an increase in temperature range can be chosen to give in one test cycle the fatigue damage from thermal stress approximately equivalent to that occurring in two supersonic flights.

For illustration, a simple example of a hypothetical piece of deep structure which follows certain assumed conditions will be considered. In particular, it is assumed that the skin and the deep structure start the climb at the same temperature and that the deep structure has warmed up only negligibly by the time the skin temperature has reached its cruise value. This would then give the condition for maximum thermal stress. It is also assumed that similar conditions apply for the descent. The comparison then becomes

	Real time conditions	Test conditions
Thermal stress due to climb:		
Skin and deep structure temperature at start of climb, °C . . .	15	22
Skin temperature at end of climb, °C	100	130
Deep structure temperature at end of climb, °C	15	22
Skin temperature range, °C	85	108
Increase in skin-temperature range over real-time conditions, percent		27
Thermal-cycle time-compression factor		≈2
Thermal stress due to descent:		
Skin and deep structure temperature at start of descent, °C	100	130
Minimum skin temperature during descent, °C	-20	-25
Deep structure temperature at same time, °C	100	130
Skin temperature range, °C	120	155
Increase in skin-temperature range over real-time conditions, percent		29
Thermal-cycle time-compression factor		≈2

The example is imprecise because clearly all the assumed conditions are not exactly met. Nonetheless, it illustrates that practical test conditions can be found which for deep structure will enable the thermal cycle to be accelerated by approximately two, that is, to represent two real flights. Clearly, a wide range of test conditions could be chosen to achieve this effect. The particular combination of a top temperature of 130° C, a bottom temperature of -25° C, and an ambient temperature of 22° C is a reasonable compromise on plant requirements, consistent with minimum effect on material properties of the specimen, particularly at elevated temperature. There are, of course, varying depths of deep structure throughout the aircraft. Because only one external temperature distribution can conveniently be prescribed for the whole aircraft, each portion of the structure will experience a different acceleration, depending upon its depth within the total structure.

A similar approach to accelerate the conditions for shallow structure is possible by increasing rates of heating and cooling, and a useful compromise is to cover the new temperature range in the original time. Again the resulting acceleration pattern is not uniform throughout the structure.

The second part of the problem is what can be done to shorten the test cycle. It has already been said that the most important reason for including the thermal cycle is to represent the thermal stresses, and for these it is important to represent the climb and descent phases in approximately real time. Thus, the only hope for shortening the test cycle lies in shortening the cruise and recovery phases. There are however two important constraints, namely, that the structural temperatures must be correct at the start of the climb and at the start of the descent so that the conditions are right for the generation of the thermal stress. If these conditions can be achieved artificially, the cruise and recovery phases can be shortened. Incidentally, a shorter cruise at higher temperature is compatible with maintaining the correct creep and overageing damage rates.

In cruise, the important criterion is that the structure reaches the conditions at the end of the cruise phase before the descent phase is started. Shallow structure will follow quite closely the temperature of the skin. Deeper structure will lag behind because of the time it takes for the heat to be conducted to it. The amount of lag will vary considerably throughout the structure. Most of the structure will, however, have reached a stable temperature by the end of the cruise phase. The problem, therefore, of shortening the cruise phase is to identify the structure which will not have reached a stable temperature in the shortened time and to force heat it in the test so that it does. The forced heating can be started as soon as the peak thermal stress has been reached in the climb. This peak will be reached at the end of the climb for deep structure and earlier for shallow structure.

Similar arguments for forced cooling apply to the shortening of the recovery phase. Forced cooling can be started as soon as the peak thermal stress has been reached; the peak thermal stress occurs at or before the time at which the skin reaches its minimum temperature. The situation is complicated by the fact that the final ambient temperature is higher than the skin temperature and lower than the temperature of the bulk of internal structure. Therefore, the forcing potentials are less than those obtained at the end of the cruise. The forced heating and cooling is being done by circulating hot and cold air and hot and cold fuel and is an extremely complex process.

For Concorde the chosen aim is to do the complete test cycle in 60 minutes, made up approximately of take-off and climb, 11 minutes; cruise, 20 minutes; descent and landing, 9 minutes; and recovery, 20 minutes. Initially test cycles will be run in real time, and results compared with measurements in flight. These have become known as "witness tests." Tests under accelerated conditions will then be made with the cycle time gradually being reduced, but ensuring always that the shortened test cycle remains meaningful. A comparison of the proposed accelerated thermal cycle with the flight cycle is shown in figure 20.

Interpreting the Test

The presence of the thermal cycle adds a number of difficulties in interpreting the test. For the fatigue test of a subsonic aircraft, numerous simplifying assumptions have to be made to set up the test, and means have to be devised to interpret the failures and to apply them to aircraft whose service history differs from the loading spectra used in the test. All this is still necessary for the supersonic transport aircraft. There is, however, the added complication of the thermal cycle and of the compromises which have been necessary to include it in the test.

It has already been shown that compression of test time, that is, increasing the thermal stress damage in each test cycle, produces a nonuniform thermal-cycle time-compression factor throughout the structure. Even though the nominal value of this compression factor is 2, it is necessary to be able to calculate the actual value at any place where a failure occurs or at other points of interest.

The principle of the accelerated cycle is to increase the magnitude of the thermal stress so that less cycles are applied and time can be saved; however, these increased thermal stresses have to be combined with the direct mechanical stresses. In fact, the thermal stress can be regarded as a shift of mean stress for the alternating mechanical stresses since it is a slowly varying stress from zero to a maximum in one direction, through zero to a maximum in the opposite direction, finally returning to zero again. In order not to raise the peak stresses to too high an unrepresentative value, it was decided to apply the mechanical loads (real level) twice during the test cycle to compensate for the acceleration of the thermal cycle. This is a complex situation. Increased thermal stresses are being combined with mechanical stresses at real-aircraft level. At any particular point in the structure, the proportions of thermal and mechanical stress damage may not be correct since the mechanical cycles are being applied overall on the assumption of a nominal value of thermal-cycle time-compression factor of 2 whereas the actual value at that point may be different.

It is important that under these special conditions the form of failure should not be altered, or if it is, the difference should be recognised. To this end, the box tests and other backup research tests are being made to explore modes of failure, times to failure, and crack-propagation rates under combinations of mechanical and thermal stress and under real and accelerated conditions.

Fortunately, shortening the thermal cycle in association with accelerating the rate of thermal-stress damage results in the application of higher temperatures in the cruise for shorter times. Thus, in part, some automatic compensation is given for the creep and overageing effects, but these need to be calculated in detail throughout the structure to determine how much the structural properties are being changed from each of these causes and comparison made with real aircraft conditions.

Therefore, the need to assess the cumulative damage under all of these conditions and relate it to aircraft conditions so that test damage can be interpreted is great. The process for correcting fatigue-test results for different service conditions is now well established for subsonic aircraft. Basically, this correction depends upon the application of Miner's law to critical parts of the structure. To this process must now be added the thermal stress and the interaction effects of the thermal cycle, creep, and overageing on the mechanical stress. Preliminary methods are being tried and verification sought from the research programme.

HEATING AND COOLING FOR THE MAJOR FATIGUE TEST

External Heating and Cooling

The purpose of external heating and cooling is to apply to the specimen the kinetic heating which the aircraft receives in the supersonic climb and cruise and the cooling which results from the descent at subsonic speeds. (See fig. 4.) The heating and the cooling is being done convectively with air, which is blown over the specimen at the required temperature and at suitable speeds so that the heat-transfer coefficients experienced in flight are reproduced in the test laboratory. The specimen is enclosed in a thermal duct which is divided into five sections, one over the fuselage and one over and under each of the two wings. There are five closed circuits linking these sections to the heating and cooling plant. Closed circuits are used so that the air can be recirculated and the heating and cooling potential conserved. Each circuit contains a fan to circulate the air and heat exchangers to heat and cool it.

Thermal duct.- Initially it was intended that the thermal duct should totally enclose the specimen. Later for reasons of expediency, it was decided not to heat and cool the wing tips and the upper part of the fin. The justification for not heating and cooling these areas is that the thermal stresses in them are low, and what effects there are can be assessed by reading across from areas of similar structure which are being subjected to the thermal cycle. The most important advantage is that this exclusion enables a rigid duct to be used since the specimen deflections can be contained within the duct spacing from the specimen. The duct can therefore be supported by rigging from the structure of the laboratory. Some flow-restriction problems arise because of the specimen deflections, but these are small compared with the problems that would have arisen from the design and construction of a flexible duct or a duct with flexible joints. Even so the design of the duct is still a major engineering task. This duct has to be easily removable so that the specimen can be inspected at frequent intervals. It has to be airtight when closed to avoid large losses of hot and cold air. It has to have a minimum of thermal mass so that it does not absorb heat and cold from the airstream in an unnecessarily wasteful manner. It must, of course, be able to withstand the effects of the continuous repetition of the thermal cycle.

As mentioned, the overall aircraft duct is divided into five main sections which are effectively in parallel – one over the fuselage and one over and under each wing. The wing ducts are further subdivided; the upper-surface duct splits into four parallel branches to cater for spanwise variation of heat-transfer coefficient, and the lower-surface duct splits initially into four branches which merge into three in order to bypass the engine nacelle. The fuselage duct is an annulus up to the wing leading edge, where it splits into two branches, a horseshoe sectioned upper duct and an approximately rectangular sectioned lower duct. The two ducts continue along the fuselage and rejoin at the wing trailing edge. Near the fin leading edge, a divider takes some of the air from the upper duct and passes it over the lower portion of the fin before rejoining the fuselage circuit in the return trunking. The ducts are shown diagrammatically in figures 21 and 22.

For each wing, the upper- and lower-surface ducts join at the trailing edge to form a plenum chamber with a static pressure common to both ducts. The return trunking for the two circuits is connected to the plenum chamber, and a short distance from the chamber the lower-surface duct trunking is provided with a vent to the atmosphere. The vent dictates the position of atmospheric static pressure in the circuits and allows the circuits to breathe during temperature changes. To prevent an increasing concentration of airborne fuel simulant in the circuits due to small fuel leakages, the circuits are constantly purged through the vent by bleeding fresh air into the circuits at appropriate positions. There are three vents, one for each wing and one for the fuselage. Provision is made for the insertion of suitable gauges in the three outer ducts of each wing circuit forward of the leading edge to adjust the mass flows in the ducts, and vane dampers are fitted in all ducts at the trailing edge for fine adjustment. Similarly, for the fuselage circuit, vane dampers are fitted in the upper duct and small fin duct.

The duct depths are designed to give the required heat-transfer coefficients from the Dittus and Boelter equation

$$\text{Nusselt number} = 0.023(\text{Reynolds number})^{0.8}(\text{Prandtl number})^{0.4}$$

with the overriding condition that the deflected aircraft structure shall not foul the duct. Average duct depths are fuselage, 7 inches; wing upper, 8 inches; and wing lower, 16 inches. The depth of the wing ducts is adjustable over a 3-inch range so that the ducts can be tuned to give the right temperature response in the fore and aft direction. The fuselage ducts also are adjustable but only in a vertical direction.

The duct is mounted on a massive steel structure with chordwise beams and spanwise intercostals bridging the specimen. Much of the duct is made up of a large number of removable panels constructed of aluminium alloy. These fit onto the beams and intercostals of the supporting structure and react to the loading due to the duct internal pressure. The duct panels and the fixed duct structure are insulated from the airflow on their inner surface by insulation panels attached to them. The insulant is a semirigid slab of mineral wool completely enclosed in a seam-welded stainless steel skin 0.010 inch thick to form insulating panels 1.25 inches thick around the aircraft and 1.75 inches thick in the inlet and exhaust ducts. The insulation panels are sealed to prevent ingress of fuel simulant which can be present within the duct in liquid and vapour form due to leakage from the specimen.

Since the aircraft moves relative to the duct, the chordwise walls separating the ducts from each other are flexible and constructed to extend and compress like an accordion. (See fig. 23.) The upper surface walls are coincident with chordwise rows of wing-load application rods which are used to give the walls lateral stability. The lower surface walls have built-in lateral stability since there are fewer loading rods attached to the lower surface. Sliding seals are provided where the wing tips protrude from the duct. The structure carrying the seal is counterpoised and follows the wing movements.

The fin duct is the only portion of duct not fixed relative to the floor. It is attached to the fuselage duct by a flexible seal and is moved vertically in step with the fin movement by means of hydraulic jacks with a self-contained hydraulic supply and control unit. With both fin and duct moving together, the problem of passing fin lateral loading rods through the duct is eased considerably.

An essential requirement of the duct is that it shall be easily removable for inspection of the specimen. To this end the duct panels are fitted with quick release devices, and as far as possible, the loading rods are passed through the joints between the panels. Nonetheless, removing the panels is still a very large task since there are about 80 around the fuselage, 32 above the wings, and 60 below the wings. Those on the fuselage are mainly removable, and those on the wing are mainly hinged.

Another major problem for the duct is the passing through it of the service pipes carrying air and fuel substitute to provide the internal heating, cooling, and pressurisation. There are some 100 of these pipes ranging in diameter from 4 to 14 inches. Many of these pipes pass through the lower fuselage duct and have a masking effect on the fuselage structure. They also increase the pressure drop through the duct considerably. In some cases it has been possible to group the pipes together and to shroud them with an aerodynamic fairing to reduce the interference to the airstream. There is a difficulty of sealing these pipes to the duct to avoid leakage and yet to allow movement of the pipes with the specimen as it deflects in the duct. Some pipes are fitted with corrugated fabric fairings to accommodate the movement and reduce the pressure drop and air leakage. For others, clearance holes are filled with a sliding-plate device, which shows a relatively smooth surface to the airstream.

The temperature of the air and its mass flow are varied throughout the test cycle to give as near as possible the correct heat-transfer coefficient to match the corresponding flight conditions. The temperature of the air is regulated by the flow of fluids to the heat exchangers and the mass flow by adjusting the speed of the circulating fans. The heat-transfer coefficients vary during the different phases of the flight and a compromise has to be achieved on the rig mainly because, once it has been set up, there is a fixed geometrical relationship between the duct and the specimen. The duct panels are individually adjustable on their supports so that duct depths can be altered locally, thereby enabling the duct to be tuned to give the best overall compromise along the length of the specimen for the chosen air temperature and mass flow. Some experience of this has already been gained on the forward fuselage specimen, as mentioned previously, and it is confidently expected that good temperature distributions along and around the specimen will be achieved.

External heating and cooling plant.- The primary heating and cooling plant consists basically of the following equipment:

(1) Axial-flow fans to circulate the air

(2) Heat exchangers to heat and cool the air

(3) Boilers and refrigerators for producing the hot and cold fluids

(4) Storage vessels for all the fluids

(5) Multitudinous pumps, control valves, and piping to distribute the fluids.

A simplified flow diagram of the plant is shown in figure 24. The plant generates hot and cold fluids continuously, and these are stored in large vessels to be transferred to the heat exchangers as required.

Some idea of the magnitude of the task can be gained from the facts that the structural specimen itself weighs about 40 tons and the fuel substitute about twice this amount. These specimens have to be taken through the appropriate temperature ranges approximately once every hour. This thermal cycling is, however, only part of the work which the plant has to do; since in circulating the air, the thermal duct, return trunking, and associated equipment are all cycled through the appropriate temperature ranges. Even though these are insulated as carefully as possible, they add up to the equivalent of about five more specimens.

The axial-flow air-circulating fan in each of the five circuits is fitted with adjustable inlet guide vanes and downstream air-straightening vanes and delivers about 3200 ft^3/sec of air. The fan drive is through a shaft connected to a 2000-hp variable-speed motor situated outside the circuit. The inlet guide vanes are set to give the best fan efficiency for the particular circuit-flow conditions. The total airflow in all five circuits is about 1250 lb/sec. The maximum air velocity is about 150 ft/sec. The fans also provide a considerable input of heat to the air. This heat input assists during the heating phase but is an embarrassment during the cooling phase, requiring additional cooling capacity from the plant to compensate for it. It may even need to be compensated for in part during the cruise if the heat input from the fans proves to be greater than the heat losses of the circuits.

The heat-exchanger fluids are water and ammonia, which are each stored at two different temperatures: water at 180° C and 5° C and ammonia at -62° C and 35° C. There are two heat exchangers in each air circuit, one for water and the other for ammonia. The water heat exchanger, immediately downstream of the fan, heats or cools the air when supplied with water at 180° C or 5° C, respectively. The ammonia heat exchanger supplies the cooling necessary to produce below-zero air temperatures and is so constructed that air can either flow through or bypass the exchanger matrix elements. The eleven elements of the heat exchanger are mounted one above the other with ten intervening gaps. Hydraulically operated shutters over the element inlets and gaps are so arranged that when the element shutters are open, the gap shutters are closed, making the air go through the elements. With the element shutters closed and the gap shutters open, the heat exchanger is virtually bypassed. The ammonia heat exchanger is bypassed whenever the circuit contains hot air; this bypass reduces the loss of heat into the exchanger mass, and in addition, the heat-exchanger mass is kept at a constant temperature by flowing ammonia at 35° C through its elements.

It is extremely important that the air leaving the heat exchangers and entering the thermal duct shall be uniformly heated or cooled over its cross section. The fluid flow across the heat exchangers has been specially designed with this in mind. In addition, the fluid in the heat exchangers is constantly recirculated so that it is at a uniform temperature. Fluids from the bulk storage are fed into these circuits to give the required air temperature.

The sequence of heat exchanger actions during a thermal cycle is

(1) Climb: The temperature of the water circulating through the heat exchanger is increased progressively by the addition of hot water at 180° C. Warm ammonia at 35° C is circulated through the bypassed heat-exchanger elements.

(2) Cruise: The hot water is gradually decreased and is cut off if the heat input of the fan is greater than the heat losses of the circuit; if this occurs, chilled water at 5° C is fed to the heat exchanger.

(3) Descent: The chilled water supply is increased progressively until it is no longer able to maintain the required air-cooling rate. Before the chilled water reaches

its maximum supply rate, the shutters over the ammonia elements open and cold ammonia, at -62° C, is fed into the ammonia heat exchanger. The chilled water continues to act as a precooler until the air temperature entering the water heat exchanger drops below the chilled water temperature. At this stage, hot water is fed to the heat exchanger to prevent freezing.

(4) Recovery: The supply of ammonia at -62° C is stopped and the air temperature increases to its datum. If the fan heat input is too large, chilled water will be pumped before the end of the cycle to keep the air at its datum temperature. At the end of the recovery phase, the ammonia element shutters are closed and the gaps opened to bypass the air.

The heating and cooling phases demand large amounts of energy in relatively short periods of time, and in order to spread the requirements of the plant over a complete cycle, the heat-exchanger fluids are generated continuously and stored.

The hot water is heated by two oil-fired boilers with a total output of 36×10^6 Btu/hr. The water is heated to 180° C, and some 100 tons are stored in the insulated storage vessel. The upper part of the vessel serves as an expansion chamber and is filled with nitrogen at 180 lb/in^2 to enable water temperature to be attained and to prevent cavitation in the water system.

Chilled water at 5° C is provided by an ammonia refrigerating machine with a two-stage piston compressor, condenser, and evaporator. The plant has a cooling capacity of 13.5×10^6 Btu/hr. About 300 tons of chilled water are stored in two insulated vessels under the same pressure as the hot water so that either can be fed to the water heat exchanger.

Ammonia liquid at -62° C is generated by two identical multistage turbocompressors working in parallel and having a total capacity of 14.3×10^6 Btu/hr. Each turbocompressor uses three stages of flash evaporation. About 145 tons of the cold ammonia is stored in two insulated vessels which are interconnected with expansion vessels containing ammonia at 35° C. These hold the system at the vapour pressure of ammonia at 35° C, which is approximately the same as the pressures used in the hot and chilled water systems. The expansion vessels also serve as storage for the supply of ammonia at 35° C for the heat exchangers while they are bypassed during the heating phase.

A considerable quantity of cooled water is also required throughout the plant. It is used for

(1) The initial cooling of the chilled water supply

(2) The condensers of both refrigeration plants

(3) Maintaining the liquid ammonia below 35° C in any parts of the plant where this temperature could be exceeded

(4) Cooling the fan-motor speed controls, which are electrolytic resistors

(5) Cooling the fluid coupling of the turbocompressors to their electric motors

(6) Cooling pump glands and other similar applications.

The water is cooled from 27° C to 22° C in a two-cell cooling tower, having a total cooling capacity of 70×10^6 Btu/hr and a cooling water flow rate of almost 0.8×10^6 gal/hr.

The circuit of the fans, heat exchangers, and thermal duct is completed by the return trunking. This is constructed as a double shell, the inner lining being fabricated from 25 SWG (0.02-inch) stainless steel sheet and having an internal diameter of 6.5 feet. The outer cladding is fabricated from 19 SWG (0.04-inch) aluminium sheet and is separated from the inner lining by a 2-inch thick layer of mineral-wool insulation. Sections of the trunking are joined together by stainless steel bellows and cascaded corners are used to assist the airflow. The assembled trunking is completely air and oil tight. The total lengths of the five circuits vary slightly; the shortest is 590 feet and the longest 680 feet.

All of the plant for the external heating and cooling of the specimen is contained in a plant house 240 feet × 130 feet × 50 feet high located at the forward end of the test frame. (See figs. 17 and 25.) Inside this building is also the control room for the external plant. This is a strong room protected against dangers which might arise from explosion in the specimen or plant. The plant is started and monitored from this control room and, in normal operation, is controlled automatically from the computers. However, individual items of the plant can be run from this room for commissioning and checking purposes, and if necessary, a thermal cycle of the whole plant can be run. The plant house is heavily insulated so that noise from the equipment does not seriously disturb work in the adjacent offices or destroy the tranquility of the surrounding townships in the quiet of the night.

Internal Heating, Cooling, and Pressurisation

As the name implies, the basic functions of the internal facility are to thermally condition the inside of the specimen and to pressurise the specimen. These are two methods by which these functions may be performed: heating, cooling, and pressurisation with circulated air and heating and cooling with circulated fuel substitute, which for safety reasons is used in place of aircraft fuel. In more detail, the tasks needed to be performed are

(1) To represent the normal air conditioning and pressurisation of the fuselage

(2) To force heat and cool those areas of the structure which would not reach their required conditions in the shortened accelerated test cycle. This forced heating and cooling is done as appropriate with air or the fuel substitute. This is the major task of the internal plant.

(3) To heat, cool, and load by pressure that area of the underside of the wing normally covered by the nacelle. In the test the real nacelle is not fitted, and all loading actions are applied to the wing by a dummy nacelle.

(4) To correct the thermal condition arising in the wing tips because these are not completely covered by the external thermal duct. This discontinuity in the external heating and cooling could give rise to unrepresentative loading in the specimen, and to correct this, special treatment is given to the fuel tanks and other structure in this area.

(5) To pressurise certain of the fuel tanks to represent inertia loads arising on the fuel during parts of the test cycle.

The whole internal facility divides into three groups, air circuits, fuel systems, and a background plant which supplies the heating energy, cooling energy, and pressurisation air to the primary systems. The major part of the internal plant is housed in a specially designed plant house, measuring 150 feet × 90 feet × 50 feet high, erected on the starboard side of the test frame. (See fig. 17.) The plant house contains the control room for the internal plant, from which the equipment is started and monitored. The plant is normally controlled by computers, but it can, if necessary, be run from this control room for commissioning or checking. Because of the extremely high noise level expected from the installed plant, the building is of massive construction to provide the necessary sound absorption qualities to avoid disturbance of the neighbourhood.

The major components of the primary circuits and systems are connected to the specimen via a very complex and congested system of piping traversing between the plant house and the main test frame.

Air circuits.- The areas conditioned by the air circuits are shown in figure 26. These cover the fuselage air-conditioning and pressurisation, the areas to be force heated and cooled by air, and the nacelle-wing areas. Among the force conditioned areas are fuel tanks 9 and 10, which are emptied in flight before the supersonic phase commences and hence do not need to be filled with fuel substitute in the test. All these areas are grouped into 16 zones, some duplicated on port and starboard sides of the aircraft. Zones which have similar thermal and pressure requirements are further grouped together to give seven primary air circuits.

The air circuits are all basically similar; each consists of a Roots blower, one or more heat exchangers, a number of control valves, and connecting piping. A typical circuit circulates about 14 pounds of air per second at a temperature of 130° C in the heating phase and at 15° C during the cooling phase. The blowers are driven by electric motors averaging about 700 hp each. Roots type blowers were chosen as air-moving machinery because of considerable pressure drops involved in each of the air circuits. Centrifugal fans would have been inadequate and centrifugal compressors were not economically competitive in the sizes required. A typical air circuit is shown in figure 27.

Each circuit is a closed loop, the air being circulated by means of the Roots blower through the conditioning system to the various zones of the specimen and then back to the suction side of the blower. The air is heated to the required temperature (130° C in most circuits) by a heat exchanger fed with water at 180° C from the background plant. For the cooling phase, the air passes through two coolers; the first, using cooling-tower water at 22° C, cools the air to about 35° C, and the second, using chilled water at 5° C, further cools the air to about 15° C. Selector valves control the passage of the air to the appropriate heat exchangers.

The total mass flow to the specimen is controlled by regulating the valve in the blower bypass which bridges the delivery and return pipes across the blower. This flow is subdivided in the appropriate circuits by setting inlet trimming valves to apportion the flow to each individual zone.

A bypass is provided between the inlet and outlet pipes to each zone to enable temperature preconditioning of the delivery pipes between phases if required and thereby allow a choice of initial air temperature into the specimen. A valve in the bypass prevents flow when not required. The specimen inlet valve dictates whether flow is allowed through the specimen.

Some circuits where the zone is not airtight are vented to atmosphere at the specimen; the remaining circuits servicing airtight zones are vented from outlet pipes adjacent to the specimen. In all instances therefore the return pipes operate at a subatmospheric pressure except when a circuit is pressurised. Circuits 1, 3, and 6 are required to be pressurised during certain phases of the test cycle and are individually supplied with air at either 7 or 14 lb/in^2 from the background plant via an inlet valve which regulates the supply when an increase of pressure is required. A separate valve decreases the pressure on command by controlled venting to atmosphere. Safety valves are provided at each specimen inlet to safeguard against overpressurisation and also at each specimen outlet to prevent negative pressure occurring within the specimen.

Each circuit is fitted with an impingement liquid separator to remove any fuel substitute which may have leaked into it. This is to avoid fouling of the heat exchangers, which would reduce their efficiency. A mist detector is installed in each circuit to give adequate forewarning should the air-fuel substitute ratio become an explosive hazard. Fire detection and suppression systems are also provided.

The Roots blowers are constructed with close running tolerances on their rotors, and it is necessary to protect them from harmful temperature fluctuations. Thus, in five of the circuits, where the temperature of the air can reach 130° C, a heat exchanger is installed at the blower inlet to precool the air returning to the blower. The air temperature in the other circuits does not exceed 60° C.

The blowers and heat exchangers are installed in the internal plant house on the starboard side of the specimen (fig. 17), and there is therefore a considerable length of piping to bring the air to and from the specimen. In a typical circuit, the distance from the heat exchangers to the specimen is about 150 feet, and considerable care has had to be taken to keep the thermal mass of the delivery pipes to a minimum to ensure the required air temperatures at the specimen. The pipes have a wall thickness of only 0.04 inch and are covered with 2-inch-thick insulation of low density. The pipes vary in diameter between 6 inches and 24 inches according to the circuit.

Attaching these pipes to the specimen is also a major problem because of specimen movement caused by the mechanical loading and thermal distortion. There are about 80 of these pipes, and most of them have had to be fitted with a sliding joint to provide the necessary flexibility. The problem for those carrying pressure is even more severe as the end loads from these could provide unacceptable spurious loads on the specimen. This problem has been overcome by the design of special balanced fittings.

Having brought the air to the specimen, there is still the mammoth task of distributing it to all the zones requiring conditioning. Essentially this is done by a gallery system with air-distribution points along its length. A typical one for the fuselage air-conditioning is shown diagrammatically in figure 28. A similar gallery system is used to collect the air and return it to the plant. All pipes are taken into and out of the structure through existing holes wherever possible so that the primary structure of the specimen is not affected.

Fuel systems.- The layout of the fuel tanks is shown in figure 29. As mentioned previously, tanks 9 and 10 are conditioned with air, but all of the remainder need to be filled with fluid in the test to represent the fuel. The choice of a suitable simulant for the fuel has been a very difficult task. The use of kerosene itself would have been too dangerous and its repeated use through the many thermal cycles and long periods at elevated temperature would have presented deterioration. The main features that have been looked for in a simulant are

(1) A sufficiently high flash point to avoid fire and explosion risks

(2) Acceptable heat-transfer characteristics so that representative thermal conditions can be achieved in the specimen tanks

(3) Compatibility with the constructional materials of both specimen and plant

(4) Slow appreciation of acidic level and general stability when thermally cycled or maintained for long periods at elevated temperature

(5) Low cost.

The fuel simulant chosen, Shell 7305c, is a mineral oil with antioxidant additives. Extensive tests have been made to develop the fluid and to show that it meets the previously mentioned qualifications. In the following description of the plant and the installations in the specimen, the fluid is referred to simply as fuel.

In the aircraft itself, there are varying levels in the tanks as the fuel is used up. These varying levels could have been represented in the test, but it was decided to simplify the procedure by using a constant quantity of fuel in the tanks. By carefully choosing the quantity of fuel and its temperature programme during the test cycle, it has been possible to achieve a close representation of the critical thermal stresses in the tank structure. Most tanks are about 75 percent full with some 90 percent full. Great care has been taken with the filling system so that the specimen shall not be damaged. The large fuel-circulating pumps cannot be used for this task, and a special small pump (25 gal/min) has been provided for the purpose. It is under manual control monitored from the computer. Thus the quantity of fuel in each tank can be chosen before cycling starts. Since each tank is in its own closed circuit, the quantity of fluid in the tank remains constant, apart from leakage, which may occur as the specimen is tested. One of the functions of the monitoring computer is to check these quantities and initiate shutdown if they go outside acceptable limits.

Special provision is available to change the level of fluid in the tank during the test cycle in order to simulate flight usage for the special witness tests in real time in which measurements on the specimen are compared with flight measurements. Varying this level, of course, changes the weight of the specimen during the cycle and has implications on the hydraulic loading and control systems.

In total there are thirteen separate fuel systems, each one serving a single tank within the specimen. Ten of the systems are temperature conditioned. Each system includes a pump, one heat exchanger, and control valves; these components are sized to meet the requirements of each particular tank. Two of the remaining three systems provide for fuel circulation only, while for the last tank provision is made for filling and emptying only. (See fig. 29.)

A typical specimen tank contains about 1800 gallons of fuel and requires a pumping rate of 350 gal/min through pipes of 5-inch diameter against a system resistance of about 120 lb/in^2. Each system is vented at the specimen tank, and the pump is located in the main test frame to prevent cavitation at the inlet. A typical temperature conditioned system is shown in figure 30.

During normal cycling operation, the fuel is pumped from the specimen tank through the single heat exchanger located in the plant house and then back to the specimen tank. The flow rate in the system is controlled by a closed-loop servocontrol operating on the throttling valve.

During the heating phase, the fuel is progressively heated until that in the specimen tanks reaches the required temperature (usually 90° C). The heating is obtained by feeding hot water at 120° C to the heat exchanger at a preselected rate. Similarly in the cooling phase, the fuel is cooled until that in the specimen tanks reaches the required temperature (usually 25° C). The cooling is obtained by feeding chilled water at 5° C to the heat exchanger at a preselected rate. Between these phases the fuel may continue to be circulated, if required, with the energy supply to the heat exchanger interrupted to prevent further unwanted temperature increase or decrease, which prevents temperature stratification within the tank due to heat transfer through the skin from the external heating and cooling system.

Considerable attention has been given to the design of an efficient distribution system inside each specimen tank with the objective of ensuring 100-percent mixing of the ingoing fuel with the bulk. Internal pipes extend to the extremities of each tank and the ingoing fuel is injected at a pressure of about 20 lb/in^2 through a large number of small holes drilled along the length of the internal supply pipes.

Plate heat exchangers are provided because of their considerably superior heat-transfer qualities at the existing low Reynolds numbers. They have the additional advantage of being easy to dismantle for inspection and cleaning. Each system includes a small pump to maintain the water flow required through the heat exchanger to provide stable flow and heat-transfer characteristics.

Specimen considerations dictate that the acidic level of the fuel should not exceed a very low level; to this end chemical filters are provided in each system. Each filter is located in a bypass fed by a metering pump through a separate heater to provide continuous filtering at 30 gal/hr. All pipes and components with large surface areas in contact with the fuel are manufactured from stainless steel to minimise fuel contamination.

The total quantity of fuel in the system is a little over 20 000 gallons, and a storage tank of 25 000 gallons is provided to hold the fuel when it is removed from the specimen for structural inspections. The tank is lined with epoxy resin to prevent contamination.

Background plant.- The background plant consists of the heating plant, refrigeration plant, cooling tower, and pressurisation plant. An oil-fired boiler of 16×10^6 Btu/hr output is provided to meet the overall heating demands of the primary air and fuel systems, the demands of which are about equal. The boiler produces water at 180° C and operates at a pressure of 180 lb/in^2. This water is used directly in the heat exchangers of the air circuits, but for the fuel systems the water is reduced to a lower temperature through a heat exchanger which produces water at 120° C.

Although the heating demands of the facility are cyclic with a maximum rate of demand of approximately three times the average, it was not considered economically advantageous to reduce the size of the boiler and install a storage system for the hot water. The boiler output will meet the demand on line for most of the cycle, the remainder being supplied from some spare capacity existing in the external plant.

Refrigeration energy is provided by means of a four-stage turbocompressor of 13×10^6 Btu/hr capacity using freon as a transfer agent. It is driven by a 1000-hp electric motor and produces chilled water at 5^o C for cooling in the air and fuel systems. The chilled water is generated continuously and stored in an insulated vessel of 28 000 gallons capacity (about 125 tons).

A single-cell tower cools almost 0.5×10^6 gallons of water per hour from 27^o C to 22^o C, thereby dissipating about 40×10^6 Btu/hr. This tower provides the eventual heat sink for all the energy going into the facility.

A battery of six Roots blowers with a total output of 18 pounds of air per second and a total power of 1500 hp provides the air for pressurisation on line when required. The air is pressurised in two stages, from ambient to 7 lb/in^2 gage and then from 7 to 14 lb/in^2 gage. Between stages the air is cooled to 10^o C in a cooler using chilled water and the precipitating droplets are removed in a separator; the dewpoint then corresponds to 5^o C at ambient pressure.

Safety Precautions

The safety of the specimen is, of course, a major consideration in any full-scale fatigue test; for the Concorde it is even more important because of the very long time of testing involved. If this specimen were lost after some years of testing, it would be impossible to catch up the programme and to achieve the desired aircraft safety requirement. The specimen must always be tested to at least three times the life of any aircraft in service. Extensive safeguards against a number of hazards arising from different sources are therefore essential.

Excess-air-pressure safeguards.- Pressure within the specimen is measured by a transducer in all discrete compartments connected to the air system, whether they are normally pressurised or not. Areas normally unpressurised are included since the power of the circulating pumps is such that a blockage in the circuits could produce a hazard to the specimen. Some 40 measurement points are fitted and are checked at all times by the monitoring computer, which informs the operator of significant deviations from the required values and in extreme cases initiates automatic shutdown.

A mechanical direct-operating safety valve is fitted on the inlet pipe to each zone. Similar valves are fitted on the pressurisation feed pipes of the circuits that are pressurised. In addition there is built into each compartment, including all the fuel tanks, a direct-operating pressure-relief valve.

Antivacuum safeguards.- Pressures measured in all compartments are checked by the monitoring computer to ensure that a malfunction of an air-conditioning system does not create a subatmospheric condition within the specimen. A mechanical direct-operating safety valve is fitted on the outlet pipe from each zone.

Fuel-level surveillance.- The fuel level in each fuel tank is measured by a transducer and checked against the expected level by the monitoring computer. An increasing level could ultimately result in excess pressure and a decreasing level would indicate that fuel simulant was escaping, thereby creating a potential explosive hazard.

Explosive-hazard safeguard.- By the very nature of the test, it is likely that at some stage fuel simulant will leak from the specimen and will enter the air circuits. If it does so, there is a danger that in the fast-moving airstream of changing temperature, it will form a potentially dangerous fuel mist. To meet this possibility, a mist detector is installed in each of the external and internal air circuits to give adequate forewarning before the mist becomes an explosive hazard.

Fire detection and suppression.- Infrared and smoke detectors are installed both inside the specimen and in the external thermal duct surrounding the specimen. The detectors are connected to a bulk-storage CO_2 suppression system which will automatically flood the external ducts and the specimen should a detector become activated. Extensive fire detection devices are also fitted in the test laboratory and plant houses.

Ammonia detection.- To safeguard against the possible corrosion of the specimen should ammonia leak from a heat exchanger into an external air circuit, an ammonia detector is installed in each circuit. Further detectors are located in the external plant house to give adequate warning to personnel.

MECHANICAL-LOADING SYSTEM FOR MAJOR FATIGUE TEST

The mechanical loading is applied by a conventional linkage system from hydraulic jacks, servocontrolled from the computer system.

Loads and Reactions

The test laboratory, approximately 200 feet × 100 feet × 40 feet high, is effectively a strong box, so that vertical and side loads can be reacted directly to the building. It was designed as a general purpose test frame. The floor is strongly reinforced with steel beams with frequent attachment points, and a series of overhead moveable bridges can be placed at convenient locations to react the up loads. For the Concorde these are supplemented by portal frames over the wing tips and fuselage nose.

The loads are applied to the specimen by conventional means. Swivel loading points are bolted to the upper and lower surfaces of the wing and to each side of the fin. Groups of loading points are connected together by a "Christmas-tree" linkage to hydraulic jacks. Fuselage loads are applied to bulkheads or distributed to the floor beams by a system of loading beams inside the specimen. These are linked by rods to a number of hydraulic jacks outside the specimen. Dummy undercarriages and dummy nacelles are fitted to the specimen, and through these, undercarriage and engine loads can be applied.

For the ground tests the specimen rests on the dummy undercarriages and is loaded through the hydraulic jacks and linkages to give the correct overall distribution. For the flight tests the specimen is balanced in its linkage system, but a number of constraints at the undercarriages restrict its movement. All of these constraints are fitted with load measuring devices and record either balancing reactions or zero load as appropriate. Table II and figures 31 and 32 give more detail of the loading system.

Hydraulic System

Each hydraulic jack is set in a simple load-control circuit, which is made up of a load cell, electrohydraulic servo valve, and control module, which holds the load under analogue control until a new set point is given it from the overall control system. All the loading jacks are controlled by a PDP8/I computer.

The jacks mainly act in tension, although some act in tension and compression. They have been sized so that they can apply proof loads to the specimen as required for fail-safe testing towards the close of the fatigue test. They are fitted with PTFE seals to keep the friction low enough to avoid stick-slip effects in the system when small loads are being applied.

The load cells have two measuring bridges. One output is fed back to the control computer and is used to set up the required load; the other is fed back to the PDP10 monitor computer, where it is compared with the requested load level. Small, but significant, deviations from the required load are printed out and larger deviations initiate shutdown. Fuller details of the monitoring procedures are given subsequently.

Moog electrohydraulic servovalves are used throughout the system. These valves are two stage. The first, a preamplifier stage, uses a torque motor to convert the electrical input signal to a hydraulic signal, which drives the second, or power, stage. The torque motor operates a flapper which pivots between two hydraulic nozzles forming two variable orifices. Fluid under pressure is supplied to these nozzles through two fixed orifices, and the pressures between the orifices and the nozzles are applied to the ends of the spring-centred second stage, or main, spool. The flow through the valve is proportional to the main spool displacement and, thus, to the input electrical signal for a known pressure drop across the valve. Where higher flows are required, two servovalves are operated in parallel or a much larger valve is used.

The jack load is controlled by a simple error-signal device, which compares the required signal with the measured signal from the load cell. The error signal is amplified and drives the electrohydraulic servovalve to correct the load and so reduce the error signal to zero. This load is then held until a new set point is input to the system.

Each hydraulic control module has a number of local safety devices which are additional to the overall surveillance exercised by the monitoring computer. These local devices limit the maximum load and travel available at the jack. A typical hydraulic module circuit for a single acting tension jack is shown in figure 33. The differential pressure switch (DPS) initiates a fail-safe shutdown if the differential pressure across the jacks exceeds that set on the switch; the differential pressure relief valve (DPRV) vents high-pressure oil from either side of the jack to the other if the differential pressure exceeds a preset limit, these valves act as a backup to the differential pressure switches and prevent excessive loads on the specimen. When any safety device is activated, the isolating valves (LV) isolate the jack from the servovalve and ensure controlled dumping through the dump valves (DV). In addition, limit switches are used to sense excessive deflection of the jack rods and these also initiate shutdown.

The hydraulic power is supplied by 20 variable delivery pumps. Each pump is driven by a 30-hp motor and delivers 14 gallons per minute at 3000 lb/in^2 pressure. The pumps are arranged in banks of 5, each bank controlled by its own master control valve. This arrangement permits the independent shutdown of a bank of pumps if necessary. The pumps are supplemented by a battery of 8-gallon accumulators to provide for any peak demands of fluid in excess of pump output and to absorb any line pressure surges. Hydraulic fluid for the system is contained in two 750-gallon reservoirs. The temperature of the fluid (OM33) is maintained at 38° C by a thermostatically controlled immersion heater in each reservoir. Fluid is distributed from the pumps to hydraulic control modules situated in the various loading areas by a complex system of piping, which is located in trunking to contain any leakage.

Considerable attention has been given to achieving a high degree of cleanliness in the fluid. This cleanliness is necessary because of the small clearances and orifice diameters within the servovalve. These are susceptible to the fine particles which can cause silting or erosion of the orifices and hence alter the performance of the servovalve and ultimately possibly result in failure of the valve. Filters are fitted at the pump inlet (0.005-inch rating), at the pump outlet (10-micron rating), and at the inlet to the servovalve (1.5-micron rating).

Loading Sequences

The weight of the specimen, fuel substitute, and rigging is carried by the loading jacks, and account has to be taken of this in determining the loads to be applied by the computer. Prior to starting a test cycle, the whole system is set up to a "weightless" condition. Small pretension loads are included where needed to remove slackness from the linkage. Under these conditions, all the load cells at the reaction points should read zero.

The test cycle commences with the ground loads, including the following conditions

(1) 1g standing on the ground

(2) Engine runup

(3) Taxying loads

(4) Take-off.

The appropriate reaction-point loads are checked throughout to ensure that the required loading pattern is being applied.

The loading is then adjusted to the various phases of the flight including

(1) 1g climb

(2) Gusts during climb

(3) Manoeuvre during climb

(4) 1g cruise

(5) Gusts during cruise (including lateral gusts)

(6) 1g descent

(7) Gusts during descent and stand off.

This is followed by the landing and final taxying conditions including

(1) Landing (including nosewheel "abattée" conditions)

(2) Braking

(3) Reverse thrust

(4) Taxying

(5) 1g standing on the ground.

Throughout these sequences, the loading has to take account of changes in the aircraft weight as the fuel is used up and of changes in the air-load distribution in subsonic and supersonic flight, together with the fuel transfer necessary to compensate these changes. The programme includes flights with different gust severities (rough flights and smooth flights) and similarly takes account of rough and smooth airfields and different landing conditions to represent real-service conditions.

Mechanical-Loading Letdown System

If for any reason a test cycle has to be aborted while the specimen is under load, it is necessary to have a safe system to return it to the no-load condition. For the Concorde this is done by a controlled letdown procedure. On receiving a failure signal, the monitor computer deenergises a shutdown relay which in turn deenergises the following equipment:

(1) The pilot control valves on each jack module, which momentarily lock the specimen in position

(2) The main solenoid valves in both pump rooms, which divert oil in supply lines to reservoir tanks

(3) The air-operated solenoid valve, which in turn vents pressure from the diverter valves in the return lines thereby directing returning oil to the letdown tank instead of the reservoir tank

(4) The main hydraulic and pilot pressure pumps, which stop oil flow

(5) The electrohydraulic servovalves, setting them to open circuit

(6) The dump valves on each jack module, which initiates the letdown of the applied loads to zero.

The basic design of the letdown system is to separate the hydraulic jack return lines into 5 discrete groups which are

(1) Over-specimen vertical jacks

(2) Under-specimen vertical jacks

(3) Fuselage and fin lateral jacks

(4) Engine-nacelle jacks

(5) Undercarriage jacks.

These groups are chosen so that a balance between port and starboard will be maintained during letdown. All jacks in groups 1, 2, and 3 have collapsible linkage of length such that compression loads cannot be transmitted to the specimen. In groups 1, 2, 3, and 4 when the dump valves are deenergised, the annulus side of all jack pistons in each group is connected to a common return pipe through a preset restrictor to the letdown tank. The restrictor flow can be varied between 0.25 and 15 gallons per minute. This flow rate determines the rate of letdown. All the undercarriage jacks (group 5) are equal area double rodded types, and during letdown, pressure is vented from one side of the piston to the other.

In general, loads are controlled by the specimen returning to its natural no-load position. Excessive pressure or load is prevented by the differential pressure relief valves fitted in the hydraulic control module for each jack.

Interactions With Multichannel Systems

When a single loading channel is controlling the load being imparted to a structure, it is relatively easy to determine the characteristics of the complete system (including the structure) and to achieve optimum response from the system. In the case of a multichannel loading system used for the fatigue testing of a large structure, it is necessary to ensure that all the loading channels are kept in phase and apply the correct loads. Each loading point in a multichannel loading system has different mechanical parameters, such as stiffness and inertia. Such a system is a compound one, with many subsystems or channels so interconnected by the test structure that they influence each other. The degree of this influence or interaction is dependent both on the strength of the coupling between respective channels and on the mechanical parameters of each channel. For example, there would be little interaction between two channels with high inertias which were weakly coupled; this type of compound system would show characteristics similar to those of the individual channels. On the other hand, if the coupling were strong, the characteristics of the compound system would be very different from those of the individual systems acting alone.

The magnitude of spurious loads caused by interaction depends on a number of factors. It will depend, firstly, on the degree of coupling between the channels and on the magnitude of the mechanical parameters of each individual channel; secondly, on the speed of application of loads; and thirdly, on the response characteristics of the individual channels. In many instances, the effects of interaction are minimal and can be ignored. Sometimes, however, significant errors arise because of interaction, and then it must either be counteracted by test techniques or, if this is impossible, taken into account in the analysis of the results.

Since the magnitude of the interaction loads is dependent on the speed of application of the loading, it can be diminished by slowing the rate of loading. It can also be diminished by increasing the response of the affected channel. Both these methods have their limitations, the first because of the time scale of the test being conducted and the second because by increasing the response, the stability margin is decreased, and unwanted oscillations can result. These oscillations can cause problems as great as the one eradicated.

Clearly, these problems are intimately connected with the particular characteristics of the specimen and system involved. They are difficult to predict. They produce further problems in the commissioning of the system which frequently has to be done channel by channel on a separate rig. Great care must therefore be exercised in the interpretation of the results from such rigs when applying them to real structure. Small multichannel tests are being done for the Concorde system using dummy specimens of representative stiffness.

CONTROL AND MONITORING SYSTEMS FOR MAJOR FATIGUE TEST

Basic Requirements

The requirements imposed upon the control and monitoring systems divide into three main categories: control of the test, monitoring, particularly concerning the safety of the specimen, and collection of data, mainly from the specimen itself. Beside these explicit requirements, there are others, such as the need to achieve high reliability and to have a configuration giving a good margin of operational flexibility.

The requirements for the control function are, of course, dictated by the task which has to be performed. Essentially, this is in two parts, control of the heating and cooling plant and control of the mechanical loading system. There are about 50 channels of plant requiring continuous control with nearly 160 switching channels. The continuous control channels involve a complex thermal plant, where nonlinearities and significant time delays abound, making this an ideal application for the potential power of direct digital control. The mechanical loading system has a capacity for 150 channels of which currently about 100 are being used to control the hydraulic jacks, which because of their speed of response would impose a formidable task to control in a direct digital mode. These channels are, therefore, controlled by force feedback on continuous data control loops which only require updating with voltages proportional to the demand loads.

Because of the large number of components in the overall plant and in the control system itself, there is a very real chance that the specimen might be damaged as a result of a system failure. Hence, very careful monitoring must take place of all the systems, and automatic action must be taken if system failure develops. The cumulative nature of the fatigue process makes it acceptable to shut down the test when any failure is detected, alleviating any need to take over control. The provision of a failure detection system must aim at reducing to a very low probability the chance of applying an incorrect condition to the test specimen, during its several tens of thousands of hours of testing.

Anything less than a completely independent monitoring system relies on the ability to predict all the possible forms of failure of a shared component. Since the difficulty of achieving this independence increases rapidly as the shared component becomes complex, the only prudent solution is the totally independent system. This totally independent system will have a finite probability of failure; therefore, the chance of applying an unacceptable condition to the specimen is directly related to the probability of both the control and monitoring systems failing within an interval which is sufficient to allow a runaway channel to deviate unacceptably. It can be shown that even with mean time between failures for the whole system of as low as a few tens of hours and checking rates of approximately once per second, the probability of dual failure is very low. Thus separate control and monitoring systems have been chosen to take care of the test environment. (See fig. 34.) Although the system is primarily designed to run as a complete entity, the control computers may be run individually on their respective systems. Equally, it is possible to use the surveillance of the monitoring computer when parts of the overall testing facility are being run on their own hardware control systems.

A special peripheral unit housed in the monitoring computer is responsible for providing the time base for all the computer systems and at the same time checking that they are running in close synchronism. It consists of two separate crystal clocks, one of which produces pulses at a rate of 1 hertz and the other at rates of 1000 hertz and 1 hertz. Basically, each processor is made to count the 1000-hertz pulses and check them against the 1-hertz pulses; the safety of the system is preserved by having the two sources of 1-hertz pulses.

The effect of the test on the specimen is measured through attached strain, temperature, and deflection transducers. In all, these number about 3500 and require to be scanned in less than 10 seconds. Facilities are needed to scan subsets of the total number of transducers and to perform various degrees of processing on the recorded data. A data logging system associated with the monitoring computer performs this task.

Hardware and Its Operation

Overall hardware configuration.- The overall hardware configuration is shown in figure 35 and may be summarised as follows:

PDP10 monitoring computer:

- Size of computer word, 36 bits
- 32K of 1.6 microsecond core store
- 16K of 1 microsecond core store
- Two 512K fixed head disc stores
- Four DEC tape controllers
- 300 lines per minute line printer
- Digital XY plotter
- VB10 visual display
- VR12 slave display
- Two British standard digital data interfaces
- 240 channel analogue multiplexer
- 174 digital inputs
- Two 10-8 data link interfaces
- 1000 ch/sec paper tape reader

300 ch/sec paper tape reader
150 ch/sec paper tape punch
50 ch/sec paper tape punch
Four KSR 35 teletypes
One ASR 33 teletype

K70 plant control computer (incorporating a PDP8/I computer):

Size of computer word, 12 bits
20K of 3 microsecond core store
32K fixed head disc store
48 channels of direct digital control input/output
190 digital outputs
63 digital inputs
ASR 33 teletype
Shared 1000 ch/sec paper tape reader } With loading computer
Shared 150 ch/sec paper tape punch } With loading computer
8-10 data link interface

PDP8/I loading computer:

Size of computer word, 12 bits
8K of 3 microsecond core store
256K fixed head disc store
Extended arithmetic unit (hardware multiplier)
5 digital outputs
2 digital inputs
150 jack output cards giving ±5 or +10 volt output
ASR 33 teletype
Shared paper tape punch and reader
8-10 data link interface.

General operational principles.- After the computers have been switched on and have had their programs loaded, they first have to be synchronised. They are each informed of the real time at which they will expect to see the first clock pulse from the special clock unit situated in the PDP10. When this unit is switched on the appropriate parts of the programmes count up time to give each computer a real-time base on which to operate its plant control and monitoring functions. All control information or instruction to the computers is input via one or more of the teletypes attached to the machines. The next stage of operation involves the input of the engineering data giving the magnitudes of the functions to be performed which have already been defined, in principle, by the application programs written to make the computers perform the dedicated tasks associated with the test.

The engineering data are prepared in advance, in duplicate, by two independent punch operators from the carefully checked manuscript information formulated around the structural demands of the test. These identical punched paper tapes are then input to the control and monitoring computers; load information only is put into the loading computer and process information into the K70 machine. The computers then transform the engineering data into special internal machine formats and check the data for consistency with respect to both the hardware and the software. In a later stage of the startup procedure, the data are cross-checked within the computer system using the data links which connect the control machines to the PDP10. By this means it is possible to be sure that the information has been input correctly. Once the data have been input and the expected configuration of the plant has been defined to the computers, the computers can accept the various parts of the plant for control. This step is necessary because on certain occasions only limited parts of the plant may be run, especially during commissioning.

As and when the plant engineers request startup of each major unit of the plant, which has direct control over the conditions at the specimen, these requests are ratified by the control and monitoring computers and relayed back to the plant initiating startup of that unit. If the various units are started up in the previously defined order, it should be possible to take the whole of the specified plant onto control with its associated checking through the monitoring computer. During or after this stage, all the control points may be instructed to move to their precycle conditions. The whole of the test rig can thus be made ready for cycling, which it will commence on receipt of an instruction defining the start time. The actual programme that is then followed is inherent in the data input to the computers and is executed entirely automatically unless terminated prematurely. Various instructions exist to enable an operator to override the automatic sequence previously defined; these allow premature termination of a cycling sequence or alteration of its contents or a return to static conditions at the end of the current cycle.

Throughout the test rig, inner and outer limits are set for the variables, and these are checked by the monitoring computer through independent transducers by comparing measured values with expected values. The inner limits are set such that small deviations which would not significantly affect the accuracy of the test or prejudice its safety are permitted. Outer limits are set at levels which would be prejudicial to the test and exceedance of these automatically causes shutdown. Any variation between these two limits is recorded on teletype for the immediate information of the operator and also on paper tape for subsequent analysis. By these means the control of the test is virtually automatic and follows a prescribed plan; the burden imposed on the operators is thereby greatly minimised. If current information is required about any of the controlled conditions, instructions are available to allow the operator to display these on the cathode-ray tube, giving all relevant data to allow an assessment of the operating status of the test rig. In a similar way, the data logger may be instructed to survey a prescribed set of transducers and print the resulting information in an engineering format on one of the teletypes. For larger data-collection surveys, the transducers to be scanned may be defined on punched paper tape, together with the times when they are to take place. The logging will take place automatically at the prescribed times, and the results may be output for subsequent processing on another machine.

Selective shutdown is possible on a predefined basis. This avoids shutdown of the whole of the plant when one small area is subject to failure and is not potentially damaging to the specimen. Later, this shutdown part of the plant may be brought back onto control during an artificially imposed pause in the cycling.

Control of Air- and Fuel-Conditioning Plant

External-air systems.- Two parameters in each of the five circuits of the external conditioning systems are controlled by the K70 process computer in a direct digital control mode. They are the air temperature and the circulating fan speed. The air temperature is controlled through a cascaded loop which involves feeding the heat-exchanger-fluid temperature back to the computer as well as the air temperature itself. A hybrid computer simulation showed that this technique should be sufficient to give the required accuracies throughout a fatigue cycle without having to change the control algorithm; accuracy is improved significantly if it is accepted that the measured value is delayed from the set point by approximately 4 seconds. If during commissioning it becomes obvious that there are significant errors, then as a first step, it is possible to programme time-varying control parameters. There is an added virtue in having a measure of the heat-exchanger-fluid temperature within the computer, since it assists restarting particularly if a test cycle has been aborted at high temperature. It then becomes necessary to pick up the specimen at its elevated temperature and to force it back to room temperature conditions without inducing large temperatures differences. This procedure requires the heat-exchanger temperature to be controlled at the current specimen temperature before the circulating fan for that duct is switched on.

The control of the speed of each circulating fan is based on measurements of the fan speed using a tachogenerator and is obtained by altering an electrolytic resistance in series with the rotor of the fan motor.

Internal-air systems.- There are seven circuits air-conditioning the internal structure of the specimen, each of which has one or more parameters under direct digital control using the K70 computer. These systems are all based on similar principles, but some circuits provide more facilities than others. One of the more complex ones controls two mass flows, one temperature, and eight pressures. Like the controlled parameters of the external circuit, the set points may be specified as a series of points varying with time which are then interpolated by the computer to derive the once-per-second values required for control. By this means it is possible to make significant economies in the amounts of input data which have to be prepared by hand. This facility is further enhanced by the provision of editing software making it possible to alter small amounts of data through a typewriter keyboard directly connected to the computer.

Internal-fuel systems.- The temperature in twelve of the thirteen tanks is controlled continuously through regulation of a single parameter per tank, namely, the fuel circulation flow. In the ten circuits which are temperature conditioned, this continuous control is achieved by an open-loop technique where the appropriate hot or cold fluid is switched into the heat exchanger; no temperature feedback is used, the method relying on the repeatability of conditions.

Jack Loading Computer

Synthesis of net jack load.- Because of the overall requirement to retain the maximum flexibility in the test system combined with economy of storage space in the computers, the net load on any jack is built up from its fundamental components. Broadly, there are two components consisting of a slowly varying or steady load due to aerodynamic lift in flight or weight of the aircraft on the ground and a second, more rapidly varying, component due to turbulent conditions and manoeuvres in flight or taxying bumps on the ground. The second component may be further subdivided into a part which defines the magnitude of the gust or bump on the aircraft as a whole, for example, a gust of 10 ft/sec at a specified time or a bump of 0.1g at another time, and another part specifying the load in that particular jack due to a unit gust or bump; this latter part defines the load distribution between jacks which may vary for the different loading conditions. In algebraic terms this becomes

$$L = S + WG$$

where

L the load on a particular jack

S the steady component of load for that jack

G the gust or bump magnitude for the aircraft as a whole

W the distribution factor defining the load seen by the jack per unit gust or bump

By this means it is possible to build up a large repertoire of flights from a relatively small amount of data.

C.2

Test cycles are quantised into phases where either or both the steady load and set of weighting factors W are constant. Gusts and bumps are required to be applied in synchronism throughout the specimen and to a constant waveform. In certain circumstances the waveform is extended in duration to limit the acceleration forces on the test specimen.

Jack set-pointing system.- The jack computer provides set-point voltages for up to 150 jack control channels, the force feedback control loops being entirely external to the computer. A flow diagram of the system is given in figure 36 which shows the basic computer, a PDP8/I, driving through a standard Kent processor interface to a special jack-driver interface through to the analogue output cards. It produces ±5-volt or 0- to 10-volt signals for bidirectional and unidirectional jacks, respectively, the particular voltage being selected by a simple shorting link on each output card. As may be seen, the hardware makes use of load synthesis as detailed in the previous section. The isolation of the computer central processor from the electrohydraulic control channels occurs at the input of the jack-driver interface and is implemented through optical coupling; it achieves a high standard of isolation allowing the use of separate power grounds, thereby helping to protect the computer from noise likely to produce malfunction.

A sample-and-hold circuit accepts the current steady-load voltage and holds it for one-half second until the next update, thereby restricting steady-load changes to a maximum rate of twice per second for small increments. Step changes of more than the odd least significant bit (the steady load is set up to a resolution of 9 bits plus sign) are unacceptable to the jack control system, so a special procedure is adopted for substantial load changes. For these changes the steady load is updated at a rate of 20 times per second during the change giving a fine linear staircase type of output. To create the gust component, a constant amplitude waveform representing a half gust is input to the jack output card. This is again to a resolution of 9 bits plus sign updated at the rate of 1000 times per second. Half gusts may be only initiated at 1-second bounds when the steady load is updated and the software imposes a constraint that the component be zero for the first and last 25 milliseconds of the half-gust period. Normally, the half-gust duration is 2 seconds, but it may be requested up to 16 seconds with an overall restriction that it be symmetric about the quarter-gust point. The constant-amplitude gust is scaled by a third digital input to the jack card which is to a resolution of 9 bits plus sign to select whether the half gust be positive or negative going.

A single jack card is set up within 160 microseconds giving a maximum delay between channel 1 and channel 150 of 24 milliseconds for the steady-load component. The comparable delay on the gust component is less than 2 milliseconds.

Droop nose.- The droop nose is activated by two digital outputs from the jack computer, the first switching on the hydraulic pump to generate supply pressure and the second switching the control valve to stroke the droop jack.

Plant Monitoring

General principles.- As mentioned previously, there is a need for a failure detection system; this system is provided by the PDP10 computer and its peripheral devices. Strictly, it is an independent system which together with the control computers is able to indicate a lack of consistency between control and monitoring. By software its use is extended into a discriminating recording facility, where it disregards information which is consistent with correct operation, and promotes shutdown when there are gross errors, but stores and subsequently outputs data values between these two extremes. This technique avoids the vast quantities of redundant information which would be created by a continuous, conventional recording system. To be successful, the system depends upon the levels of discrimination being set up with great care; information which is intended to be disregarded must not have a significant effect on the test result, and that which initiates shutdown must preserve the safety of the specimen and the meaningfulness of the test.

In most cases the parameter which is controlled by the control computer is also monitored by the PDP10, but within the internal plant there are several exceptions. These exceptions occur either because the control function may be open loop or because the parameter of direct interest is only implicitly related to that which is directly controlled. Typically, in the internal air circuits the air temperature near the energy source and mass flow are controlled, but it is considered sufficient to monitor the temperature much nearer the specimen together with the state of any air distribution valves in that circuit. Because the digital computer inputs associated with valve monitoring are considerably cheaper than the analogue inputs for, say, mass flow, considerable economies can be achieved. There are complementary savings in computer time and storage.

Types of checking and their frequency.- Apart from the load channels, all checking is carried out at the same frequency as the related control functions are updated, that is, once per second. Analogue parameters are checked against inner and outer, upper and lower limits. Valve positions, which are input on a pair of digital inputs, are checked for the correct state, for example, binary 10 for off, 01 for on, and 00 for the transient state, which is allowed a preset time.

Since the loading channels can deviate more rapidly to an unacceptable level, their checking is conducted at a considerably higher rate, directly related to the required bandwidth necessary in control to produce the planned gusting rates and accuracies. Outer limits are checked twenty times per second and inner limits once per second unless extended duration gusts are being executed; then inner limits are only checked at the quarter cycle points.

Types of output.- There are three basic types of output available from the monitoring computer:

(1) Typed output on teleprinters

(2) Paper tape output

(3) Visual display output

The first two are produced automatically when a variable exceeds inner limits. The purpose of the typed output is to draw the attention of the test controller to the current test situation, namely, that one or more channels are deviating from their expected conditions, so that a close watch can be kept on any developments. If more than a prescribed number of printouts occur, shutdown takes place automatically. This limit would normally be set at the number which can be output in any one test cycle so that there is not a steady accumulation of results. If the deviation on a channel does not change, it does not repeat printout; thereby, the output capacity is preserved.

The paper-tape output provides a record of the exceedances of the inner limits in a form which can subsequently be fed to a computer for further analysis.

The third form of output is via the visual display which can give rapid access to any of the monitored variables at a request through a keyboard input message. Up to two variables may be displayed concurrently against a time axis; and a data table giving the current measured values and the expected values of the inner and outer limits may accompany them. It may also be used for the display of logged information if a user program is written to interface with the display servicing software.

Data Logger

Multiplexing configuration.- In order to achieve consistent measurements from strain gauges attached to specimens operating in unfavourable conditions, it is necessary to avoid pressure-type electrical contacts within the normal bridge measuring system. Thus small groups of gauges are collected into terminal units in which the bridge is formed using all soldered joints. Any initial imbalance of the bridge is catered for by extending the range of the recording apparatus. The terminal units are sited as near to the group of gauges as possible to minimise the effects of leads in the arms of the bridge. Up to 16 of these terminal units are then collected via cables into a sampling unit where they may be successively sampled by reed switches and the resulting signal amplified and fed to the recording console. Each terminal unit may accommodate up to 10 gauges with a further two calibration points available. Similar units containing cold junction compensators are used for collecting thermocouple signals.

The main console can accept up to 30 sampling boxes which are sampled through a high-speed solid-state multiplexer into a successive approximation analogue-to-digital converter. This converts the measured signal into digital form with a resolution of 12 bits (1 in 4096) when it is then transferred to the PDP10 computer through one of its two British standard digital data interfaces.

British standard interfaces.- Two of these units are attached to the memory buss of the PDP10 computer; each is capable of handling 8-bit words at transfer rates of more than 100 kilohertz. One is used for transferring control information to the logger main console while the other collects the resulting data; a useful feature of this arrangement is that the interfaces may be directly linked for fault diagnosis. An extension to the interfaces, on the logger side of them, provides isolation of the logger from the computer processor through an opto-electronic link for the reasons stated previously.

Basic operational facilities.- A total scan of all points on all the sampling boxes can be made in 6 seconds. The sampling time on each point is about 30 milliseconds, which is achieved by sampling all the sampling boxes concurrently. This concurrent sampling allows ample time to filter off any electrical noise at frequencies equal to or higher than the frequency of ac line voltage by a combination of analogue and numerical techniques. By using this method, it is possible to have available in the computer a measure of this noise level on each channel during sampling giving a useful guide to the effectiveness of any measurements. The diagnostic capability of the measuring system is further extended by having computer controlled grounding alternatives of the strain-gauge bridges. By this means it is possible to assess the electrical leakage between the gauge and specimen (a common cause of errors in elevated temperature strain measurement).

Integration of the logger with the computer gives a high degree of software control over its scanning ability from both conversational and preprogrammed input. By using the latter facility, logging can be made synchronous with the process control and loading functions. Input may be in either logger-channel-number format or gauge-code format.

Various types of output are available, their extent only being limited by the ingenuity of the programmer and the spare core store. Conversational type input normally results in a processed output in engineering terms, rather than machine code. Further processing and analysis of results is possible when the machine is dedicated to this task, that is, when fatigue cycling is not functioning. Alternatively, the raw data may be output on any of the output media to be subsequently processed on another computer.

Operation for Testing

Startup and shutdown.- The requirements of both startup and shutdown necessitate that the computer controlled plant be partitioned into blocks that can be independently started and stopped. Whereas the former state will be initiated by a plant engineer when he considers that the correct conditions have been satisfied, the latter action will normally be taken automatically by the computer or plant hardware. To satisfy these demands, each section of the controlled plant is coupled to its appropriate computer and the monitoring computer by an interlock loop which operates as shown by the following example.

Considering one of the external air circuits and assuming that the appropriate background conditioning plant is running and that the K70 and PDP10 computers are operating and loaded with their correct programs, the startup sequence commences with the plant engineer pushing a button to start the air-circulating fan. If the associated background plant is ready, a request will be sent to the PDP10 for permission to start. When the computer has checked to see if this is a legitimate request, it will start upper limit checking and also relay the request on to the K70 computer. The K70 computer, in turn, will check for legitimacy and initiate control action at the same time as sending a signal to the plant confirming the startup request. The fan should then start; this action will consolidate the engineer's request to start and therefore latch the interlock loop. Thereafter, if either the plant or the two computers fail to activate the interlock loop, it will open and hence produce shutdown of the controlled plant on that loop.

The following sections of plant have interlock lines to the computers:

(1) Each of the external circulating fans

(2) Each of the internal circuit circulating blowers

(3) One from the set of pressure blowers

(4) One from the electrohydraulic loading system

(5) One from the droop nose system

(6) Each of the thirteen fuel systems.

This partitioning of the plant allows batched shutdowns where, under certain circumstances, only part of the plant is shut down if the outer limits of a monitored variable are exceeded.

Data input and cross-checking.- Before a test is started, the input data for control and monitoring functions have to be input to the computers. These input data are oriented towards user formats and in engineering units; therefore, they have to be processed to compressed computer formats after initial input. Following this it is necessary to check that the data have been input correctly into the stores of the computers. To facilitate the operation, the same data are input to both the control computer and the monitoring computer and then cross-checked through the data link between them. At this point, the monitoring data in the control computer and the control data in the monitoring machine may be discarded.

As the load data are input in a derived form, as discussed previously, an additional function of the programme is to calculate all the jack loads and print them out for comparison with the original data.

Facilities for commissioning.- The configuration of two control computers was adopted to add flexibility for the commissioning stages of the project. Each control computer can be operated independently of the other and of the monitoring computer. Thus, for example, parts of the plant or loading system can be commissioned independently. It would not be desirable however to operate on the specimen without the monitoring computer in use, as the fail-safe properties of the complete system would be absent.

In general, the software has been designed to allow almost all the quantitative data defining the conditions of a test cycle to be replaced very quickly. For example, the standard three-term control algorithms available to control the plant may have their parameters changed, via the K70 console, by push buttons. Special provisions have also been made on the loading computer for a conversational type programme to control loads on up to 10 jacks. With these facilities, it is considered that most of the special problems which may arise during commissioning can be accommodated.

REFERENCES

1. Mann, J. Y.; and McMillan, I., eds.: Aircraft Fatigue – Design, Operational, and Economic Aspects. Programme of 5th ICAF Symposium (Melbourne, Australia), May 1967.
2. Ripley, E. L.: Structural Tests for the Supersonic Transport Aircraft. Paper presented at 11th Anglo-American Aeronautical Conference (London), Sept. 1969.
3. Anon.: Tentative Airworthiness Standards for Supersonic Transports. Flight Standards Service, FAA, Nov. 1, 1965.
4. Anon.: TSS Standards. Air Registration Board (England) or Secrêtariat Général à l'Aviation Civile (France), July 28, 1969.

TABLE I.- CONVERSION FACTORS

Physical quantity	Basic unit	Conversion factor (*)	SI unit	Supplementary unit
Length	inch	25.4	millimeter	
Weight	long ton	2240		pounds
		1016.05	kilograms	
Volume	gallon	4.546		liters
		4.546×10^{-3}	$meters^3$	
Acceleration	g	32.174		ft/sec^2
		9.806	m/sec^2	
Pressure	lbf/in^2	6.895	kN/m^2	
		6.895×10^{-4}		hectobar
		7.03×10^{-4}		kgf/mm^2
Power	hp	746	watts	
	Btu/hr	0.293	watts	

*Multiply value given in basic units by conversion factor to obtain equivalent values in SI and supplementary units.

TABLE II.- DETAILS OF LOADING SYSTEM

Structural component	Loading points to structure	Jacks
Wing vertical loads:		
Upper surface	284	42
Lower surface	60	14
Fuselage:		
Vertical loads:		
Up	165	4
Down	181	9
Side loads (forward fuselage):		
Port	34	2
Starboard	34	2
Fin side loads:		
Port	32	3
Starboard	32	3
Nacelles:		
Vertical loads:		
Port	1	1
Starboard	1	1
Thrust loads:		
Port	2	2
Starboard	2	2
Reverse-thrust loads:		
Port	2	2
Starboard	2	2
Nose undercarriage (at bottom of leg):		
Vertical loads	1	Reaction point
Fore and aft loads	1	1
Side loads	1	1
Main undercarriage (port):		
Vertical loads at bottom of leg	1	Reaction point
Fore and aft loads:		
Bottom of leg	1	1
Top of leg	1	Reaction point
Side loads:		
Bottom of leg	1	1
Top of leg	1	Reaction point
Main undercarriage (starboard):		
Vertical loads bottom of leg	1	Reaction point
Fore and aft loads:		
Bottom of leg	1	1
Top of leg	1	Reaction point
Side loads at bottom of leg	1	1

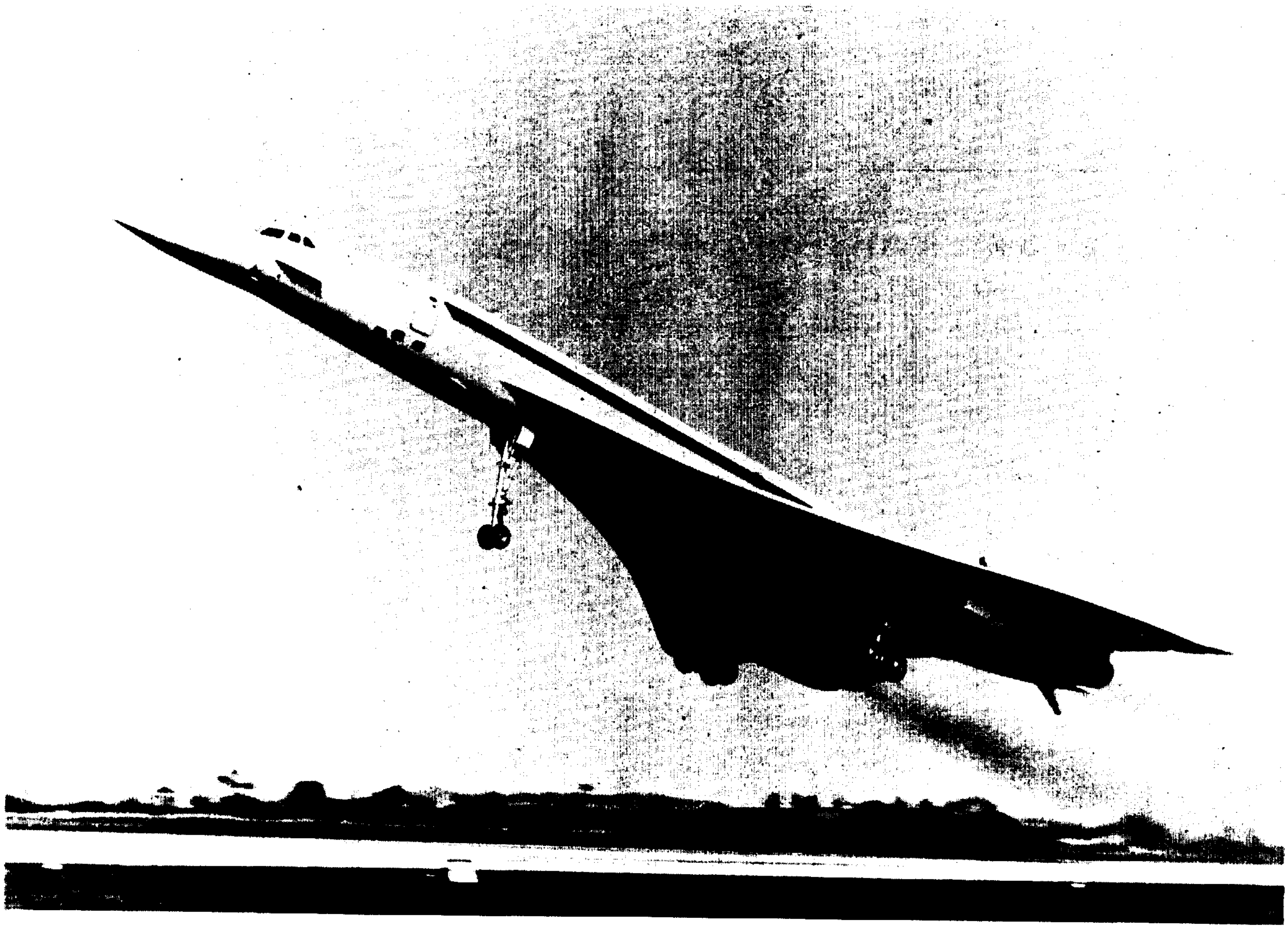


Figure 1.- Prototype Concorde aircraft 002.

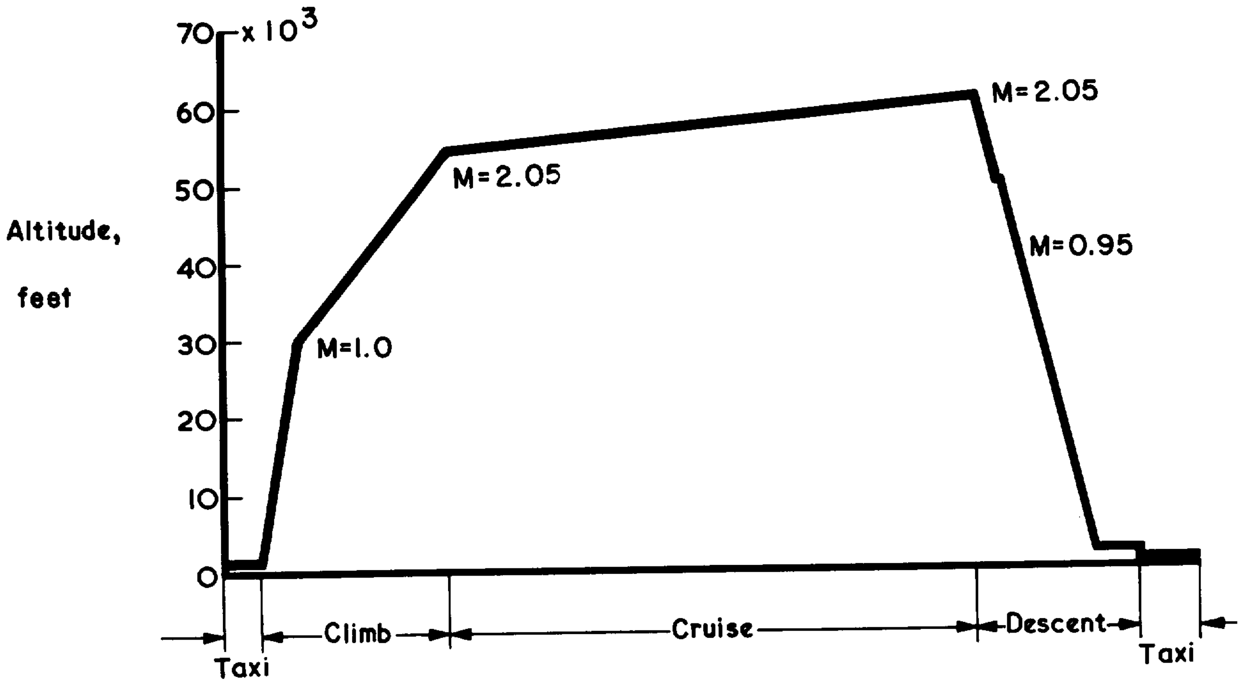


Figure 2.- Altitude and speed for a typical flight. M is Mach number.

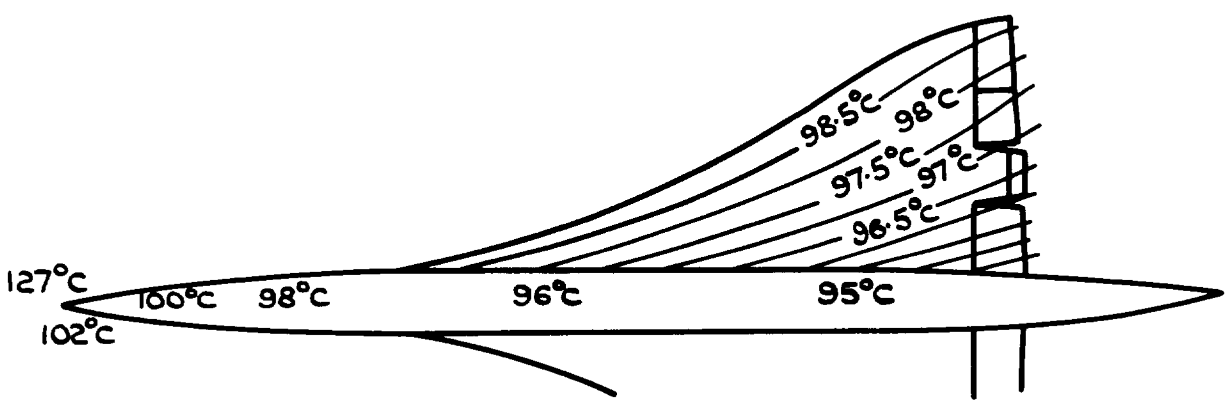


Figure 3.- External-structure temperature during cruise.

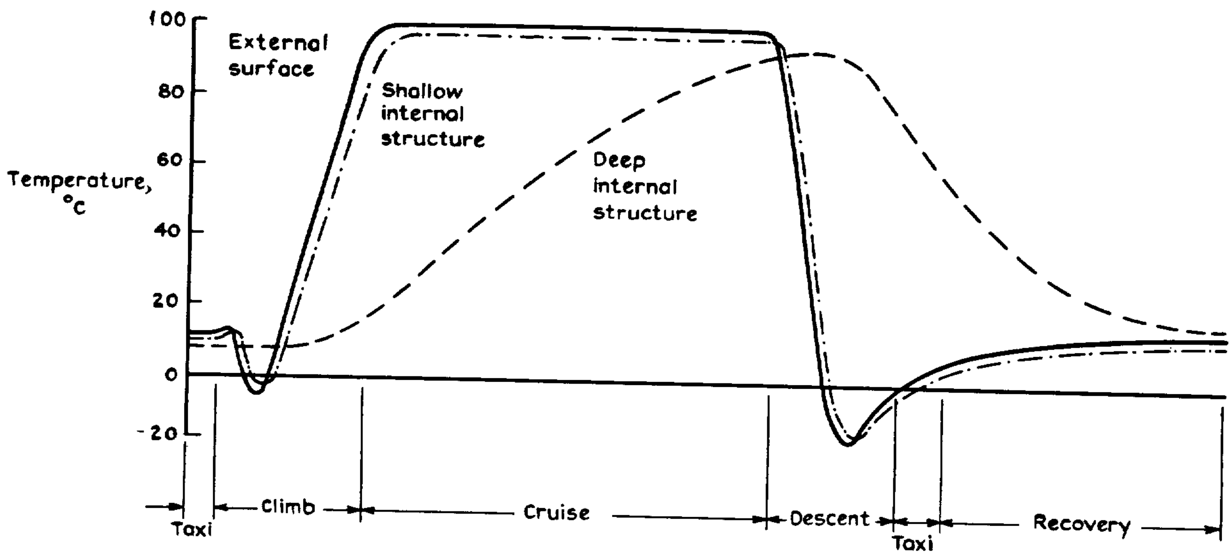


Figure 4.- Structural temperature for a typical flight.

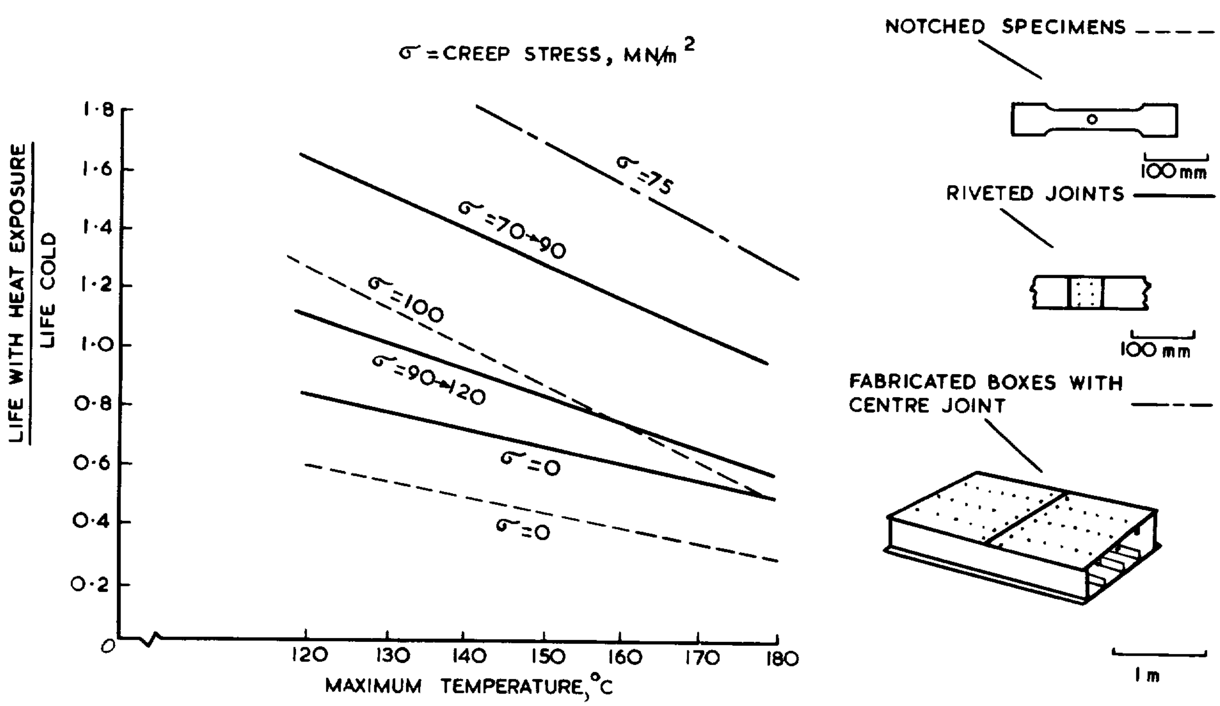


Figure 5.- General trends of influence of temperature and mean stress on life with intermittent heating.

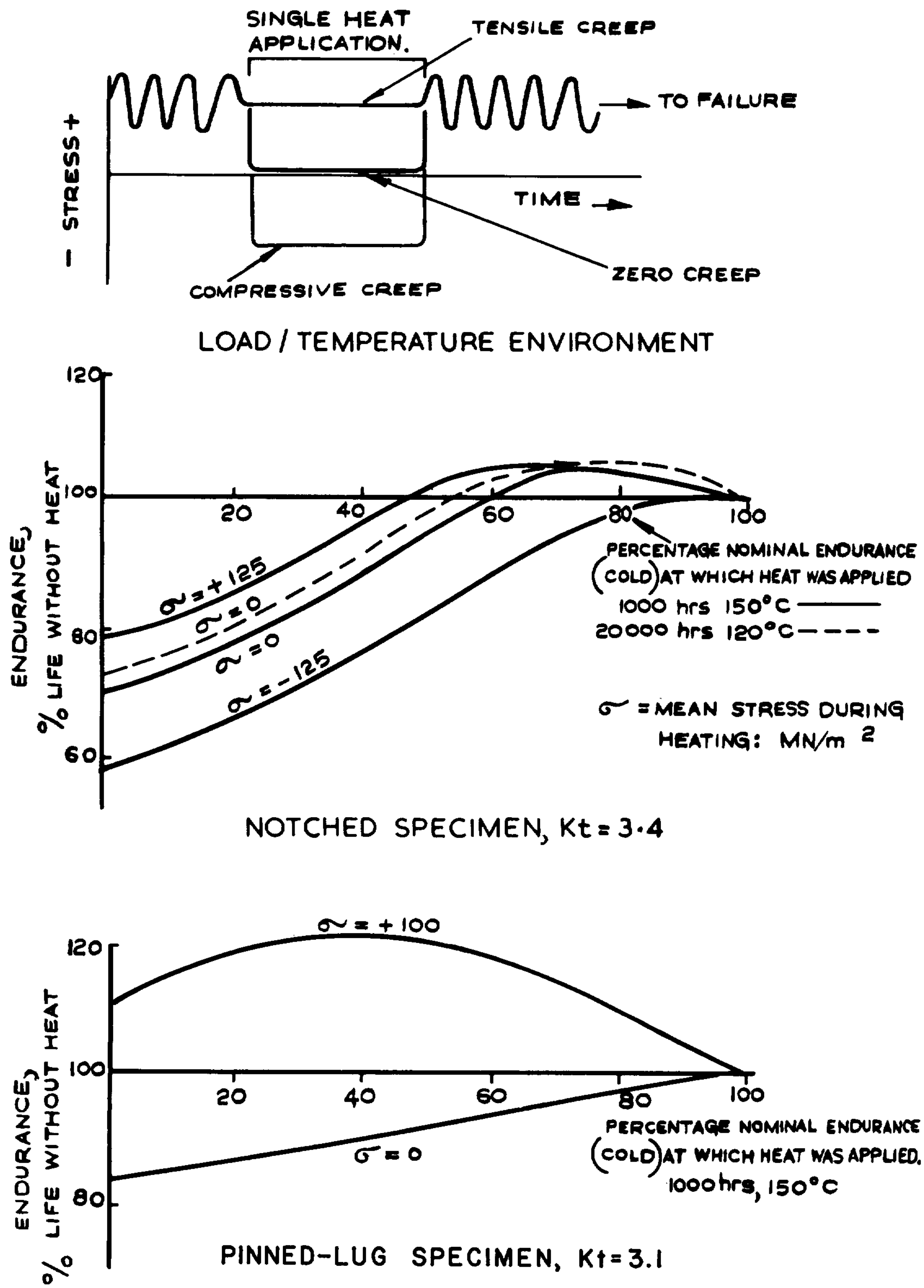
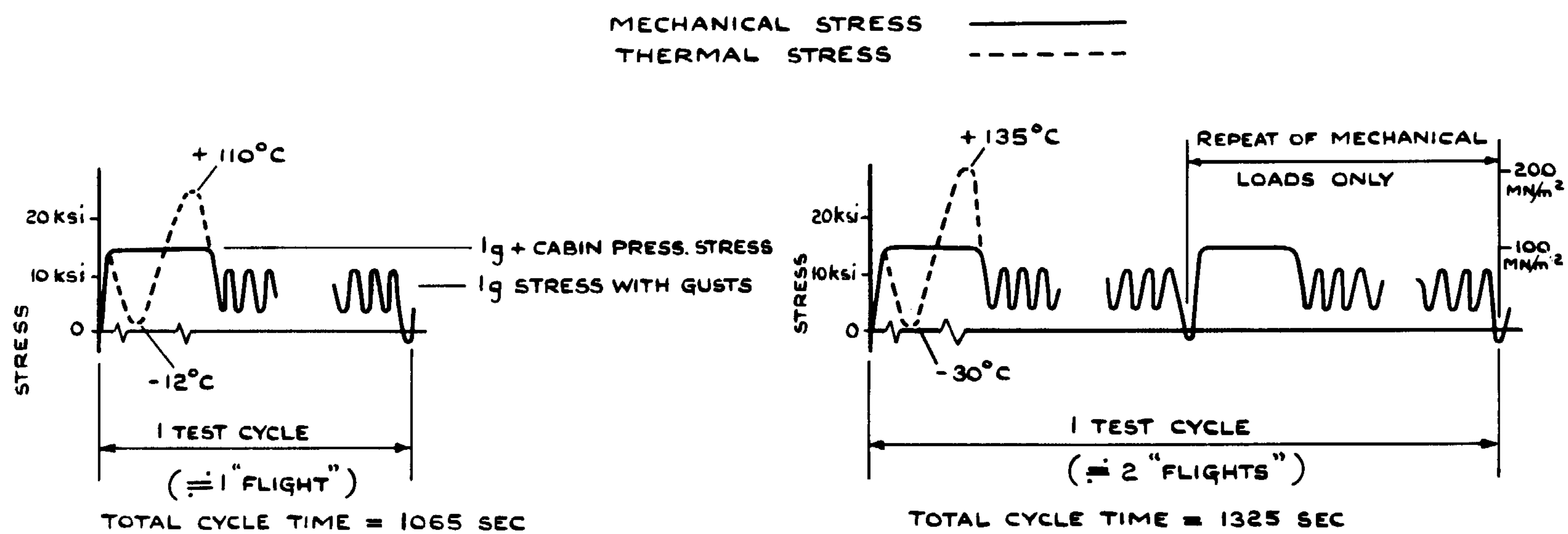


Figure 6.- Effect of heat exposure on fatigue. Kt is stress-concentration factor.



TEMPERATURE RANGE	TEST NUMBER	TEST CYCLES TO 1st CRACK	"FLIGHTS" TO 1st CRACK
−12°C +110°C	1	7600	7600
	2	7200	7200

TEMPERATURE RANGE	TEST NUMBER	TEST CYCLES TO 1st CRACK	"FLIGHTS" TO 1st CRACK
−30°C	3	3400	6800
+135°C	4	3500	7000

Figure 7.- Real-time and accelerated tests on box-beam specimens.

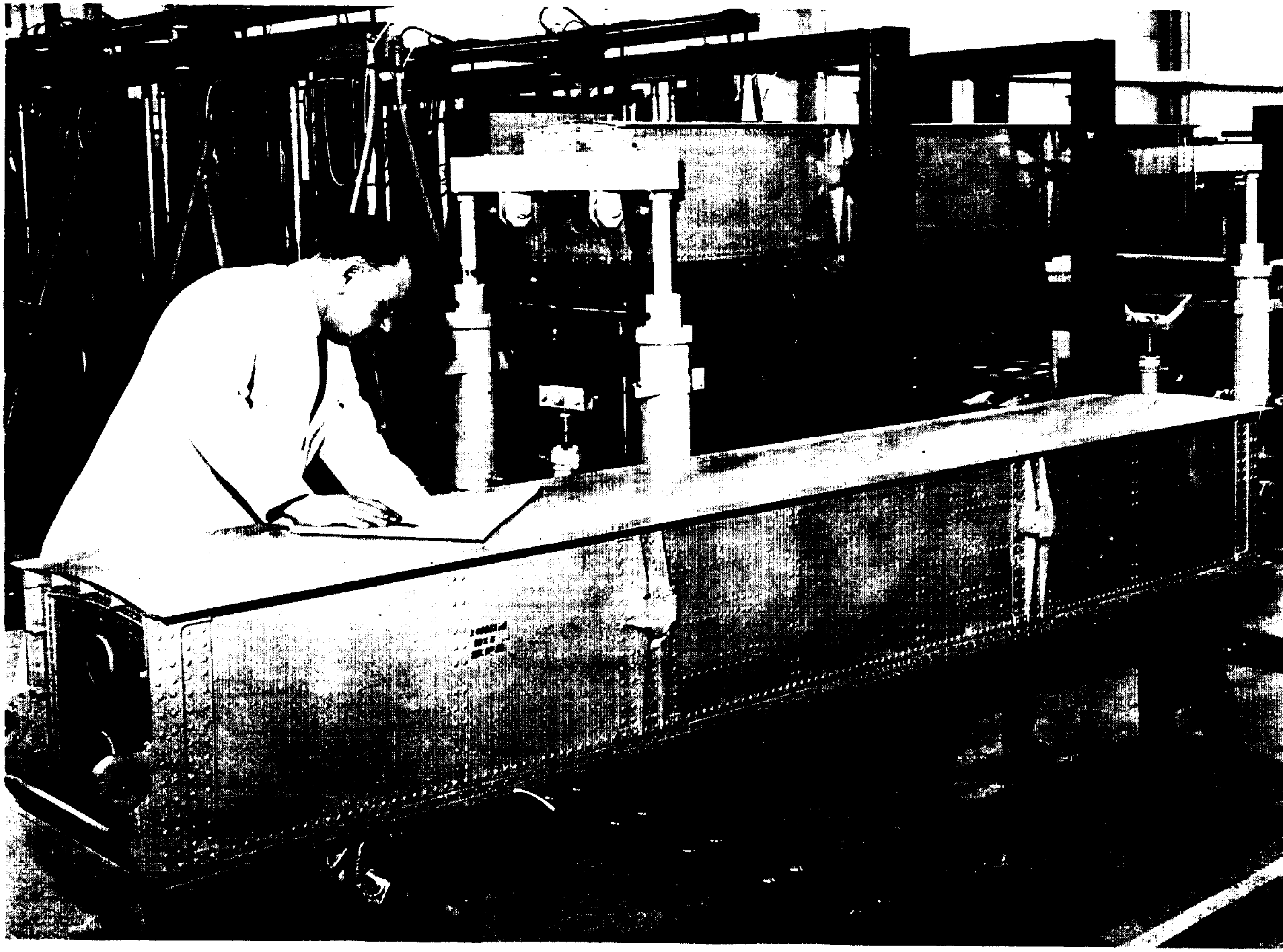


Figure 8.- Box-beam specimen for fatigue tests with thermal cycles.

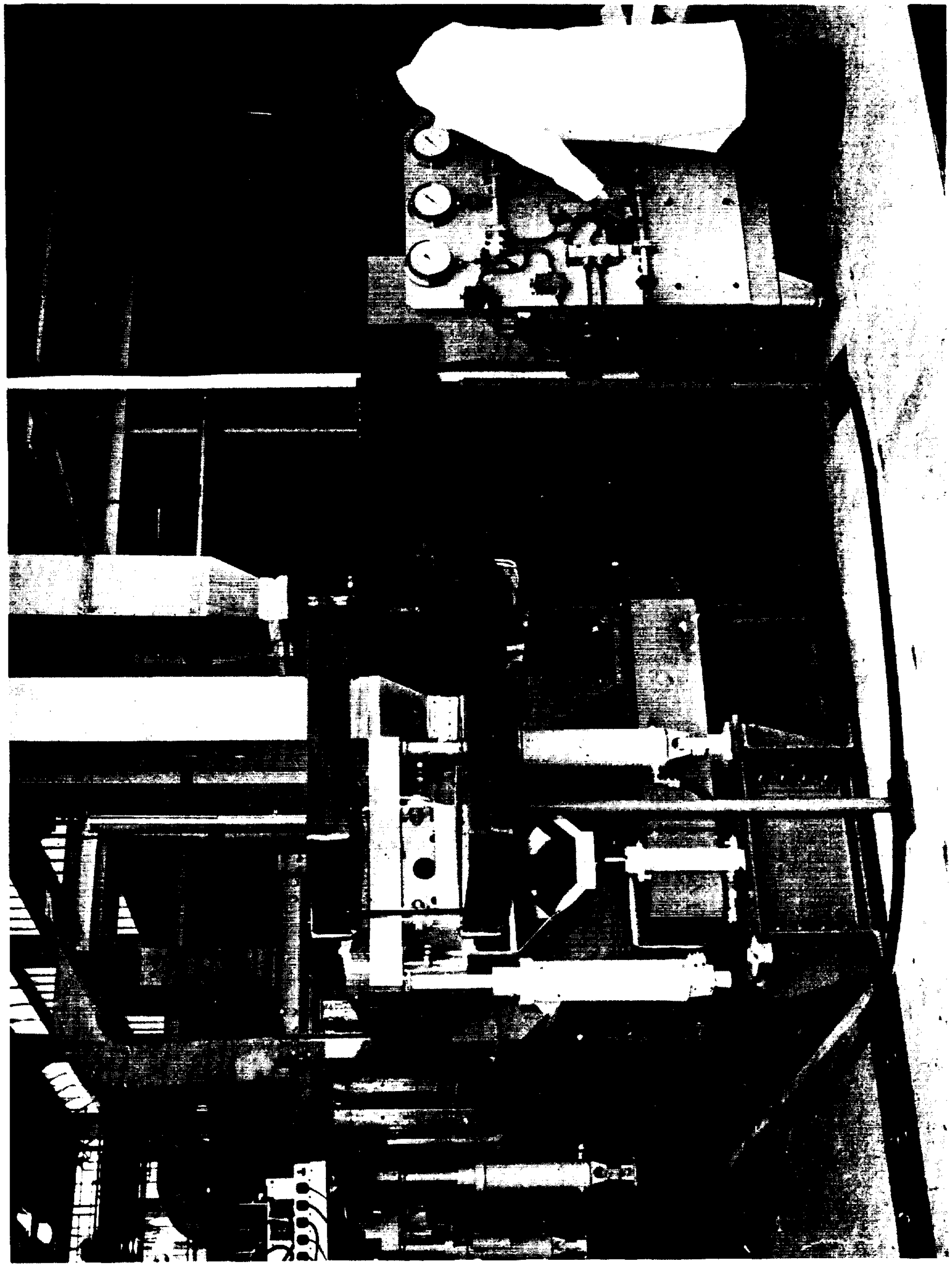


Figure 9.- Test rig for box-beam specimens at R.A.E.

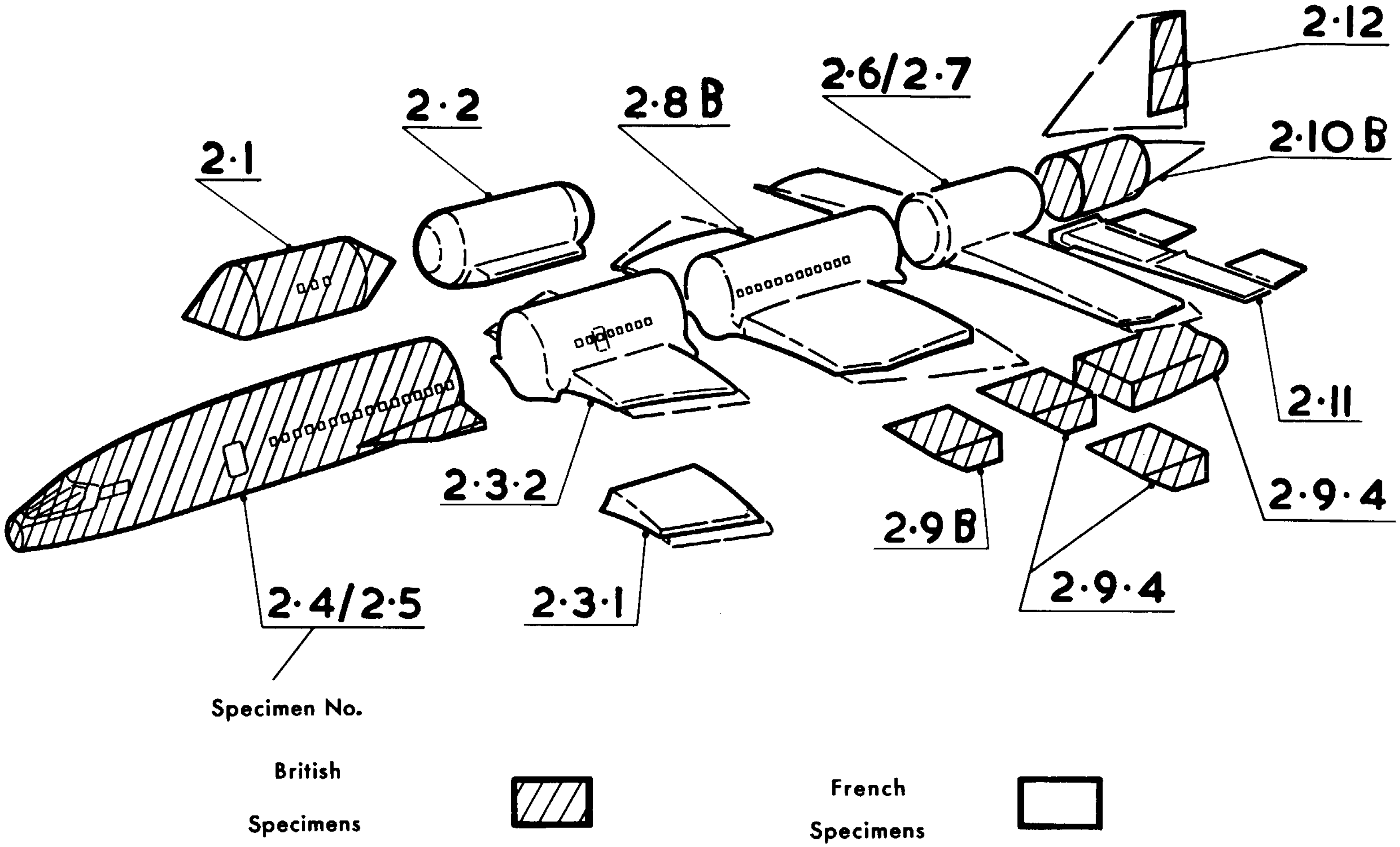


Figure 10.- Component test specimens.

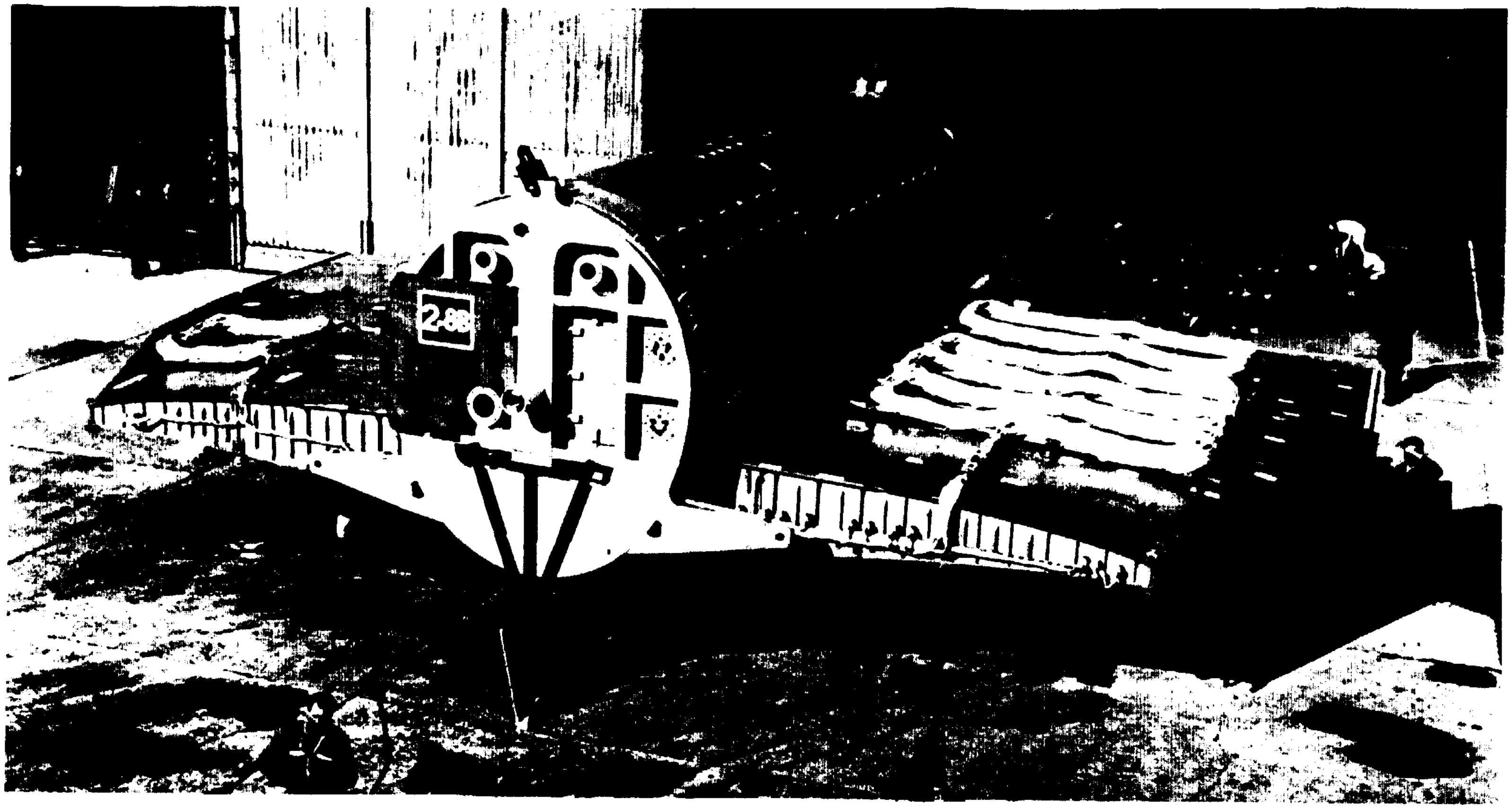


Figure 11.- Centre wing and fuselage specimen (2.8B).

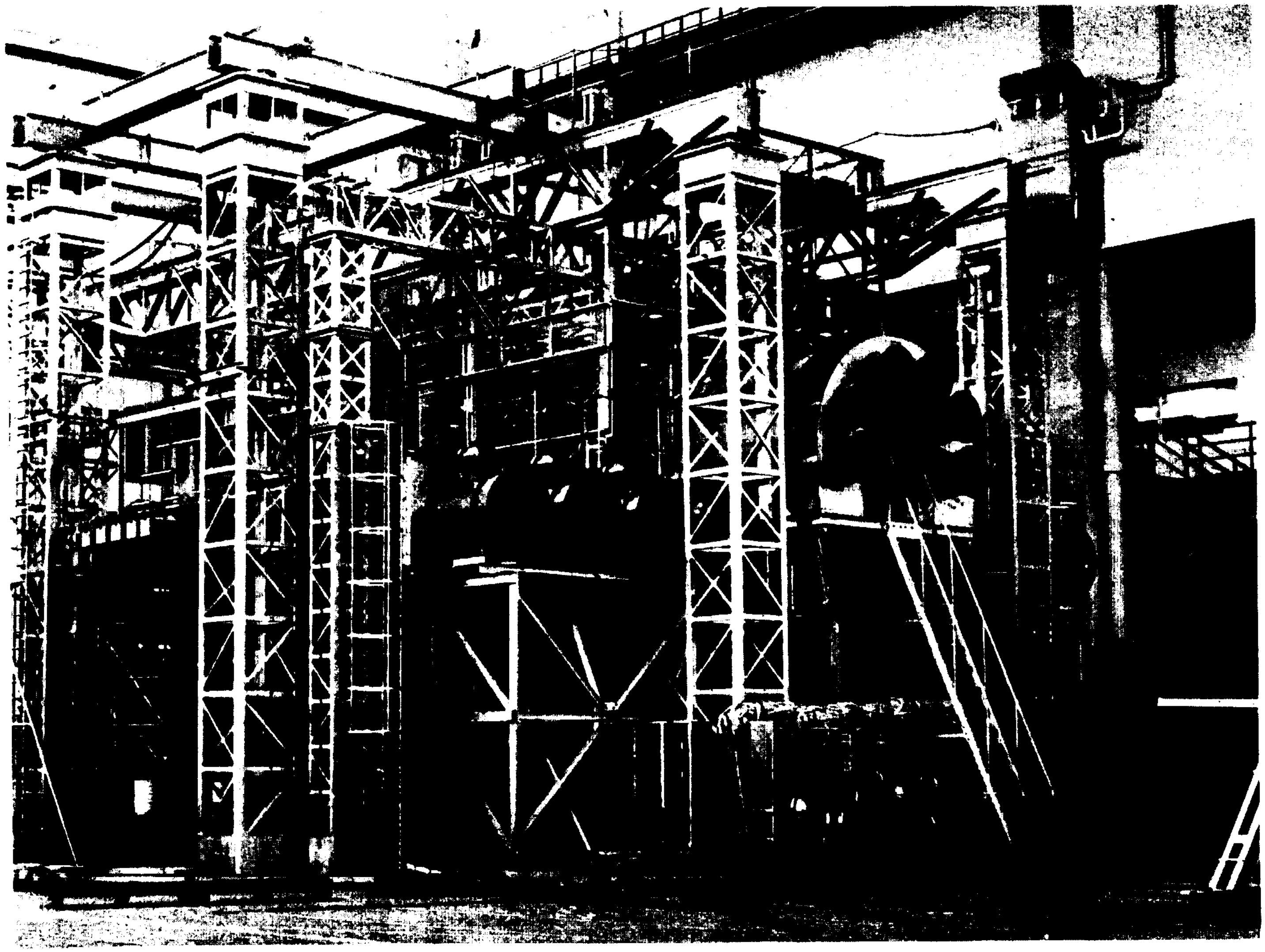


Figure 12.- Test rig for centre wing and fuselage specimen at C.E.A.T.

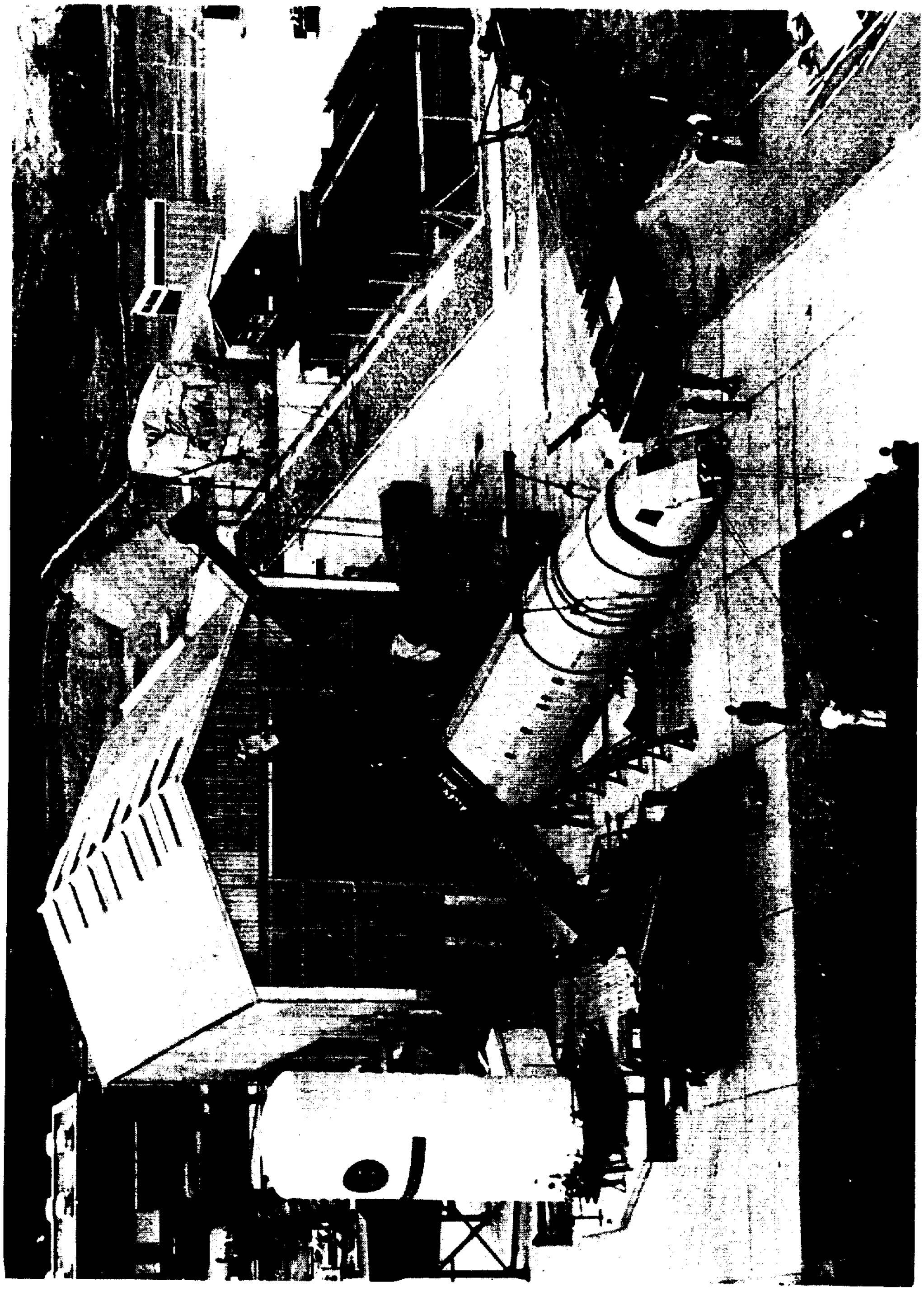


Figure 13.- Forward-fuselage specimen (2.4/2.5) and test rig at R.A.E.

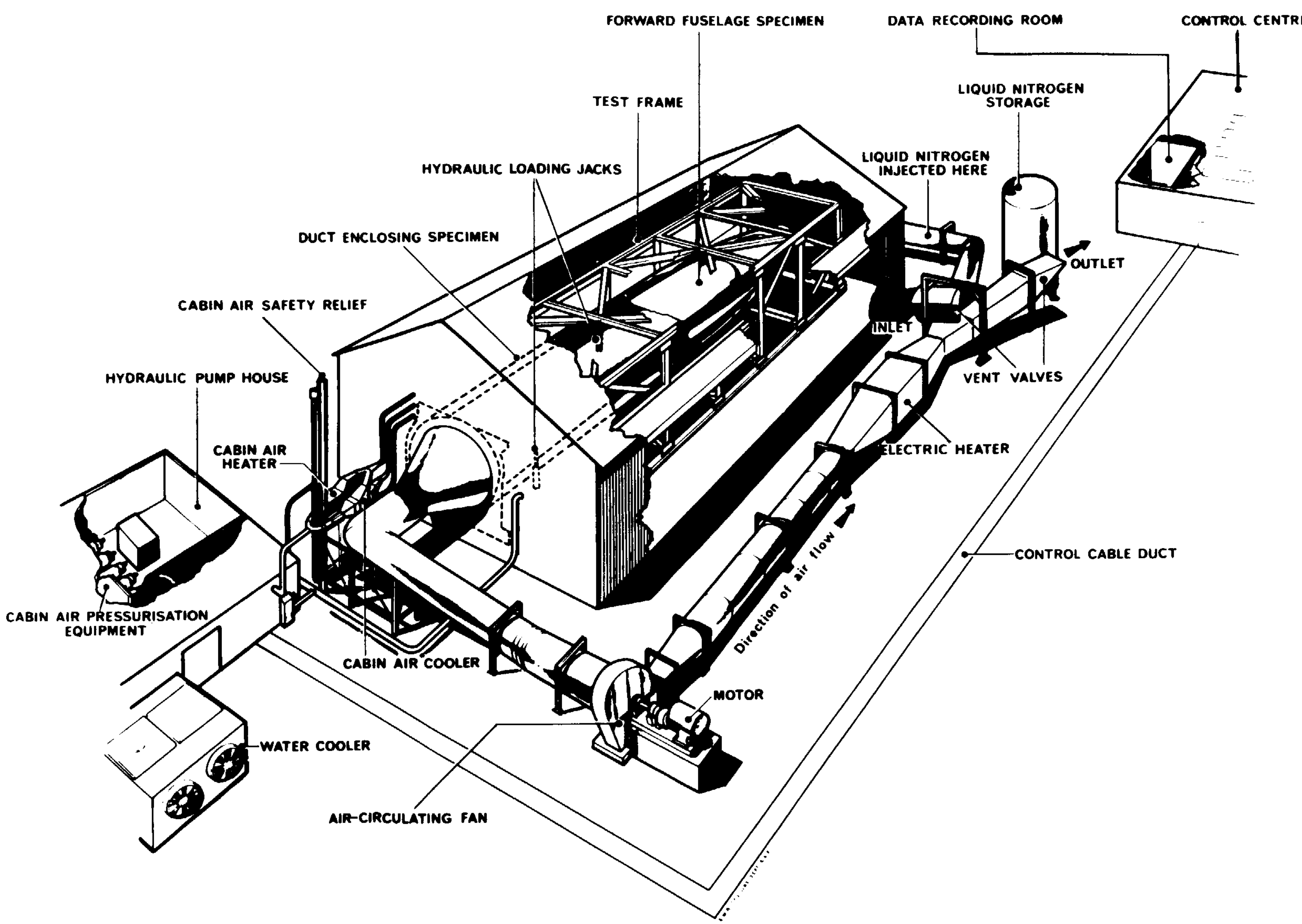


Figure 14.- Test rig for forward-fuselage specimen at R.A.E.

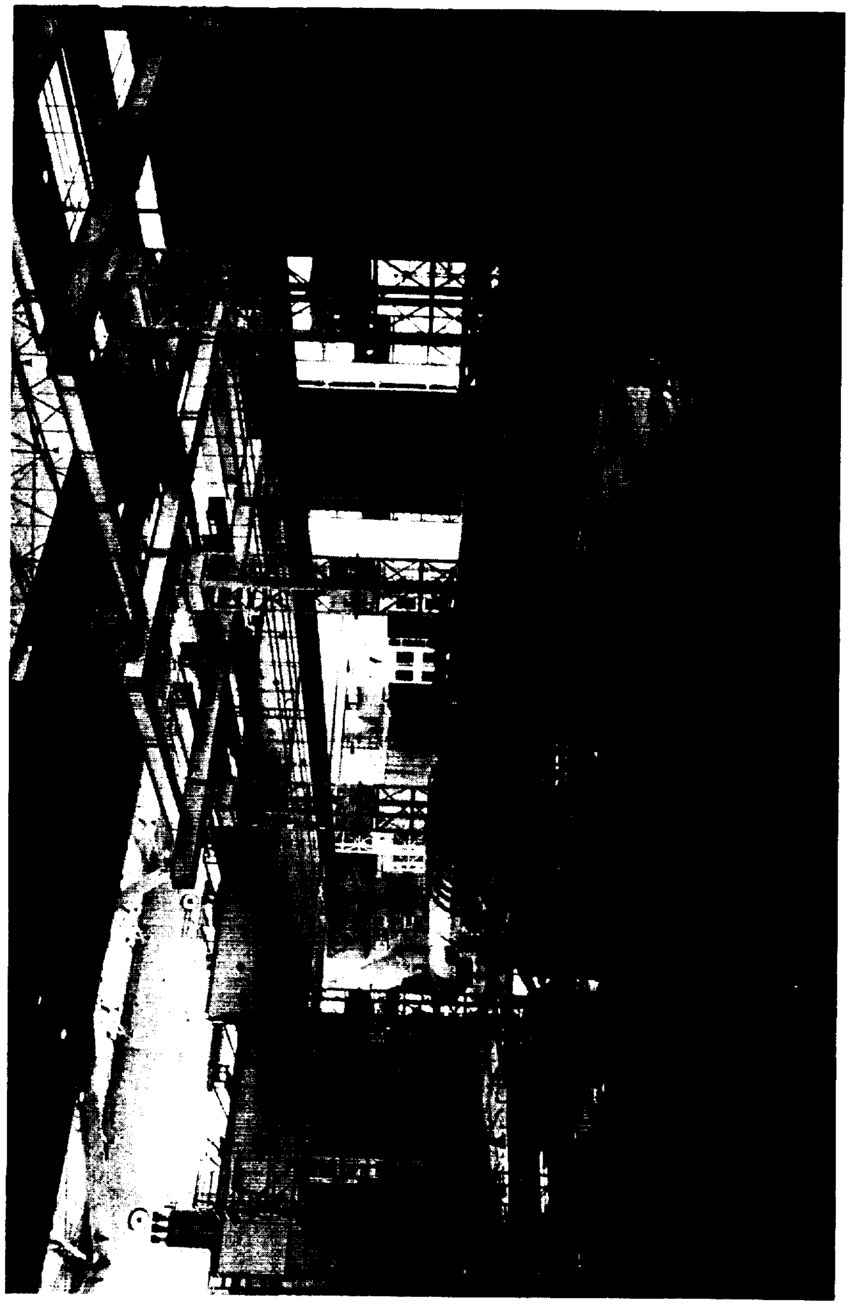


Figure 15.- Static-test specimen in test frame at C.E.A.T.

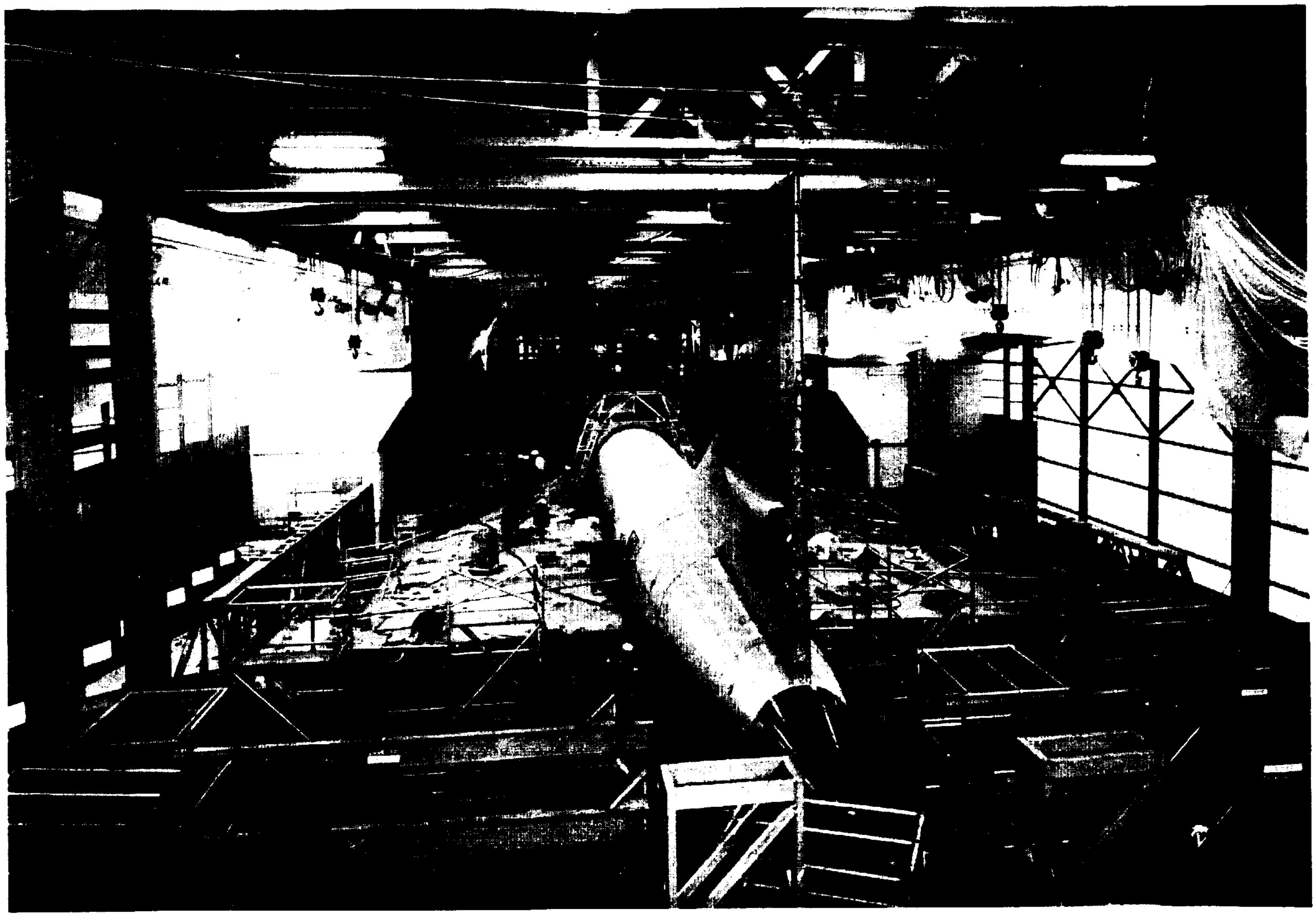


Figure 16.- Fatigue-test specimen in test frame at R.A.E.

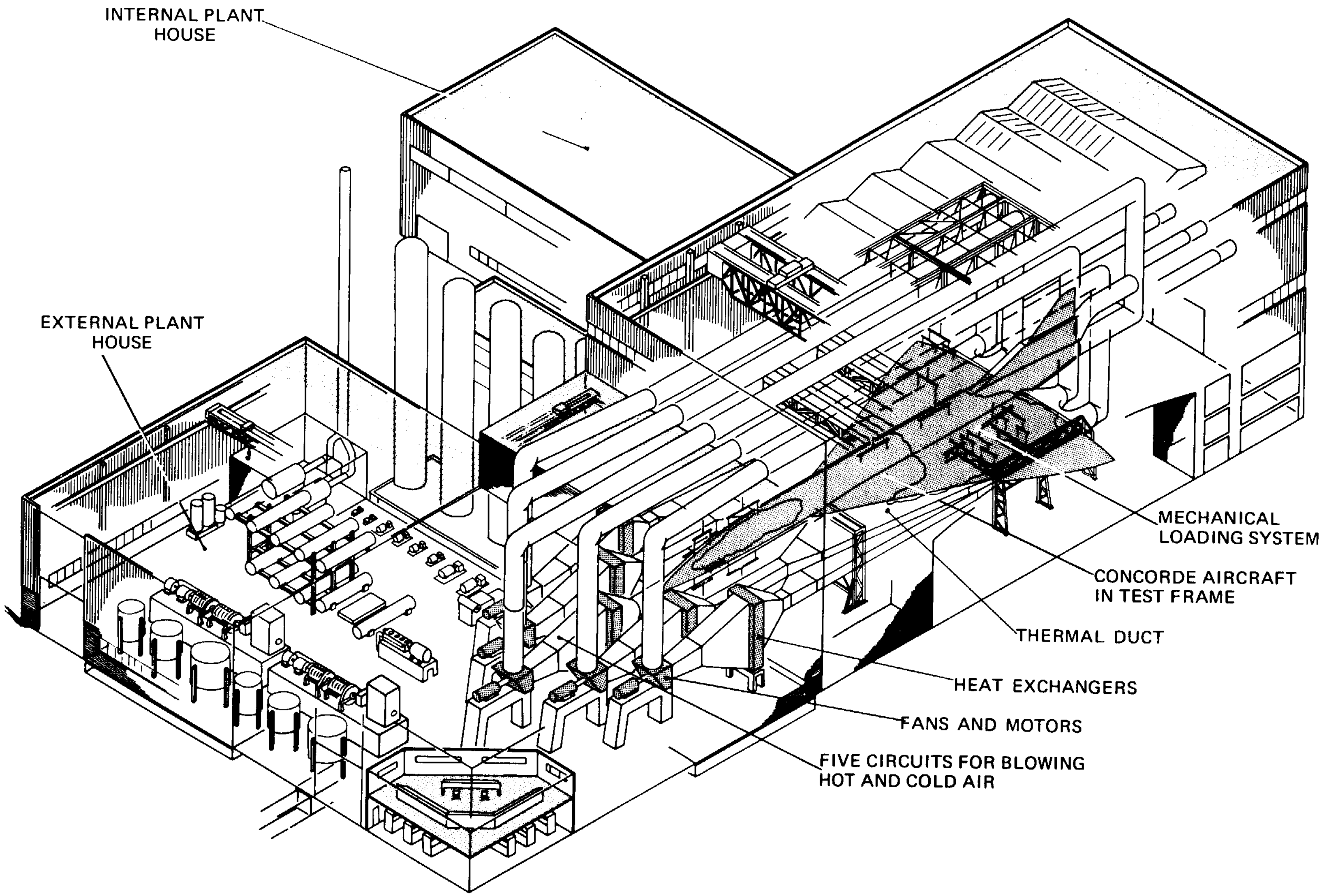


Figure 17.- Test rig for major fatigue test at R.A.E.

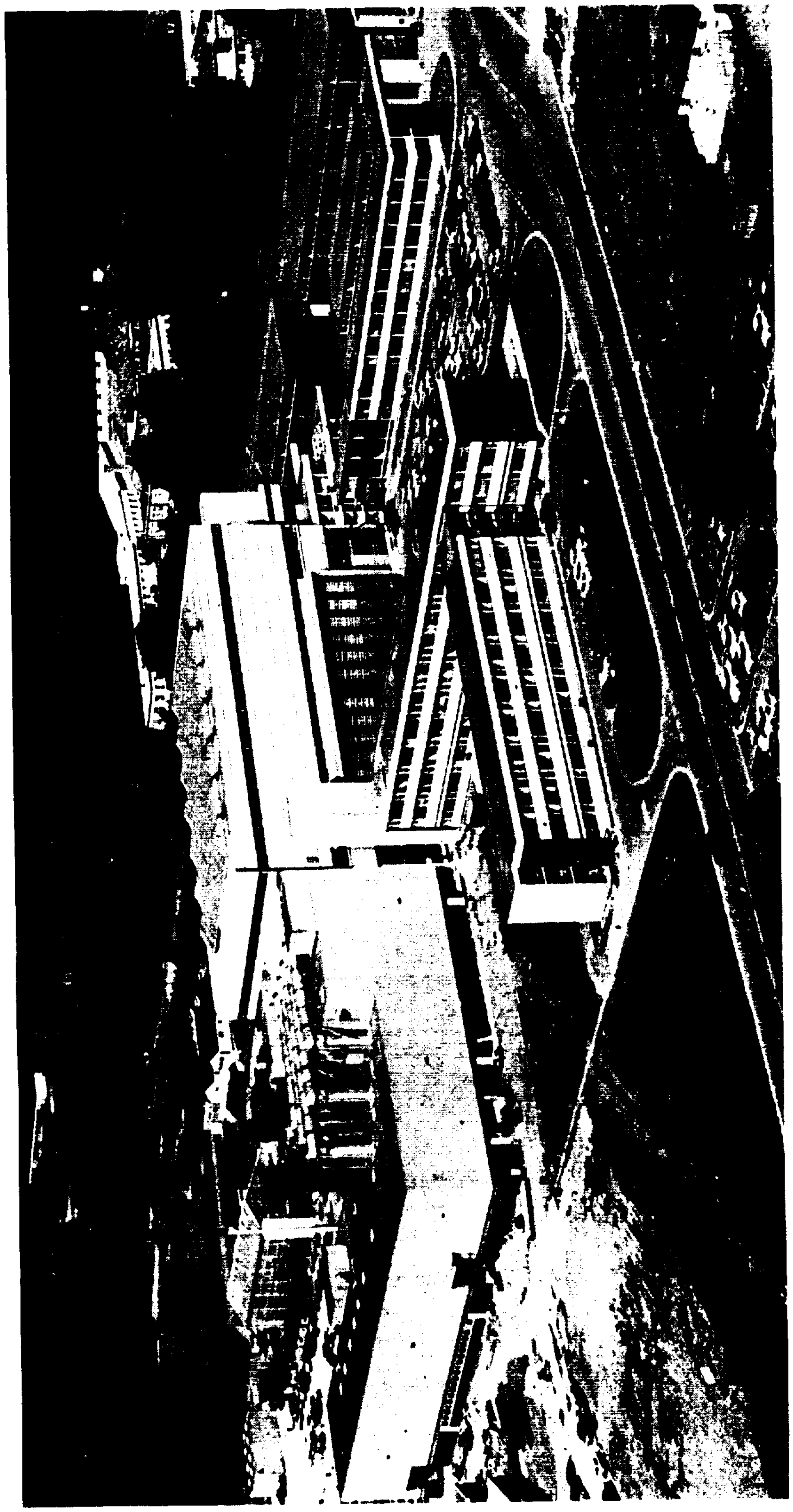


Figure 18.- Test facility at R.A.E.

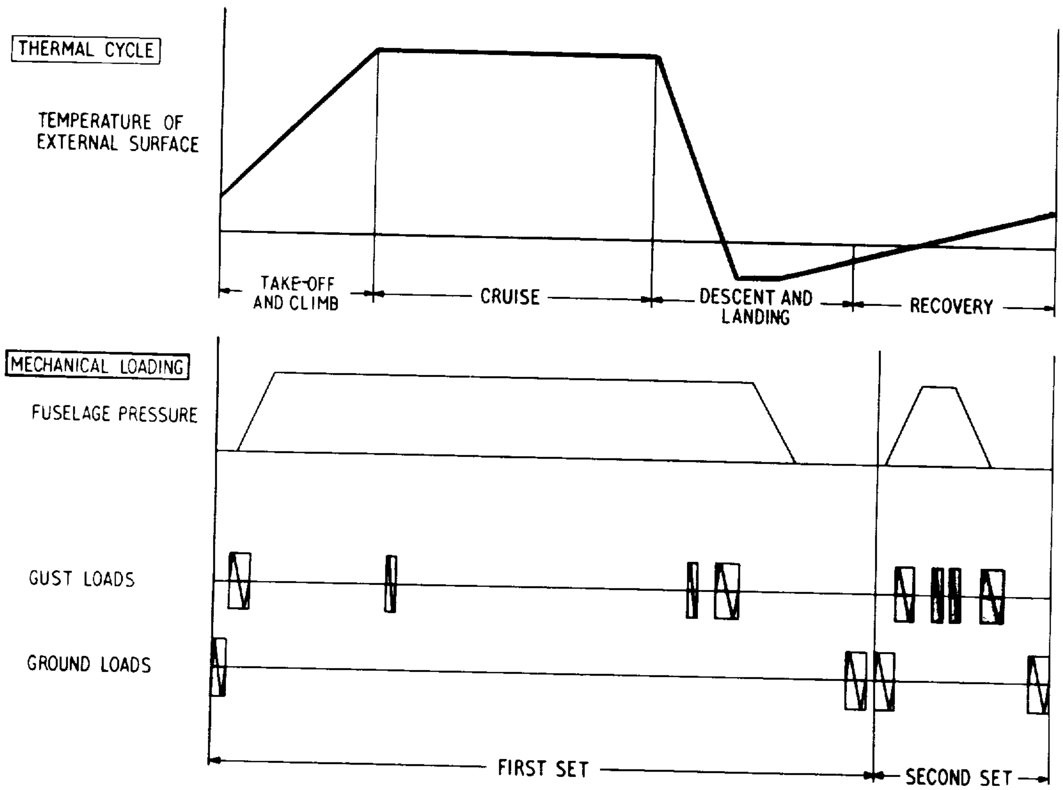


Figure 19.- Thermal cycle and mechanical loading in accelerated test cycle.

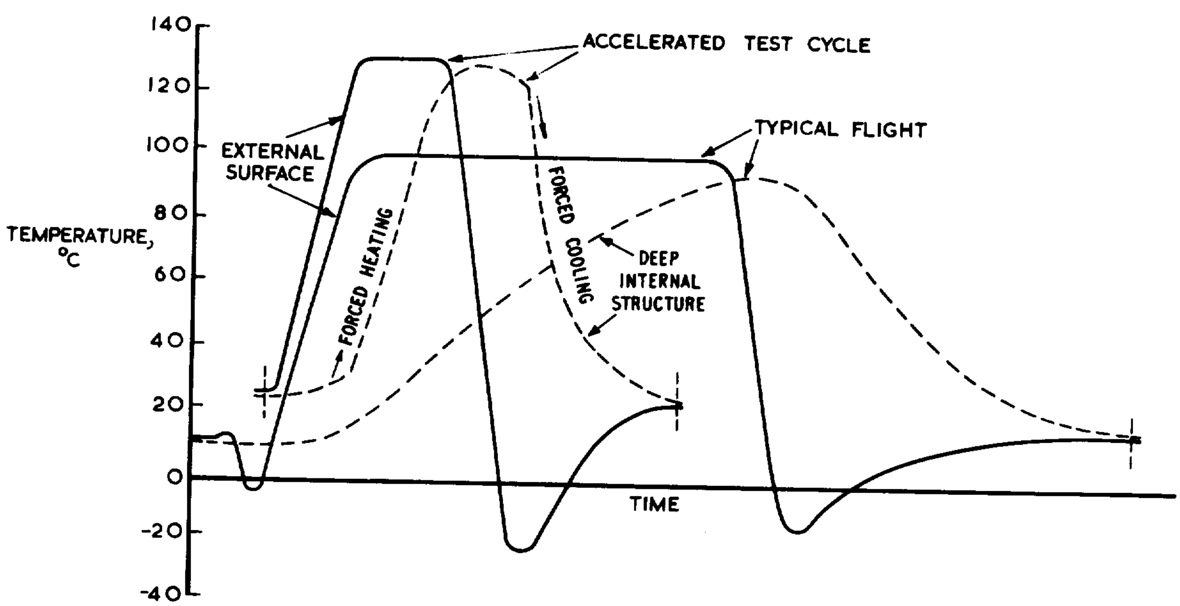


Figure 20.- Structural temperatures in accelerated test cycle and typical flight.

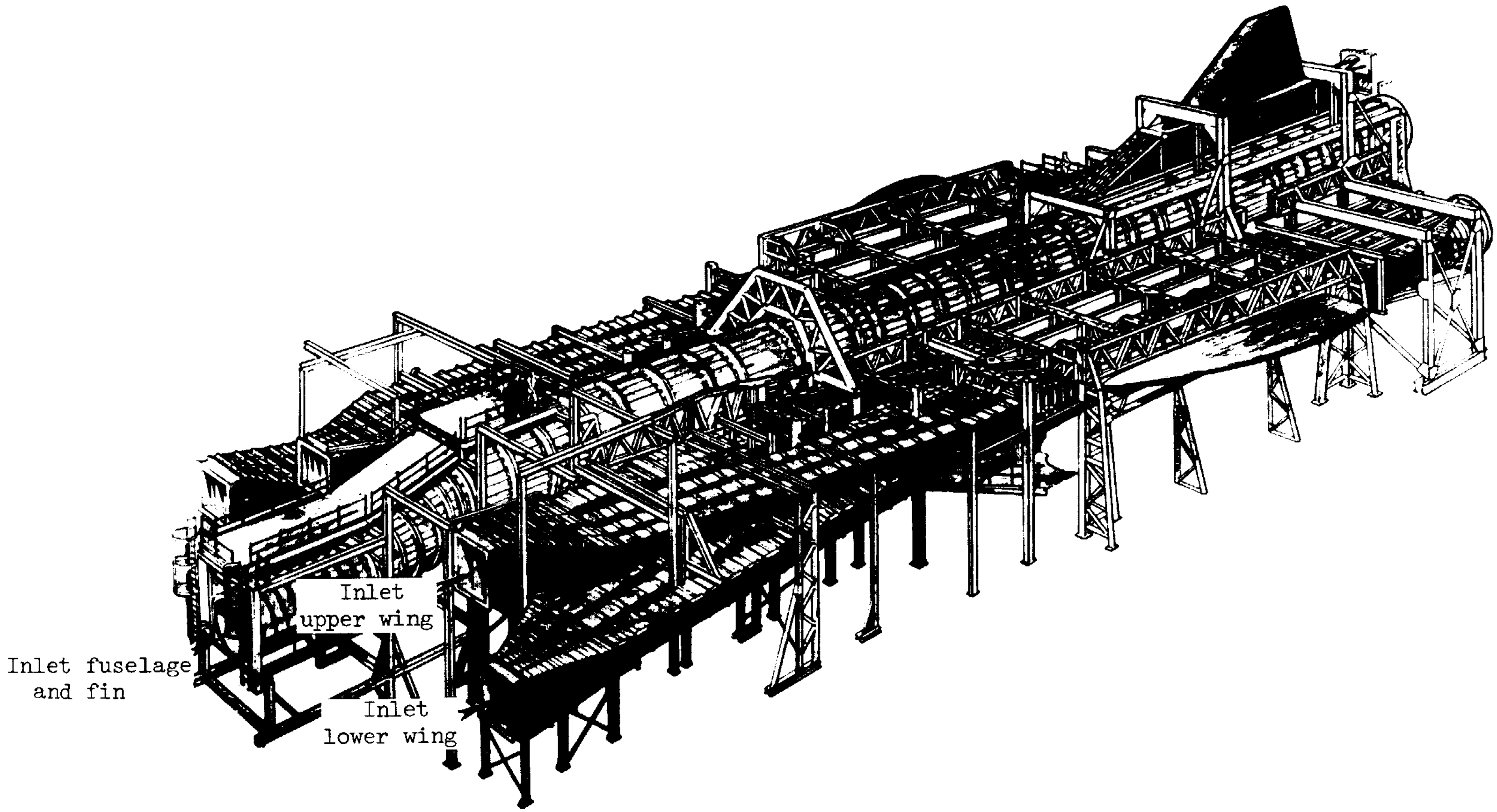


Figure 21.- Thermal duct surrounding specimen.

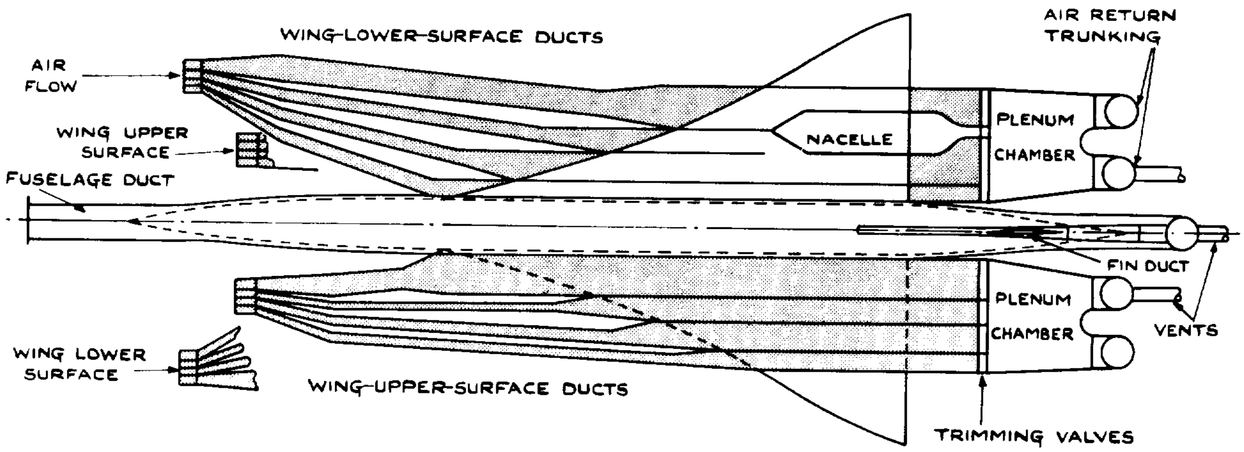


Figure 22.- Details of duct arrangement.

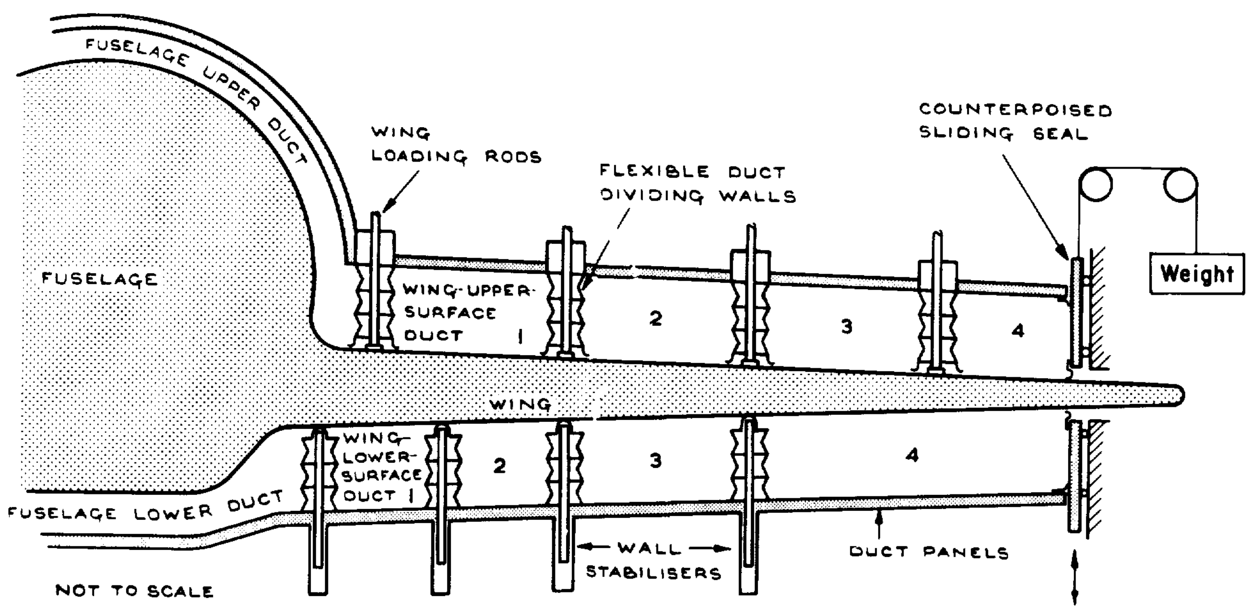


Figure 23.- Wing and fuselage duct dividers.

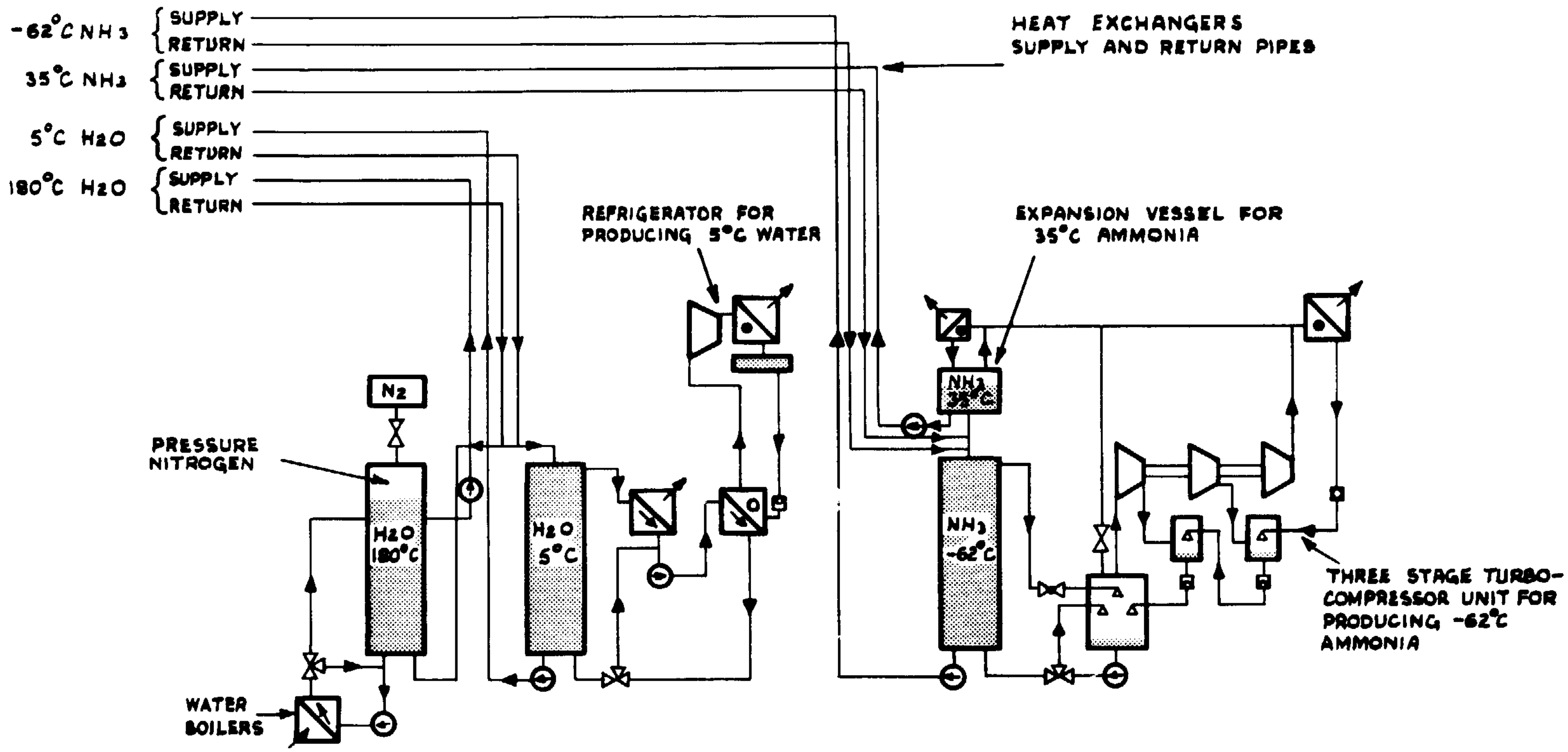
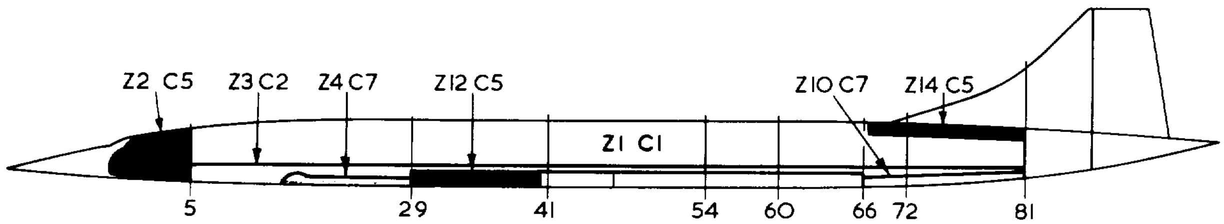


Figure 24.- Simplified flow diagram of external plant.

Ammonia refrigeration plant.

Three of the main air-circulating fans and motors.

Figure 25.- Views of external plant house.



CIRCUIT No	ZONE	LOCATION	IDENTITY
1	1	FR 5—FR 81	CABIN AIR CONDITIONING
2	3	FR 5—FR 81	FLOOR BEAMS
3	15 16	NACELLES NACELLES	4 ENGINE BAYS 4 INTAKES
4	11	FR69—FR72B RIBO—RIB 12	INSIDE WING AFT OF TANKS 5A AND 7A
5	2 12 13 14	FORWARD PRESS BLKHD TO FR5 FR 28—FR 38 FR 54—FR 58 FR 67—FR 81	FLIGHT DECK FUSELAGE WING MASKED AREA & FORWARD BAGGAGE HOLD KEEL BETWEEN MAIN U/C BAYS UNDER FIN INSIDE FUSELAGE
6	5 6	FR 26—FR 47 FR 38—FR 46	2 PARTS PORT & STBD FOREMOST WING TANKS 4 PARTS PORT & STBD WING TANKS, CENTRE TANK, CENTRE TANK, EXTENSION
7	4 7 8 9 10	FR 18—FR 28 FR 54—FR 60 FR 64—FR 72 FR 69—FR 72 FR 72—FR 81 FR 66—FR 73	NOSE U/C BAY MAIN U/C BAYS KEEL TO RIBS 21 INSIDE WINGS OVER ENG BAY RIBS 12-21 INSIDE WINGS AFT OF TANKS 2&3 RIBS 21-28 UNDER PRESSURE FLOOR & EQPT BAY

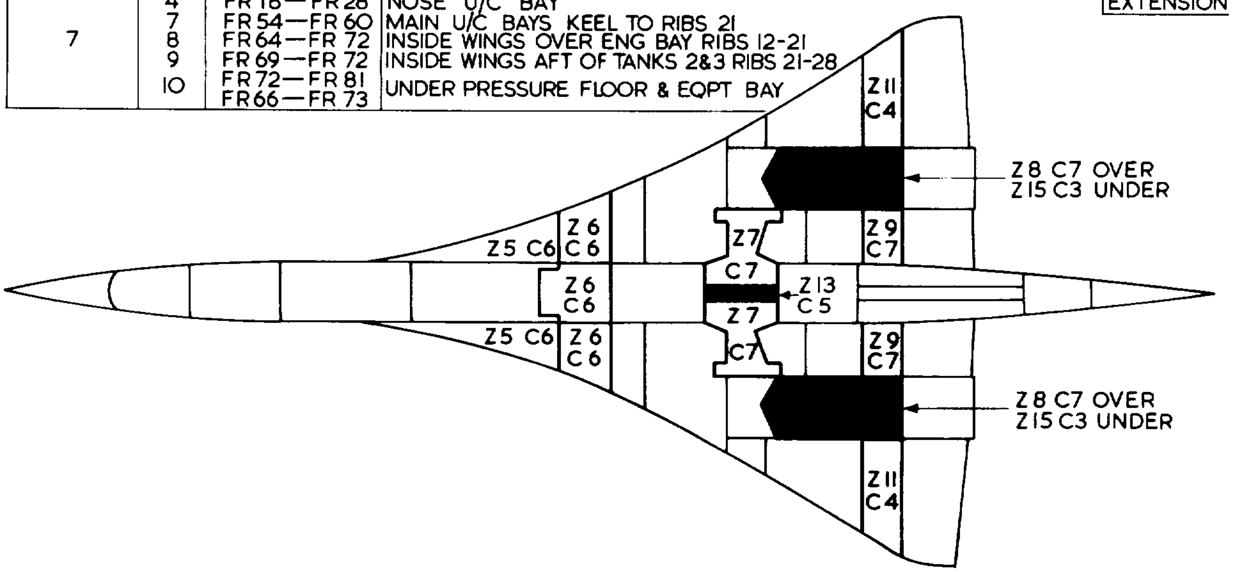


Figure 26.- Internal air-conditioning circuits.

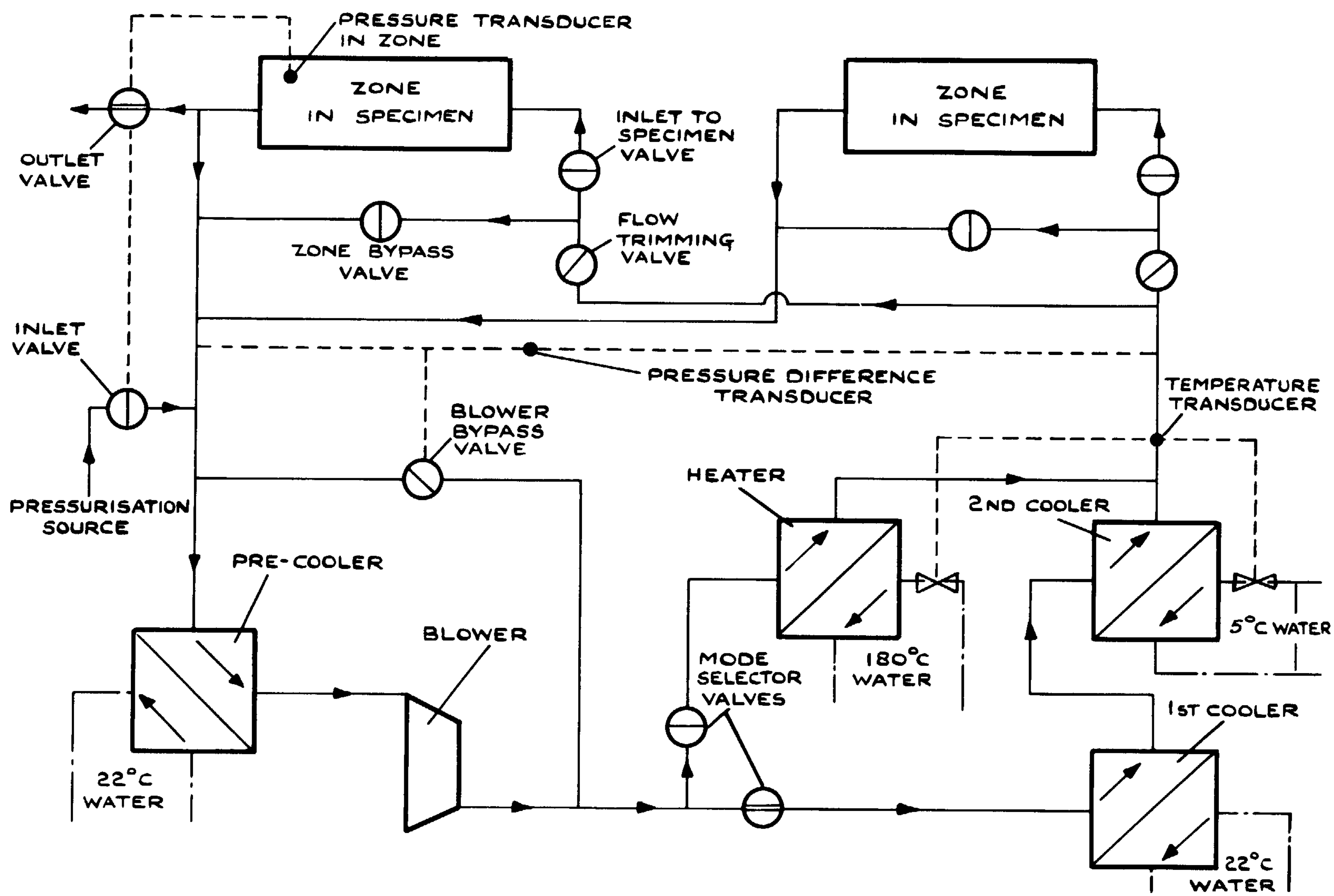


Figure 27.- Typical air circuit for internal plant.

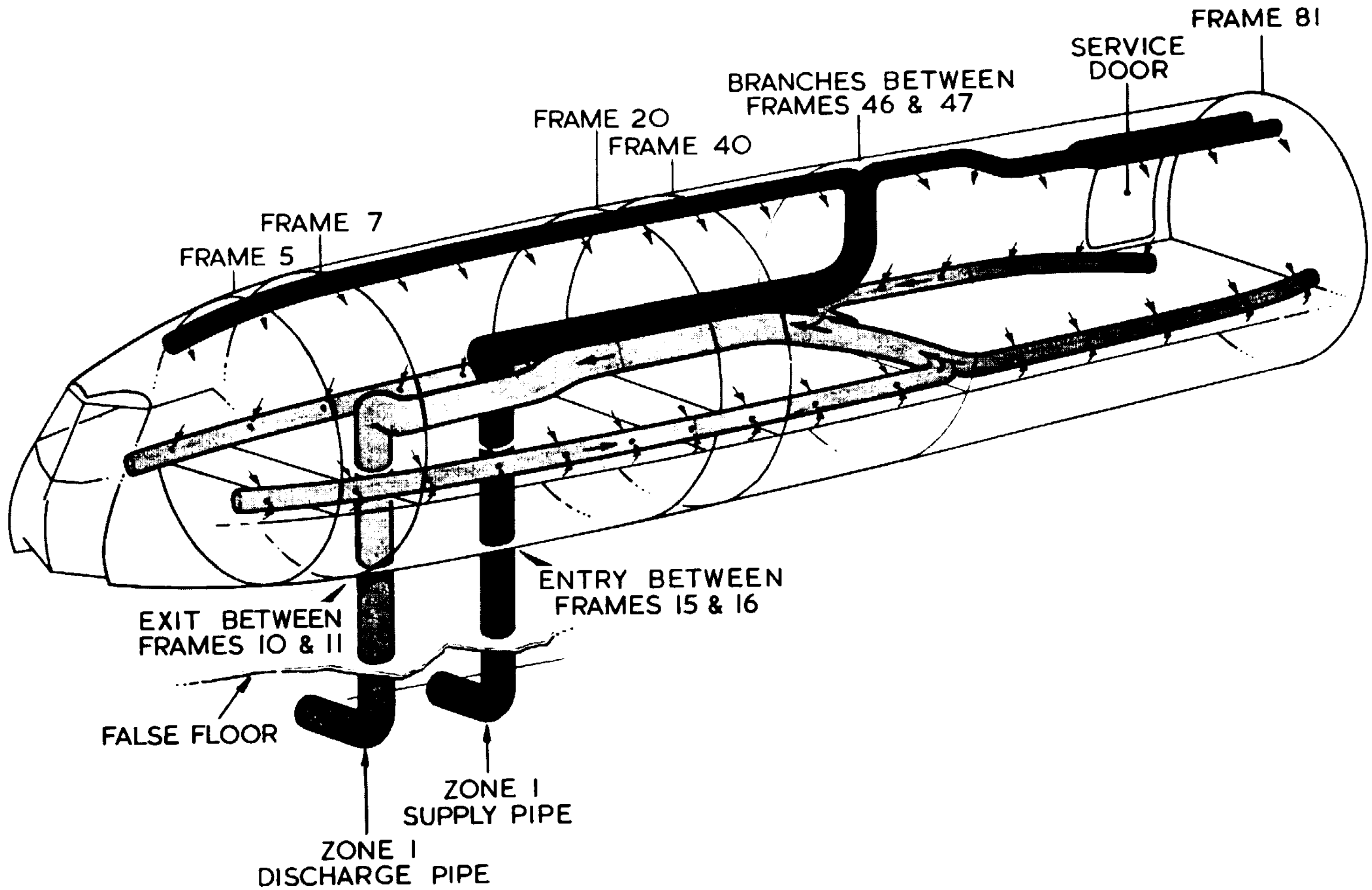


Figure 28.- Fuselage air-conditioning system.

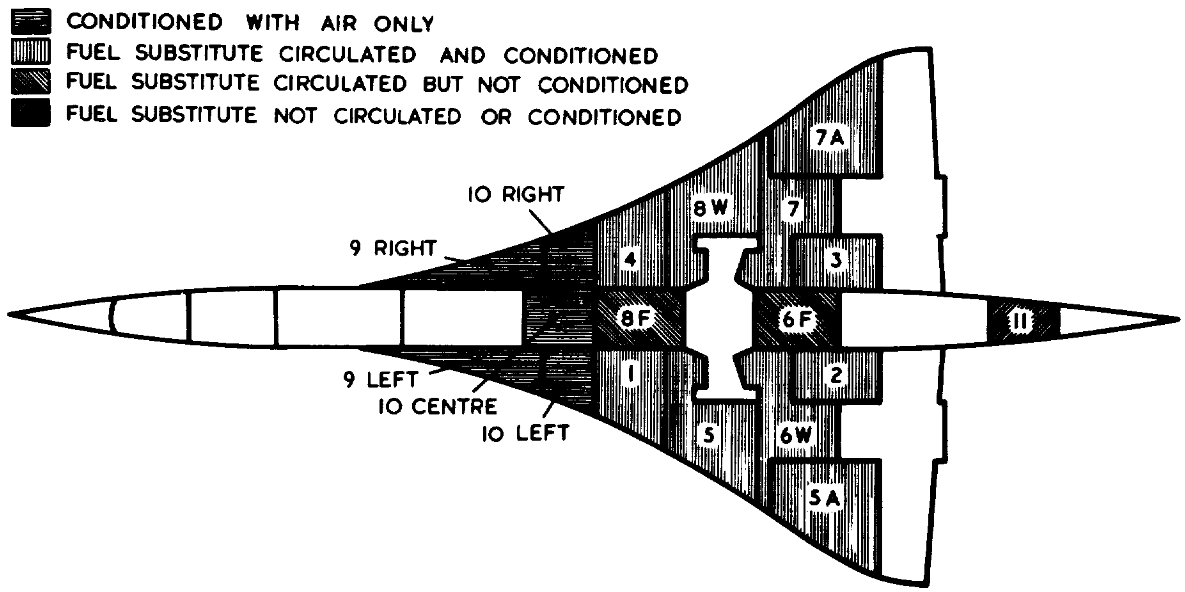


Figure 29.- Internal conditioning of fuel tanks.

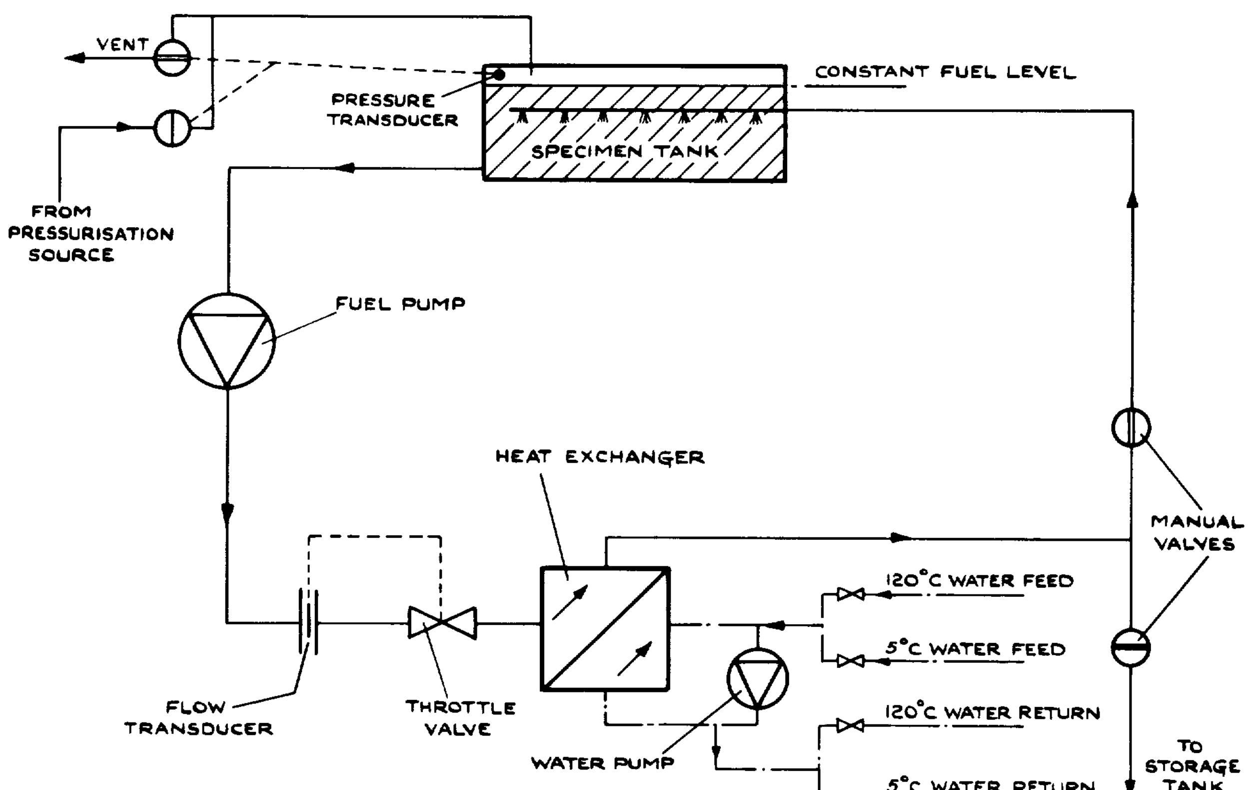


Figure 30.- Typical fuel system for internal plant.

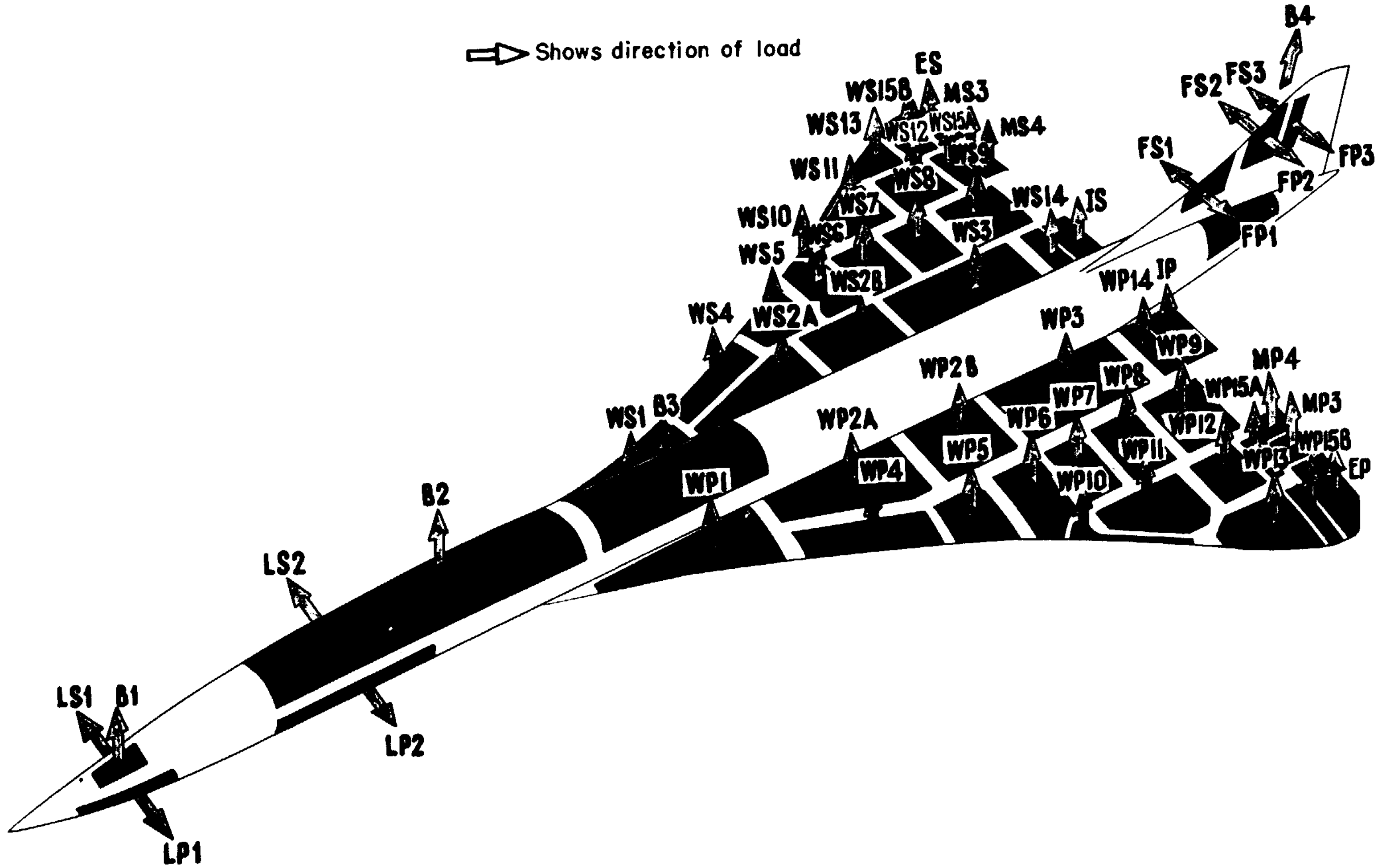


Figure 31.- Loading system, upper surface.

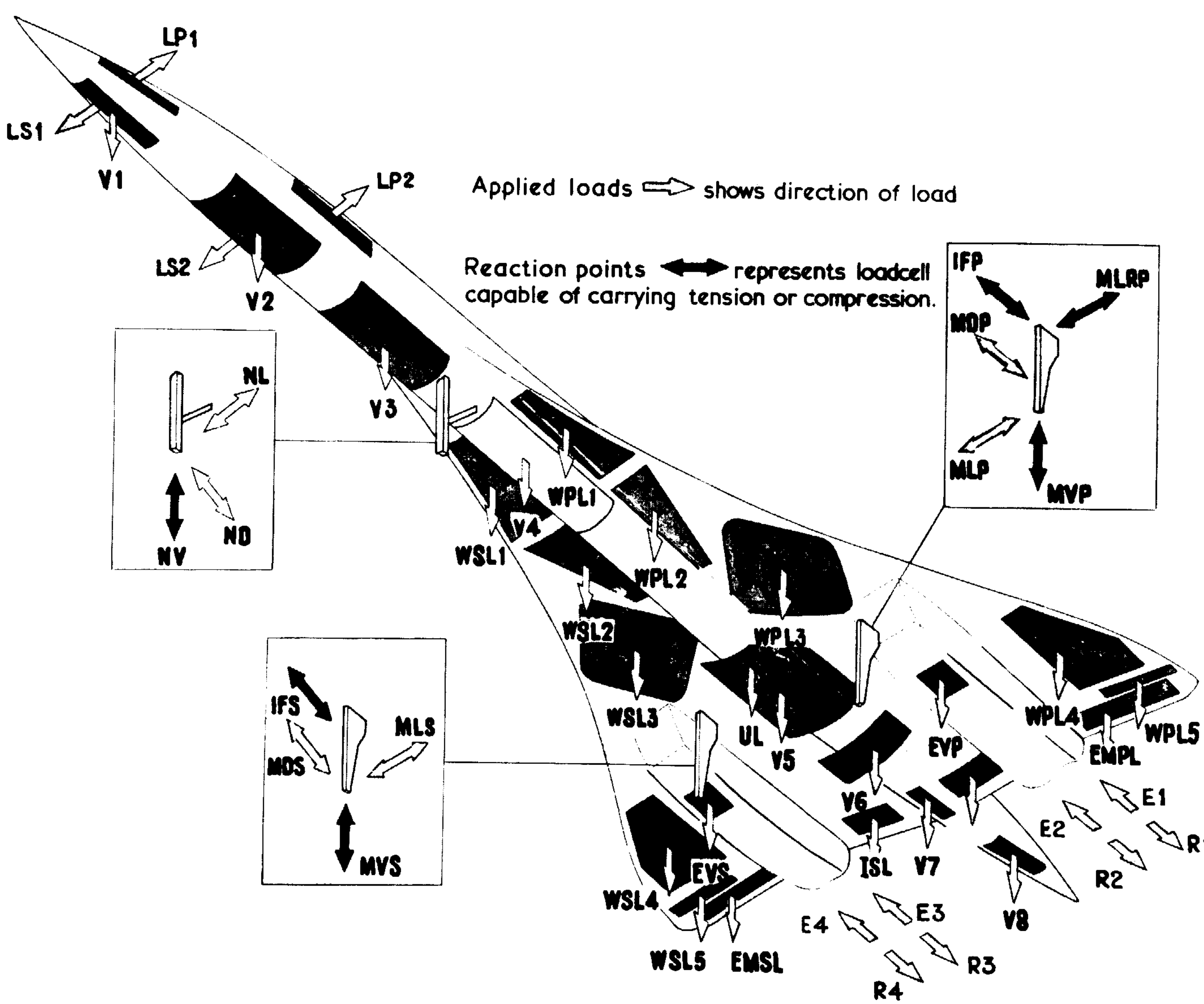


Figure 32.- Loading and reaction systems, lower surface.

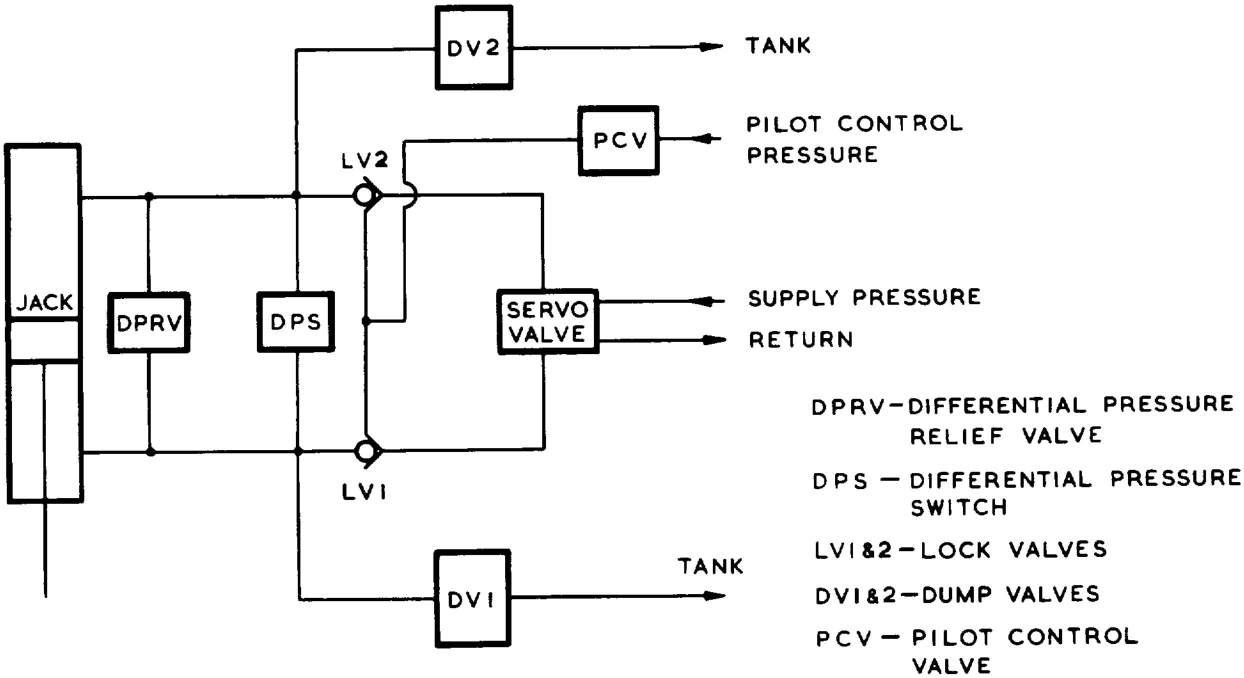


Figure 33.- Diagram of tension-jack-module circuit.

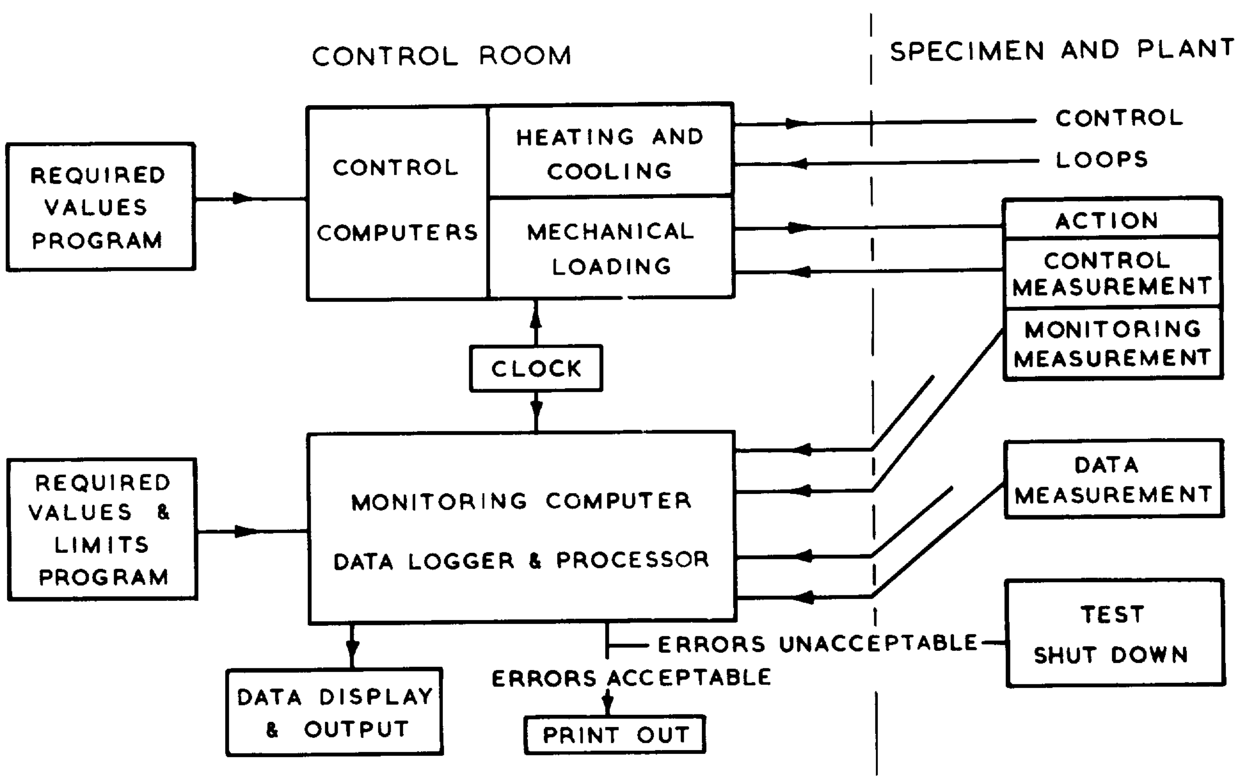


Figure 34.- Principles of control and monitoring system.

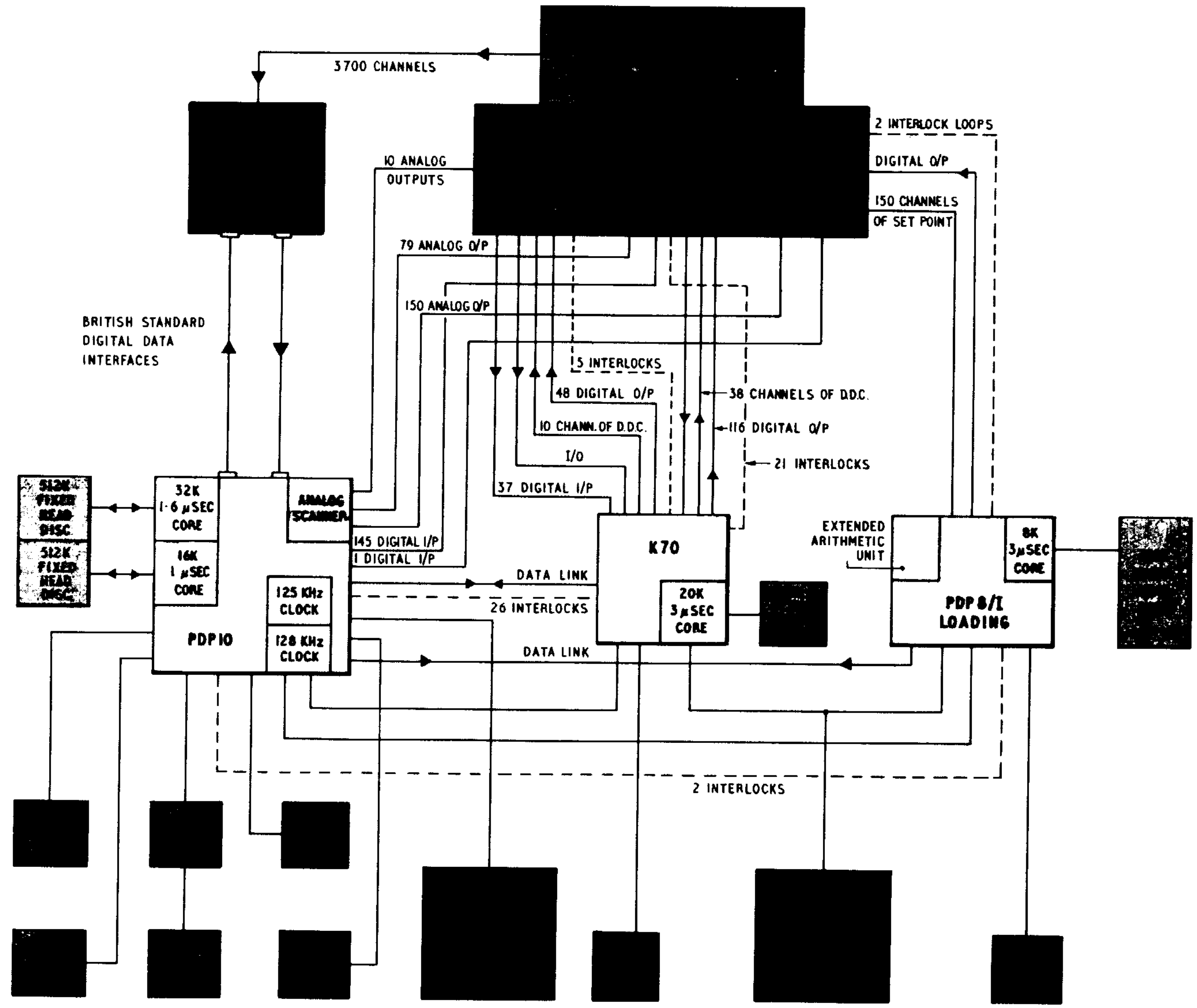


Figure 35.- Flow diagram of control and monitoring system.

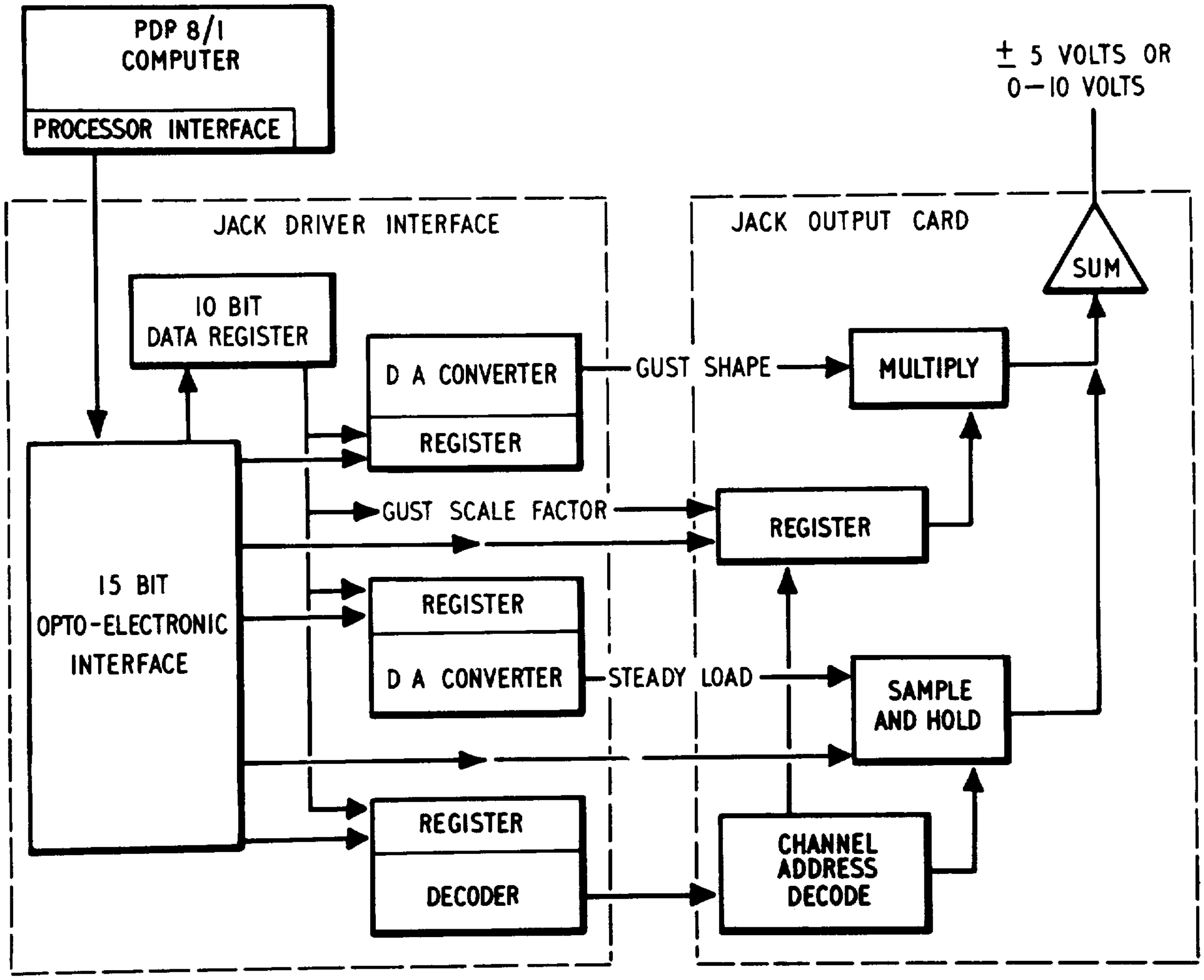


Figure 36.- Loading computer system.