DEPARTMENT OF AEROSPACE ENGINEERING

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UNIT II - ADVANCED PROPULSION TECHNIQUES

Rocket Testing Types of tests

Types of Rocket Testing/ Ground Testing and Flight Testing

Before rocket propulsion systems are put into operational use, they are subjected to several different types of tests, some of which are outlined below in the sequence in which they are normally performed.

- **Manufacturing inspection and fabrication tests on individual parts** (dimensional inspection, pressure tests, x-rays, leak checks, electric continuity, electromechanical checks, etc.).
- **Component tests** (functional and operational tests on igniters, valves, thrusters, controls, injectors, structures, etc.).
- **Static rocket system tests** (with complete propulsion system on test stand):

  o Partial or simulated rocket operation (for proper function, calibration, ignition, operation--often without establishing full thrust or operating for the full duration);

  o Complete propulsion system tests (under rated conditions, off-design conditions, with intentional variations in environment or calibration). For a reusable or restartable rocket propulsion system this can include many starts, long-duration endurance tests, and post operational inspections and reconditioning.
- **Static vehicle tests** (when rocket propulsion system is installed in a restrained, nonflying vehicle or stage).
- **Flight tests:**

- o With a specially instrumented propulsion system in a developmental flight test vehicle;
- o With a production vehicle.

Each of these five types of tests can be performed on at least three basic types of programs:

- Research on and development or improvement of a new (or modified) rocket engine or motor or their propellants or components.
- Evaluation of the suitability of a new (or modified) rocket engine or motor for a specified application or for flight readiness.
- Production and quality assurance of a rocket propulsion system.

The first two types of programs are concerned with a novel or modified device and often involve the testing and measurement of new concepts or phenomena using experimental rockets. The testing of a new solid propellant grain, the development of a novel control valve assembly, and the measurement of the thermal expansion of a nozzle exhaust cone during firing operation are examples.

Production tests concern themselves with the measurement of a few basic parameters on production propulsion systems to assure that the performance, reliability, and operation are within specified tolerance limits. If the number of units is large, the test equipment and instrumentation used for these tests are usually partly or fully automated and designed to permit the testing, measurement, recording, and evaluation in a minimum amount of time.

Types of Tests Facilities and Safeguards

For chemical rocket propulsion systems, each test facility usually has the following major systems or components:

- A test cell or test bay where the article to be tested is mounted, usually in a special test fixture. If the test is hazardous, the test facility must have provisions to protect operating personnel and to limit damage in case of an accident.
- An instrumentation system with associated computers for sensing, maintaining, measuring, analyzing, correcting, and recording various physical and chemical parameters. It usually includes calibration systems and timers to accurately synchronize the measurements.
- A control system for starting, stopping, and changing the operating conditions.
- Systems for handling heavy or awkward assemblies, supplying liquid propellant, and providing maintenance, security, and safety.

- For highly toxic propellants and toxic plume gases it has been required to capture the hazardous gas or vapor (firing inside a closed duct system), remove almost all of the hazardous ingredients (e.g., by wet scrubbing and/or chemical treatment), allow the release of the nontoxic portion of the cleaned gases, and safely dispose of any toxic solid or liquid residues from the chemical treatment. With an exhaust gas containing fluorine, for example, the removal of much of this toxic gas can be achieved by scrubbing it with water that contains dissolved calcium; it will then form calcium fluoride, which can be precipitated and removed.
- In some tests specialized test equipment and unique facilities are needed to conduct static testing under different environmental conditions or under simulated emergency conditions. For example, high and low ambient temperature tests of large motors may require a temperature-controlled enclosure around the motor; a rugged explosion-resistant facility is needed for bullet impact tests of propellant- loaded missile systems and also for cook-off tests, where gasoline or rocket fuel is burned with air below a stored missile. Similarly, special equipment is needed for vibration testing, measuring thrust vector forces and moments in three dimensions, or determining total impulse for very short pulse durations at low thrust.

Most rocket propulsion testing is now accomplished in sophisticated facilities under closely controlled conditions. Modern rocket test facilities are frequently located several miles from the nearest community to prevent or minimize effects of excessive noise, vibrations, explosions, and toxic exhaust clouds.

Figure 20-1 shows one type of an **open-air test stand for vertically down-firing large liquid propellant thrust chambers** (100,000 to 2 million pounds thrust). It is best to fire the propulsion system in a direction (vertical or horizontal) similar to the actual flight condition.

Figure 20-2 shows a **simulated altitude test facility for rockets** of about 10.5 metric tons thrust force (46,000 lbf). It requires a vacuum chamber in which to mount the engine, a set of steam ejectors to create a vacuum, water to reduce the gas temperature, and a cooled diffuser. With the flow of chemical rocket propellant combustion gases it is impossible to maintain a high vacuum in these kinds of facilities; typically, between 15 to 4 torr (20 to 35 km altitude) can be maintained. This type of test facility allows the operation of rocket propulsion systems with high-nozzle-area ratios that would normally experience flow separation at sea-level ambient pressures.

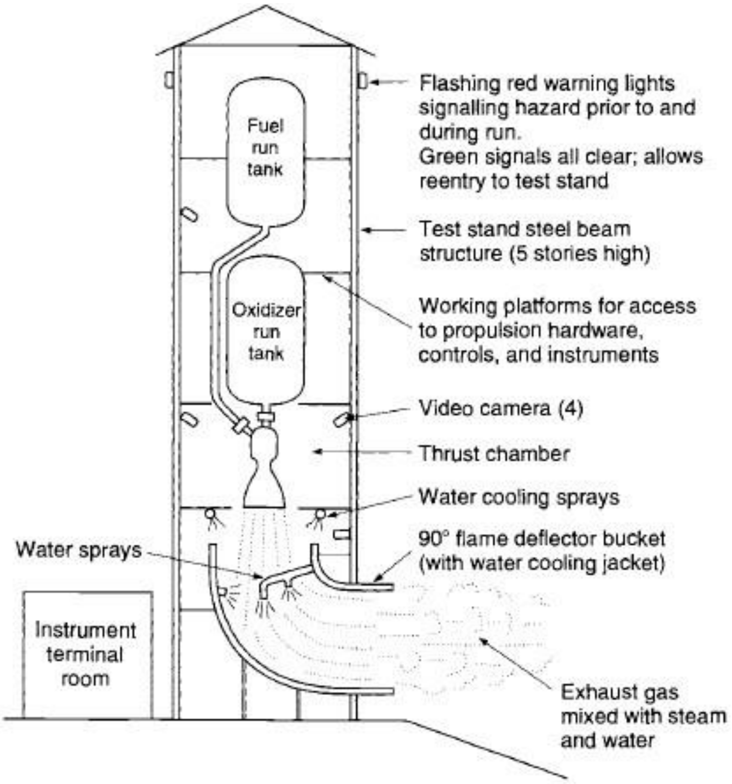

FIGURE 20–1. Simplified sketch of a typical static test stand for a large liquid propellant thrust chamber firing vertically downward. Only a small part of the exhaust plume (between the nozzle exit and flame bucket entrance) is visible. The flame bucket turns the exhaust gas plume by 90° (horizontal) and prevents the flame from digging a hole in the ground. Not shown here are cranes, equipment for installing or removing a thrust chamber, safety railings, high pressure gas tank, the propellant tank pressurization system, separate storage tanks for fuel, oxidizer, or cooling water with their feed systems, or a small workshop.

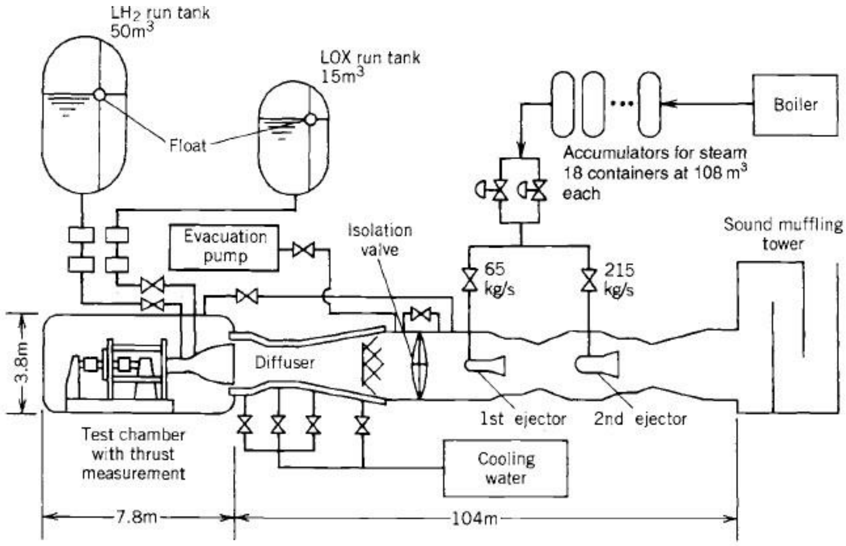

FIGURE 20–2. Simplified diagram of a simulated altitude, horizontal firing test facility for the LE-5 Japanese-designed thrust chamber (liquid oxygen–liquid hydrogen propellants) showing the method of creating a vacuum (6 torr during operation and 13 torr prior to start). The operating duration is limited to about 10 min by the capacity of the steam storage. (Reproduced from Ref. 20–1 with permission of the AIAA.)

Prior to performing any test, it is common practice to train the test crew and go through repeated dry runs, to familiarize each person with his or her responsibilities and procedures, including the emergency procedures.

Typical personnel and plant security or safety provisions in a modern test facility include the following:

- Concrete-walled blockhouse or control stations for the protection of personnel and instruments remote from the actual rocket propulsion location.
- Remote control, indication, and recording of all hazardous operations and measurements; isolation of propellants from the instrumentation and control room.
- Automatic or manual water deluge and fire-extinguishing systems.
- Closed circuit television systems for remotely viewing the test.
- Warning signals (siren, bells, horns, lights, speakers) to notify personnel to clear the test area prior to a test, and an all-clear signal when the conditions are no longer hazardous.
- Quantity and distance restrictions on liquid propellant tankage and solid propellant storage to minimize damage in the event of explosions; separation of liquid fuels and oxidizers.
- Barricades around hazardous test articles to reduce shrapnel damage in the event of a blast.
- Explosion-proof electrical systems, spark-proof shoes, and nonspark hand tools to prevent ignition of flammable materials.
- For certain propellants also safety clothing, including propellant- and fire-resistant suits, face masks and shields, gloves, special shoes, and hard hats.
- Rigid enforcement of rules governing area access, smoking, safety inspections, and so forth.
- Limitations on the number of personnel that may be in a hazardous area at any time.

Monitoring and Control of Toxic Materials

Open-air testing of chemical rockets frequently requires measurement and control of exhaust cloud concentrations and gas movement in the surrounding areas for safeguarding personnel, animals, and plants. A toxic cloud of gas and particles can result from the exhaust gas of normal rocket operation, vapors or reaction gases from unintentional propellant spills, and gases from fires, explosions, or from the intentional destruction of vehicles in flight or rockets on the launch stand. Environmental regulations usually limit the maximum local concentration or the total quantity of toxic gas or particulates released to the atmosphere.

One method of control is for tests with discharges of moderately toxic gases or products to be postponed until favorable weather conditions are present.

In ground tests, the toxic cloud source is treated as a point source, and in flight tests it is a ribbon source. The rate of exhaust cloud diffusion is influenced by many propulsion variables, including propellant, rocket size, exhaust temperature, and thrust duration; by many atmospheric variables, including wind velocity, direction, turbulence, humidity, and vertical stability or lapse rate, and by the surrounding terrain. Extensive analytical studies and measurements of the environmental exposure from explosions, industrial smoke, and gases, and exhausts from missile and space vehicle launchings give background useful for predicting the atmospheric diffusion and downwind concentrations of rocket exhaust clouds.

A few definitions basic to the study of atmospheric diffusion of exhaust clouds are as follows:

- **Micrometeorology**. Study and forecasting of atmospheric phenomena restricted to a region approximately 300 m above the earth's surface and a horizontal distance of approximately 5 miles.
- **Lapse Rate**. The rate of decrease in temperature with increasing height above the earth's surface. The United States Standard Atmosphere has a lapse rate of about 6.4°C per 1000 m. Lapse rate is also affected by altitude, wind, and humidity.
- **Inversion, or Inversion Layer.** Condition of negative lapse rate (temperature increases with increasing height). Usually formed near the ground at night.

The following are a few general rules and observations derived from experience with the atmospheric diffusion of rocket exhaust clouds:

- Inversion presents a very stable layer and greatly reduces the vertical dispersion (the higher the lapse rate, the greater the vertical dispersion).

- A highly stable atmospheric condition tends to keep the exhaust plume or cloud intact and away from the earth's surface except when the exhaust products are much heavier than the surrounding air.
- High wind increases the rate of diffusion and reduces the thermal effects.
- For short firings (< 500 sec) the approximate dosages downwind are about the same as from an instantaneous point source.

- When the plume reaches about one-fourth the distance to a given point before emission is stopped, peak concentration will be about three fourths of that from a continuous source of equal strength.
- The presence of an inversion layer significantly restricts the mixing or diffusion capacity of the atmosphere in that the effective air mass is that mass existing between the earth's surface and the inversion layer.
- Penetration of the inversion layer due to the buoyance force of the hot exhaust cloud seldom occurs.
- Earth surface dosage drops rapidly when missiles or space launch vehicles are destroyed in flight above a height of 1500 m as compared to lower altitudes of 600 to 1000 m.

Interpretation of the hazard that exists once the concentration of the toxic agent is known also requires knowledge of its effects on the human body, plants, and animals. There are usually three limits of interest: one for the short-time exposure of the general public, one for an 8-hr exposure limit, and an evacuation concentration. Depending on the toxic chemical, the 8-hr limit may vary from 5000 ppm for a gas such as carbon dioxide, to less than 1 ppm for an extremely toxic substance such as fluorine. Poisoning of the human body by exhaust products usually occurs from inhalation of the gases and fine solid particles, but the solid residuals that sometimes remain around a test facility for weeks or months following a test firing can enter the body through cuts and other avenues.

Instrumentation and Data Management

Some of the physical quantities measured in rocket testing are as follows:

- Forces (thrust, thrust vector control side forces, short thrust pulses).
- Flows (hot and cold gases, liquid fuel, liquid oxidizer, leakage).
- Pressures (chamber, propellant, pump, tank, etc.).
- Temperatures (chamber walls, propellant, structure, nozzle).
- Timing and command sequencing of valves, switches, igniters, etc.
- Stresses, strains, and vibrations (combustion chamber, structures, propellant lines, accelerations of vibrating parts).
- Time sequence of events (ignition, attainments of full pressure).
- Movement and position of parts (valve stems, gimbal position, deflection of parts under load or heat).
- Voltages, frequencies, and currents in electrical or control subsystems.

- Visual observations (flame configuration, test article failures, explosions) using high-speed cameras or video cameras.
- Special quantities such as turbopump shaft speed, liquid levels in propellant tanks, burning rates, flame luminosity, or exhaust gas composition.

Measurement System Terminology:

Each measurement or each measuring system usually requires one or more sensing elements (often called transducers or pickups), a device for recording, displaying, and/or indicating the sensed information, and often also another device for conditioning, amplifying, correcting, or transforming the sensed signal into the form suitable for recording, indicating, display, or analysis. Recording of rocket test data has been performed in several ways, such as on chart recorders or in digital form on memory devices, such as on magnetic tapes or disks.

Range refers to the region extending from the minimum to the maximum rated value over which the measurement system will give a true and linear response. Usually an additional margin is provided to permit temporary overloads without damage to the instrument or need for recalibration.

Errors in measurements are usually of two types: (1) human errors of improperly reading the instrument, chart, or record and of improperly interpreting or correcting these data, and (2) instrument or system errors, which usually fall into four classifications: static errors, dynamic response errors, drift errors, and hysteresis errors. Static errors are usually fixed errors due to fabrication and installation variations; these errors can usually be detected by careful calibration, and an appropriate correction can then be applied to the reading. Drift error is the change in output over a period of time, usually caused by random wander and environmental conditions. To avoid drift error the measuring system has to be calibrated at frequent intervals at standard environmental conditions against known standard reference values over its whole range. Dynamic response errors occur when the measuring system fails to register the true value of the measured quantity while this quantity is changing, particularly when it is changing rapidly.

A maximum frequency response refers to the maximum frequency (usually in cycles per second) at which the instrument system will measure true values. The natural frequency of the measuring system is usually above the limiting response frequency. Generally, a high-frequency response requires more complex and expensive instrumentation. All of the instrument system (sensing elements, modulators, and recorders) must be capable of a fast response. Most of the measurements in rocket testing are made with one of two types of instruments: those made under nearly steady static conditions, where only relatively gradual changes in the quantities occur, and those made with fast transient conditions, such as rocket starting, stopping. This latter type of instrument has frequency responses above 200 Hz, sometimes as high as 20,000 Hz. These fast measurements are necessary to evaluate the physical phenomena of rapid transients.

Linearity of the instrument refers to the ratio of the input (usually pressure, temperature, force, etc.) to the output (usually voltage, output display change, etc.) over the range of the instrument. Very often the static calibration error indicates a deviation from a truly linear response. A nonlinear response can cause appreciable errors in dynamic measurements. Resolution refers to the minimum change in the measured quantity that can be detected with a given instrument. Dead zone or hysteresis errors are often caused by energy absorption within the instrument system or play in the instrument mechanism; in part, they limit the resolution of the instrument.

Sensitivity refers to the change in response or reading caused by special influences. For example, the temperature sensitivity and the acceleration sensitivity refer to the change in measured value caused by temperature and acceleration. These are usually expressed in percent change of measured value per unit of temperature or acceleration. This information can serve to correct readings to reference or standard conditions.

Use of Computers:

Computers have become commonplace in the testing and handling of data in rocket propulsion. They are usually coupled with sensors (e.g., pressure transducers, actuator position indicators, temperature sensors, liquid level gauges, etc.), which provide the data inputs, with controllers (valve actuators, thrust vector controllers, thrust termination devices), which receive commands resulting from the computer outputs causing a change in the sensed quantity, and with auxiliaries such as terminals, data storage devices, or printers. Computers are used in one or more of the following ways:

- The **analysis of test data** becomes a time-consuming difficult job without computers, simply because of the huge volume of data that is generated in many typical rocket propulsion system tests. All the pertinent data need to be reviewed and evaluated. The computer will permit automated data reduction, including data correction (e.g., for known instrument error, calibration, or changes in atmospheric pressure), conversion of analog data into digital form, and filtering of data to eliminate signals outside the range of interest. It can also include data manipulation to put the test information into graphic displays or summary hard-copy readouts of selected, specific performance parameters.

- Modern testing systems use digital data bases for **recording and documenting test records**. Often only a portion of the recorded data is actually analyzed and reviewed during or after the test. In complex rocket propulsion system tests, sometimes between 100 or 400 different instrument measurements are made and recorded. Some data need to be sampled frequently (e.g., some transients may be sampled at rates higher than 1000 times per second), whereas other data need to be taken at lower frequencies (e.g., temperature of mounting structure may be needed only every 1 to 10 sec).
- **Sensing and evaluating failures or overlimit conditions** (excessive local temperature, vibration, or limiting local pressure) is aimed at detecting an impending malfunction and at deciding whether it is a serious problem. If serious, it can cause either an automatic correction or an automatic and safe shutdown of operation. Sensing of undesirable operating conditions can be accomplished much more rapidly on a computer than would be possible if a human operator were in the control loop.
- **Simulation** of tests can be accomplished by devising algorithms that allow a computer to respond in a manner similar to a rocket propulsion unit. The computer receives inputs from various sensors (valve position, thrust vector control position, unsafe temperatures, etc.), processes the data in a simulation algorithm, and then provides output of control signals (e.g., thrust change, shutdown) and also of simulated rocket performance (e.g., chamber pressure, specific impulse, side force, etc.).
- **Control of test operation** by computer allows the attainment of the desired test conditions in a minimum amount of time. This could entail a preprogrammed set of pulses for an attitude control thruster, a desired set of different mixture ratios to be achieved for a short time (say, 1 sec each) in a single test, or a planned variation of thrust vector control conditions.

Flight Testing

Flight testing of rocket propulsion systems is always conducted in conjunction with tests of vehicles and other systems such as guidance, vehicle controls, or ground support. These flights usually occur along missile and space launch ranges, sometimes over the ocean. If a flight test vehicle deviates from its intended path and appears to be headed for a populated area, a range safety official (or a computer) will have to either cause a destruction of the vehicle, abort the flight, or cause it to correct its course. Many propulsion systems therefore include devices that will either terminate the operation (shut off the rocket engine or open thrust termination openings into rocket motor cases) or trigger explosive devices that will cause the vehicle (and therefore also the propulsion system) to disintegrate in flight.

Flight testing requires special launch support equipment, means for observing, monitoring, and recording data (cameras, radar, telemetering, etc.), equipment for assuring range safety and for reducing data and evaluating flight test performance, and specially trained personnel. Different launch equipment is needed for different kinds of vehicles. This includes launch tubes for shoulder-held infantry support missile launchers, movable turret-type mounted multiple launchers installed on an army truck or a navy ship, a transporter for larger missiles, and a track-propelled launch platform or fixed complex launch pads for spacecraft launch vehicles. The launch equipment has to have provisions for loading or placing the vehicle into a launch position, for allowing access of various equipment and connections to launch support equipment (checkout, monitoring, fueling, etc.), for aligning or aiming the vehicle, or for withstanding the exposure to the hot rocket plume at launch.

During experimental flights extensive measurements are often made on the behavior of the various vehicle subsystems; for example, rocket propulsion parameters, such as chamber pressure, feed pressures, temperatures, and so on, are measured and the data are telemetered and transmitted to a ground receiving station for recording and monitoring. Some flight tests rely on salvaging and examining the test vehicle.