ITEM 15
Test Equipment

Test Equipment

Produced by companies in

- France
- Germany
- Russia
- United Kingdom
- United States

Test facilities and test equipment usable for the systems in Item 1 and Item 2 as follows; and specially designed software therefor:

(a) Vibration test systems and components therefor, the following:

(1) Vibration test systems employing feedback or closed loop techniques and incorporating a digital controller, capable of vibrating a system at 10g RMS or more over the entire range 20 Hz to 2000 Hz and imparting forces of 50 kN (11,250 lb.), measured "bare table," or greater;

(2) Digital controllers, combined with specially designed vibration test software, with a real-time bandwidth greater than 5 kHz and designed for use with vibration test systems in (1), above;

(3) Vibration thrusters (shaker units), with or without associated amplifiers, capable of imparting a force of 50 kN (11,250 lb.), measured "bare table," or greater, and usable in vibration test systems in (1), above;

(4) Test piece support structures and electronic units designed to combine multiple shaker units into a complete shaker system capable of providing an effective combined force of 50 kN, measured "bare table," or greater, and usable in vibration test systems in (1) above.

Note to Item 15(a):

The term "digital control" refers to equipment, the functions of which are, partly or entirely, automatically controlled by stored and digitally coded electrical signals.

Nature and Purpose: Vibration test systems of this type are large and powerful equipment for simulating the flight vibrations and shocks that rockets and unmanned air vehicles (UAVs) experience during launch, stage separation, and normal flight. Missiles and their subsystems are tested to determine their elastic modes, frequencies, and sensitivities to vibration and shock. This information is used to improve missile design and to qualify systems, subsystems, and components as flight-worthy. Sometimes they are used in quality assurance testing to detect poor connections and loose components.

A typical vibration test system includes a vibration shaker unit, or thruster, to vibrate test articles attached to it; a power amplifier or other source of power to drive the shaker; a controller to command the power amplifier according to the desired vibration frequency and amplitude test profile; and an air- or liquid-cooling system for the shaker and amplifier.

Method of Operation: Vibration test systems use mechanical thrusters that usually operate on an electromagnetic drive principle like that of an audio loudspeaker, except that they are much larger and drive a massive test item rather than a delicate speaker cone. The digital controllers regulate complex vibration patterns with frequency content of controlled amplitude throughout the 20 to 2,000 Hz range. These patterns are designed to simulate the vibration frequencies and amplitudes expected during the mission, including simulation of vibration bursts or shocks. The output from these controllers must be greatly amplified to drive the thrusters. Hydraulic- and pneumatic-based vibration systems, although capable of the vibration testing of items of MTCR concern, are not generally capable of meeting the above performance specifications.

The armatures of two or more thrusters may be joined together with a test equipment support structure to obtain the required vibration levels. These structures must be both strong and light. Electronic units are needed to control multiple thrusters in a synchronous manner. They accept commands from the digital controller and relay them to multiple amplifiers, each driving one of the thrusters.

Typical Missile-Related Uses: All rockets and UAVs are subjected to vibration and shock during transport and flight. If vibration and shock are properly understood, flight vehicles can be made stronger and lighter because safety margins can be reduced. Use of such equipment also helps avoid costly test flight failures.

Other Uses: Vibration test systems are used to test other military and commercial equipment and products such as aircraft parts. Vibration testing is done on numerous other consumer goods, but MTCR-controlled vibration test systems are much more powerful and expensive than those needed for less demanding applications.

Appearance (as manufactured): MTCR-controlled vibration test systems are large devices that occupy a roughly 3 m by 3 m floor area. Details on the components are given below.

- *Digital controllers and specially designed vibration test software:* The digital controller is approximately the same size as the system unit for a personal computer (PC), 0.5 m wide × 0.5 m deep × 0.25 m high. In some cases, the controller is an electronic device small enough to be rack mounted above the power amplifier. In others, it is a desktop computer complete with monitors and customized interface cards for connection to the power

Photo Credit: Unholtz-Dickie

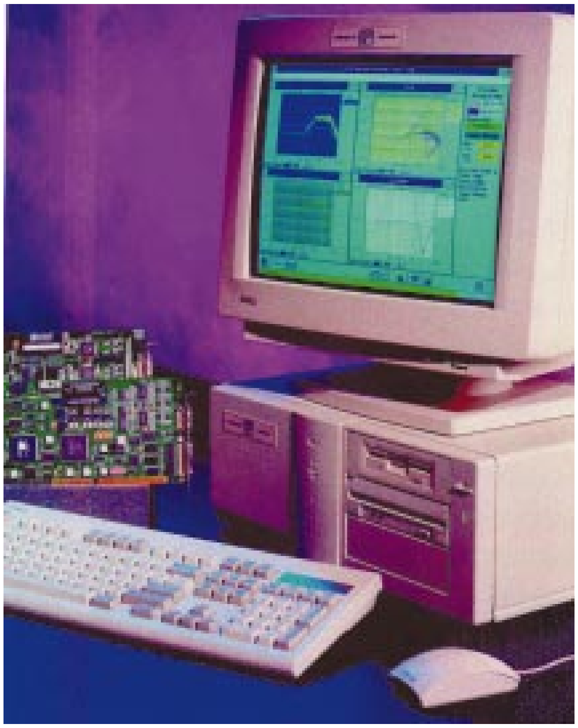

Figure 15-1: A desktop computer with customized interface cards and software.

Photo Credit: Unholtz-Dickie

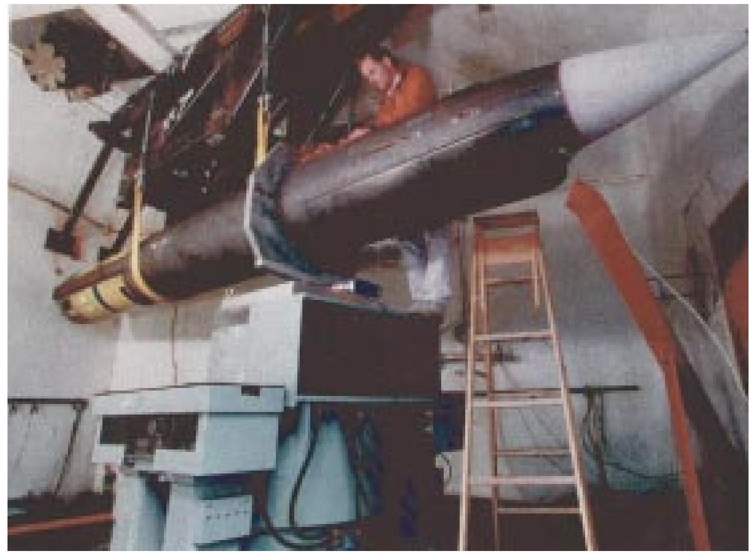

Figure 15-2: A thruster being prepared to vibration-test a missile.

Photo Credit: Unholtz-Dickie

Figure 15-3: A missile vibration test facility and thruster.

amplifier, as shown in Figure 15-1. Controllers require special purpose vibration control software. Manufacturers of vibration test systems are now offering PC-based software that integrates the functions for test system control, data recording, and data analysis.

- *Thrusters (shaker units):* An MTCR-controlled thruster usually has a very heavy, U-shaped, cast-steel base with thick flanges for securely attaching it to the floor. It measures about 1.3 m on a side and weighs several metric tons. The cylindrical or drum-like steel shaker housing, about 1 m in length and diameter, is hung between the vertical sides of the base. These vertical sides usually have trunnions (pivots) that allow the shaker housing to be rotated to change the thrust direction. A thruster in the vertical position in preparation for vibration testing a cruise missile is shown in Figure 15-2; another thruster preparing to test a sounding rocket is shown in Figure 15-3.

The part of the thruster that shakes the test item is a round metal armature emerging from one end of the shaker housing. The armature is drilled in a pattern of holes for bolts used to attach the test item. A rubber diaphragm between the armature plate and the thruster housing body is often used to seal the inner workings. Figure 15-4 shows a thruster with an expanded head for mounting larger test items.

Photo Credit: Unholtz-Dickie

Figure 15-4: A thruster with an expanded head.

Photo Credit: A Handbook for the Nuclear Suppliers Group Dual-Use Annex, *Report No. LA-13131-M (April 1996)*.

Figure 15-5: Thruster (in rear) connected to a slip table on common base.

Photo Credit: Unholtz-Dickie

Figure 15-6: A power amplifier and its associated thruster.

The thruster system may include an accessory slip table, which is often made of magnesium to minimize weight. It supports the weight of the test article on an oil film or air bearing above the slip table base, which is often made of granite. To use the slip table, the thruster itself is pivoted on its trunnions until the axis of motion of its armature is horizontal. The armature is then attached to the side edge of the slip table in order to vibrate the unit under test in either horizontal axis. Such a slip table assembly has the same size and weight as the thruster assembly itself, and both may be mounted on a common base, as shown in Figure 15-5.

- *Power amplifier:* The power amplifier for an MTCR-controlled electrodynamic vibration test system occupies one or more full racks (each 0.5 m wide × .75 m deep × 2 m high) of electronic power control equipment, as shown in Figure 15-6. The electric input power required to drive such a system is about 60 to 80 kW. The power draw is so large that it must be hard-wired to the building electrical supply; it cannot use a standard electrical cord and plug.

- *Cooling:* Because the thruster and amplifier give off about one-half of their input electrical power as heat, cooling by forced air or circulating liquid coolant is required. The fan for air-cooling a typical installation measures 1.5 m × 0.5 m × 0.8m and weighs 200 to 250 kg. Liquid cooling circulates cooling water through the test system and into a cooling tower or a radiator equipped with electric fans. Either liquid-cooling system is at least as large as the air-cooling fan. Alternatively, a continuous supply of site water can be simply run through the cooling system and drained away.

- *Support structures:* Test equipment support structures used with such vibration test equipment are custom-made assemblies, which measure as much as 3 m × 3 m × 3 m or more, depending upon the test unit, and weigh as much as 5 to 10 tons. Electronic units designed to combine multiple thruster units into a complete thruster system range from an ordinary PC equipped with multiple, special internal interface cards, each controlling a single thruster unit, to one or more racks of custom-built electronic equipment. Recent trends in vibration testing increasingly use PC-based systems because they provide flexibility at low cost. Because specialized vibration system control interface cards are installed within the PCs, it may not be evident from external examination that the PCs are MTCR controlled.

Appearance (as packaged): With the exception of the system controller, which is typically the same size as a personal computer and can be packaged for shipping in typical PC packaging, the components of a vibration test system of MTCR concern are so large and heavy that they must be packaged in custom-built wooden crates of extremely robust construction.

(b) Wind-tunnels for speeds of Mach 0.9 or more;

Produced by companies in

- Canada
- China
- France
- Germany
- Japan
- Netherlands
- Russia
- Switzerland
- United Kingdom
- United States

Nature and Purpose: Wind tunnels are large enclosures in which air is circulated or blown through a test section containing a replica of the rocket or UAV. They are used to measure the aerodynamic performance of the airframe design during a simulated flight through the atmosphere. Instrumentation in the test section gathers data on vehicle lift and drag, stability and control, engine inlet and exhaust configuration, thermal effects, and infrared signature. Wind tunnels are of either the continuous-flow (e.g., closed-circuit) or the blow-down (e.g., shock tube) type and measure aerodynamic parameters for long or short duration, respectively.

Method of Operation: A continuous-flow wind tunnel uses a large, electrically driven fan compressor to move air through the tunnel entrance cone to achieve the desired Mach number in the throat, or test, section. After it leaves the test section, this air moves through a diffuser and then circulates back through the fan to create a continuous flow of air past the test object. A blow-down wind tunnel stores air or other gas in a large reservoir under high pressure, releases it through a control valve into the tunnel entrance cone and on to the test section, and then exhausts it through a diffuser into the atmosphere.

Typical Missile-Related Uses: Wind tunnels capable of exceeding Mach 0.9 are used to test rockets, supersonic UAVs, and reentry vehicles. For high-speed flight, generally above Mach 3, heat transfer tests may be conducted. High-enthalpy, continuous-flow tunnels, or shock tubes, are needed to produce wind speeds beyond Mach 5 for testing long-range ballistic missiles.

Figure 15-7: The exterior of a large wind tunnel showing the closed-loop circuit for continuous airflow.

Figure 15-8: Exposed adjustable nozzle section of wind tunnel.

Other Uses: Wind tunnels are used in designing supersonic aircraft.

Appearance (as manufactured): Wind tunnels are usually large facilities with several buildings housing the test section, compressors, data acquisition systems, and power supplies. A continuous-flow wind tunnel suitable for testing full size missiles is usually 50 to 100 m in length and 25 to 50m in width, with diffusers 10 to 15 m in diameter. The large closed-loop circuit for airflow can be seen in Figure 15-7. A tunnel to test small-scale models may be much smaller in diameter. The larger-size wind tunnel is generally laid out in a horizontal oval 10 to 20 times the length of the test section length and 5 to 10 times its width. The tubular sections of the tunnel are generally made of steel plates welded together to form the circuit, which is supported from the outside by steel I-beams. Some wind tunnels use adjustable nozzle sections, as shown in Figure 15-8, to vary the characteristics of the airflow.

The test section, located on one side of the tunnel, often has large access doors so that test objects can be moved into and out of the wind tunnel and mounted on the test support. The test section may have windows for observing supersonic air flow around the missile with special Schlieren photographic recording devices (or other flow visualization devices). Test objects in typical wind tunnel test sections are shown in Figures 15-9 and 15-10. The test section usually has an associated operations building that houses the controls and data collection instrumentation, and may handle the insertion, positioning, or removal of test objects. Testing of full size missiles in continuous-flow wind tunnels produces the most accurate results but requires high power (on the order of 200,000 hp) to move the large volumes of air at flight speeds.

The blow-down tunnel stores air or other gases under high pressure in large tanks or cylinders. An air duct sealed by a large valve or diaphragm connects the tanks to the tunnel entrance cone and test section. The tunnel walls are

Figure 15-9: Test objects in test section of a hypersonic wind tunnel.

Figure 15-10: Test object under inspection in test section of a 5-meter transonic wind tunnel.

generally made of relatively thick steel and are sometimes coated with insulation because of the high temperatures generated by very high wind speeds. A large compressor is used to pump air under pressure into the tanks before each test.

Appearance (as packaged): Because wind tunnels and their associated operations buildings are very large structures, they are seldom, if ever, shipped in their assembled state. Individual components like the compressor motor, fan blades, corner turning vanes, complete test section or test section walls, viewing windows, and control and instrumentation panels are crated or mounted on heavy pallets for shipping. The main tunnel walls are generally shipped as structural components to be assembled together at the facility location.

(c) Test benches/stands which have the capacity to handle solid or liquid propellant rockets or rocket motors of more than 90 kN (20,000 lbs) of thrust, or which are capable of simultaneously measuring the three axial thrust components;

Produced by companies in

- China
- Germany
- Japan
- Russia
- United Kingdom
- United States

Nature and Purpose: Test benches and test stands for testing rocket systems, solid rocket motors, and liquid rocket engines of more than 90 kN of thrust are large rigid structures. They securely hold test items being operated at full power in order to collect performance data on critical parameters. These data support design development and confirm design integrity and performance. Liquid rocket engines are sometimes tested in test stands to verify performance before delivery.

Method of Operation: The test item is mounted on the test bench or test stand. Sensors are positioned and checked. Personnel are cleared from the test area, and data are collected while the rocket is operated at full power.

Photo Credit: Fiat Avio Sp.A.

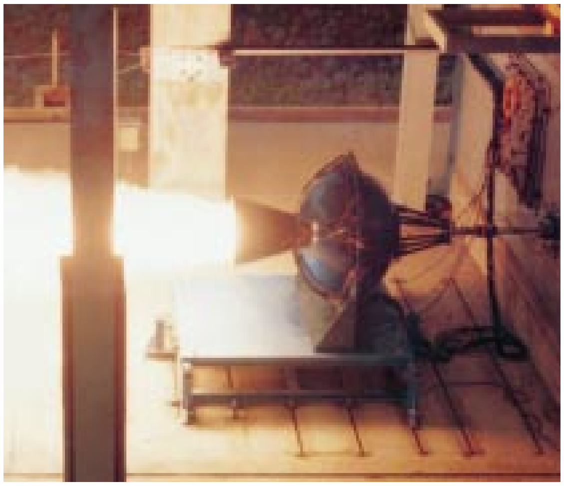

Figure 15-11: A small rocket motor test stand.

Photo Credit: Aerojet

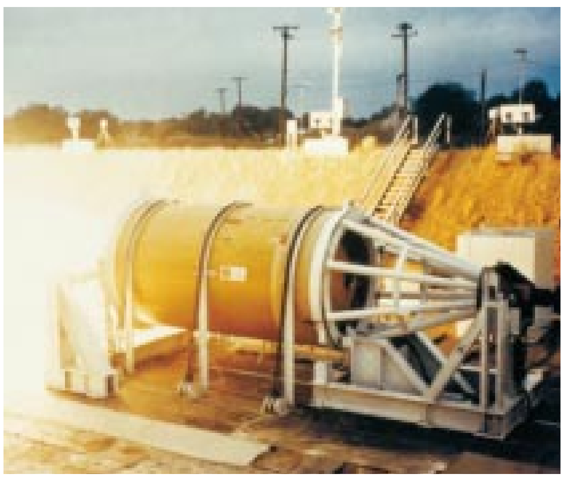

Figure 15-12: An outdoor, horizontal solid rocket motor test stand showing the dolly and frame holding the motor

Photo Credit: Rockwell International

Figure 15-13: A single liquid rocket engine vertical test stand.

Solid rocket motors are usually tested horizontally, and liquid rocket engines are usually tested vertically. Sensors measure pressures, propellant flow rates, forces, event timing, vibrations, displacements, and temperatures. Solid propellant rocket motors run to exhaustion; by contrast, liquid rocket engines and hybrid rocket motors can be throttled or shut down. Post-test inspections are conducted, and data are analyzed.

Typical Missile-Related Uses: Test benches and stands are essential equipment in the development phase of a missile program. Liquid rocket engine test stands are also used for full-scale testing of engine components such as turbopumps.

Other Uses: Similar, though often smaller, horizontal test benches and stands are used to test jet engines, including for use in UAVs.

Appearance (as manufactured): A horizontal solid rocket motor test stand generally consists of a dolly, thrust cup, load cell, thrust block, and instrumentation. The solid rocket motor is first secured horizontally on a movable dolly and locked down. Larger motors are often connected to a frame, which is then inserted into the thrust-cup; smaller motors are often inserted directly into the thrust-cup. The thrust-cup is mated to a load cell, which measures the three axial thrust components, and the load-cell is mounted on a large concrete vertical block or metal frame called the thrust block, which absorbs the forward force as the motor is being fired. Instrumentation connected to the load cell sends data to a blockhouse containing recording equipment. The entire assembly is usually outdoors but may be either partially or totally enclosed in a concrete building or a trench, as shown in Figures 15-11 and 15-12.

Most liquid rocket engines use a vertical test stand, a large gantry-type structure made of steel beams and girders. The liquid rocket engine is attached to load cells, which measure the three axial thrust components; these data are sent to a block house for recording. Run tanks carrying the propellants, the flame bucket, and usually a concrete apron that directs the exhaust away from the test stand are also parts of the installation. Two different test stand configurations are shown in Figures 15-13 and 15-14; a close up of the middle test bay of the latter stand is shown in Figure 15-15.

Photo Credit: Aerojet

Figure 15-14: A liquid rocket engine test stand with three testing bays. The bay on the right is for testing turbopumps.

Photo Credit: Aerojet

Figure 15-15: Close-up of the missile testing bay in Figure 15-14 showing the engine, feed lines, and run tanks.

Appearance (as packaged): Rocket test benches and stands are seldom shipped as assembled structures. Instead, their materials and components are shipped separately and assembled at the test site. A review of the design drawings and fabrication or assembly instructions can identify the intended use of the construction materials and components.

(d) Environmental chambers and anechoic chambers capable of simulating the following flight conditions:
   (1) Altitude of 15,000 meters or greater; or
   (2) Temperature of at least minus 50 degrees C to plus 125 degrees C; and either
   (3) Vibration environments of 10 g RMS or greater between 20 Hz and 2,000 Hz imparting forces of 5 kN or greater, for environmental chambers; or
   (4) Acoustic environments at an overall sound pressure level of 140 dB or greater (referenced to 2×10^{-5} N per square metre) or with a rated power output of 4 kiloWatts or greater, for anechoic chambers.

Produced by companies in

- Canada
- China
- France
- Germany
- India
- Israel
- Italy
- Japan
- Russia
- United Kingdom
- United States

Nature and Purpose: Environmental testing in ground facilities exposes components, subsystems, and entire vehicles to the low pressures, high and low temperatures, vibrations, and acoustics of powered flight in order to measure the responses. The data generated are used to confirm or correct designs and thereby ensure flight worthiness.

Method of Operation: High altitude is simulated by sealing test objects into rugged pressure chambers that are then evacuated with vacuum pumps. Flight temperatures are simulated inside thermally insulated chambers equipped with heaters and refrigeration equipment. MTCR-controlled temperature chambers must also be equipped to replicate specific vibration or acoustic environments. Vibration equipment are motor-driven tables capable of providing amplitude-frequency spectra to the levels stated above and replicating the range of vibrations experienced by a component, subsystem, or system during powered flight. Acoustic chambers use a combination of electrostatically or electromagnetically driven horns, like loudspeakers, to provide a spectrum of sound pressures like those generated by rocket motor exhaust and very high-speed aerodynamic flight.

Typical Missile-Related Uses: Altitude tests are used to investigate engine performance, heat transfer, altitude ignition, nozzle development, and propellant dynamics phenomena. Simultaneous temperature-vibration and temperature-acoustic tests are used to subject missile hardware to high-fidelity flight environments to develop technology and qualify missiles for flight. Such testing is not required for basic missile programs, but is necessary for advanced development. This equipment can also decrease the cost of a flight test program, but some of this equipment, particularly the large environmental chambers, can be quite expensive.

Other Uses: High-altitude and simultaneous temperature-vibration and temperature-acoustic testing is routinely done on satellites, tactical missiles, and aircraft components.

Appearance (as manufactured): Environmental pressure chambers are rugged, usually metal, airtight, cylindrical chambers with bulged or hemispherical ends to withstand the external pressure of one atmosphere (plus safety margin). They often have thick glass or acrylic viewing ports. An access panel or door at one end is used to insert and remove test items. They are often linked to large vacuum pumps that evacuate the chamber. Their size is a function of the items to be tested; thus, they can range from less than a meter to tens of meters on a side. They are usually supported by numerous buildings housing pumps, power, data collection, and operations. Two different approaches to pressure chambers suitable for rocket motor testing are shown in Figures 15-16 and 15-18; Figure 15-17 shows an interior view of a solid rocket motor being tested at simulated altitude in a facility similar to that shown in Figure 15-16. A large facility capable of testing large solid rocket motors at simulated altitudes of up to 33,000 m is shown in Figure 15-19, and a view of the inside of the test cell of that facility is shown in Figure 15-20.

Temperature chambers are thermally insulated chambers or rooms with heating and cooling equipment. MTCR-controlled temperature chambers have provisions for vibration or acoustic testing at various temperatures encountered in flight.

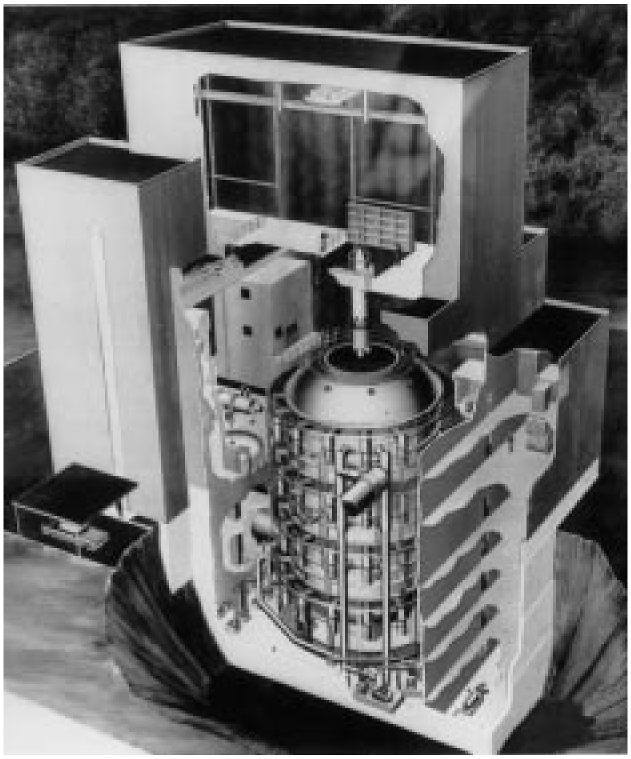

Figure 15-16: A large environmental chamber for simulating high altitude.

Figure 15-17: A solid rocket motor being tested at simulated altitude.

Figure 15-19: A large rocket test facility capable of simultated altitudes of up to 33,000 m.

Figure 15-18: A different approach to an altitude test stand. The test object is shown in red inside the pressure vessel.

Figure 15-20: The test cell of the facility shown in Figure 15-19.

Photo Credit: RMS Dynamic Test Systems

Figure 15-21: A thruster table and its power supply.

Photo Credit: RMS Dynamic Test Systems

Figure 15-22: A controlled environmental chamber with vibration capability.

Photo Credit: Unholtz-Dickie

Figure 15-23: Another vibration and environmental test apparatus configuration.

Temperature chambers for vibration testing contain a powerful device to shake test items. This device, known as a thruster or shaker, usually has a round, flat, steel table, which may have predrilled/tapped mounting locations for attaching test articles. Table motion is often driven by a cylindrical, variable-speed linear electric motor. Depending on the size of the items tested, these tables range from tens to thousands of kilograms in weight. A table capable of imparting 5 kN or greater is shown in Figure 15-21. Environmental chambers controlled under this item can simulate flight conditions of 10 or more g rms from 20 Hz to 2,000 Hz, impart forces of 5 kN or greater, and have operating temperatures of at least –50° C to +125° C, as shown in Figure 15-22. Figure 15-23 shows a different combined environmental test apparatus.

Temperature chambers for acoustic testing are large rooms with acoustic horns mounted in the walls. The horns themselves are monotonic (operate at one frequency) and range in length from several centimeters for high-frequency horns to 1 m for low-frequency horns, with corresponding exit area, or mouth, sizes. Acoustic testing usually requires that the chamber be lined with very coarsely corrugated (often conic-shaped), soft, porous, sound-absorbing material.

Appearance (as packaged): External pressure chambers vary in size, but they are usually very large and constructed onsite. Large MTCR-controlled temperature chambers may be shipped as prefabricated panels of construction materials. The assembly instructions or construction plans can help identify intended use. Smaller temperature chambers are shipped much like a common refrigerator. Dynamic test tables in a partially assembled state are shipped in simple wooden crates, usually with some internal contouring and cushioning for the parts. The shipping containers of these rugged pieces of equipment are not likely to have any special handling markings. Acoustic horns are shipped in metal canisters or wooden crates. Because the driver diaphragms in these horns are sensitive components, shipping containers may have special handling markings.

(e) Accelerators capable of delivering electromagnetic radiation produced by "bremsstrahlung" from accelerated electrons of 2 MeV or greater and systems containing those accelerators.

Note: The above equipment does not include that specially designed for medical purposes.

Produced by companies in

- China
- Germany
- India
- Japan
- Russia
- United Kingdom
- United States

Nature and Purpose: MTCR-controlled accelerators are of three basic types: linear radio frequency (RF) accelerators (linac), flash X-ray machines, and mechanically charged, high-voltage electrostatic accelerators (Van de Graaff type). Their primary use is to create X-rays capable of penetrating missile parts (such as solid rocket motors) so that X-ray photographs can be made of their interiors. Other uses for energetic X-rays include simulating nuclear weapon effects and stop-action X-ray photography of very high-speed events like explosions and impacts.

Method of Operation: The accelerators of most interest are the linac type. They accelerate a beam or cluster of electrons to speeds approaching the speed of light by passing them through cavities charged with an electric potential (voltage) supplied by an RF generator. Because the effect of these cavities is additive, total electron energies of millions of electron volts (MeV) can be obtained from relatively small devices. This energetic beam of electrons exits the linac and strikes a target (usually a dense metal such as tungsten). The electrons give off X-ray radiation as they are decelerated inside the target; this phenomenon is called "bremsstrahlung," German for braking radiation. The X-rays pass through the object and are recorded on film or, increasingly, in electronic sensors that immediately display the picture on a computer screen. A Van de Graaff accelerator normally creates a large electrostatic potential by mechanically driving a vulcanized rubber belt or insulating string of polished metallic beads on an insulating surface. The targets used to stop the electrons in the electrostatic generators are metal foil like that used in linear accelerators. Most flash X-ray machines operate by charging a very large bank of capacitors to high voltage and then suddenly discharging them. Like the linac, the resulting electron current strikes a heavy metal target and creates X-rays.

Typical Missile-Related Uses: One of the most important uses of linacs is to produce X-rays for non-destructive testing of solid rocket motors. They are

Photo Credit: Titan Beta

Figure 15-24: A 10 MeV X-ray machine used for sterilization (not MTCR-controlled).

Photo Credit: Varian Associates, Inc.

Figure 15-25: Typical linac X-ray system.

used to find cracks and voids in the propellant grain, cracks and incomplete welds in the case, or incomplete bonds to the insulation or interior lining. Such X-ray equipment can be used to inspect most missile components such as structural members, welds, nozzles, and turbopump parts. Linacs are also used to investigate nuclear radiation effects of missile electronics and to test equipment and parts for radiation hardness. These are also the primary uses of large flash X-ray machines. Van de Graaff accelerators are not usually used for these purposes because of their size and low beam current (and thus low X-ray) output.

Photo Credit: Varian Associates, Inc.

Figure 15-26: A linac control console.

Other Uses: Industrial microwave, accelerator-based, high-energy X-ray machines have been routinely used for a wide variety of industrial applications for more than 30 years. These applications include defect-detection large casting and welded assemblies used in automotive, shipbuilding, aerospace, and power production component manufacturing. A high-energy X-ray machine used for sterilization is shown in Figure 15-24. These machines also are used in large security systems for detection of contraband or explosives in container shipments. Similar technology is employed in the production of machines used to treat cancer.

Photo Credit: Varian Associates, Inc.

Figure 15-27: A linac RF amplifier on the left with the water pump cabinet on the right.

Appearance (as manufactured): The most commonly used 2 MeV + accelerator is the linac, as shown in Figure 15-25, because of its small size and ruggedness. These X-ray machines consist of five major parts: the accelerator, the X-ray head, the RF amplifiers or modulators, a control console, and a water pump cabinet. The box-like structure of Figure 15-25 contains the accelerator and the X-ray head. Figure 15-26 shows the control console. Figure 15-27 shows the RF amplifier on the left and the water pump cabinet on the right.

The source of the X-rays is the X-ray head. It is connected to the RF modulator by means of a waveguide, which is a rectangular rigid or semi-rigid conduit or cable. The accelerator portion of the X-ray head is a tube or pipe with semi-circular disks on alternating sides along its length. This assembly may be in the center of a larger diameter electromagnet. The modulator or RF amplifier, which supplies RF energy to the acceleration tube, is often in a separate cabinet. This energy is normally coupled through a rectangular waveguide or, less frequently, a coaxial cable. The modulator operates at a frequency corresponding to the accelerating structure, normally in the 1 to 3 GHz range. The other supporting components are the control system and the water-cooling system. These systems control and cool the accelerator to keep it within a narrow range of operating temperatures. Typical dimensions for the X-ray head, modulator cabinet, and control console are shown in Table 15-1.

Table 15-1: Typical linac dimensions.

	X-ray Head	Modulator Cabinet	Control Console
Height:	0.5 m	1.0 m	0.2 m
Width:	0.5 m	0.5 m	0.3 m
Depth:	1.0 m	1.0 m	0.3 m
Weight:	200 kg	300 kg	2 kg

X-rays produced by MTCR-controlled accelerators are energetic enough to require lead shielding several centimeters thick. These accelerators are often shipped without shielding since the shielding can be readily manufactured and installed by the recipient. Often an unshielded system is placed inside a shielded building.

The other type of accelerator for use in high-energy X-ray generation is a mechanically driven Van de Graaff type generator. These systems are much larger than linear accelerators and more difficult to position, and thus are not normally used for radiography. They consist of a high-voltage power supply capable of generating electrostatic potentials of 2 MV or more, an acceleration tube made of highly polished nickel, and a control console. The power supply and the acceleration tube are usually integral parts. They are contained within a high-pressure tank made of thick-walled steel, which when operational, contains a high dielectric gas such as sulfur hexafloride or pure nitrogen at a pressure of several atmospheres. Unlike the linear accelerators, which are small enough to be rotated around the piece being X-rayed, the very large electrostatic accelerators remain stationary, and the test piece is moved as needed to achieve the desired relative positioning. Typical dimensions of a Van de Graaff system are given in Table 15-2.

Table 15-2: Typical dimensions for a Van de Graaff system.

	Pressure Vessell	Control Console
Length:	2.5 m	0.2 m
Diameter:	1.0 m	
Width:		0.2 m
Weight:	1,200 kg	2 kg

Figure 15-28:
A 2.3MeV flash X-ray unit used for inspecting solid rocket motors.

Flash X-ray equipment varies in size from a desktop unit to huge systems that require special buildings. A typical unit used for inspection of solid rocket motor grains is shown in Figure 15-28.

Appearance (as packaged): Linear accelerators are packaged for shipment in crates or boxes. They may appear as three separate cabinets. The X-ray head and modulator normally come from the same vendor. The cooling system and the control system can be purchased separately. The packaging uses foam, Styrofoam, or other shock-attenuating fill to protect the modulator from excessive vibration and shock. The equipment may be labeled with X-ray caution labels, RF field signs, and possibly labels indicating high-voltage. The system may be heavier than lower-energy systems because of the amount of lead shielding, if shipped with shielding installed, required to shield personnel from penetrating X-rays.

The electrostatic accelerators are much larger. The high-voltage supply and the acceleration tube are shipped together inside the pressure vessel. Because of its weight, the pressure vessel is most likely shipped in a crate made for fork-lift handling. The unit is not likely to be shipped in operational condition and usually has additional packing material inside the pressure vessel to support the high-voltage supply and acceleration column.