Jet Propulsion Laboratory Edwards Facility
(JPL Edwards Test Station)
Edwards Air Force Base
Boron Vicinity
Kern County
California

HAER No. CA-163

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Historic American Engineering Record
National Park Service
Western Region
Department of the Interior
San Francisco, California 94107

HISTORIC AMERICAN ENGINEERING RECORD

JET PROPULSION LABORATORY EDWARDS FACILITY
(JPL Edwards Test Station)

HAER No. CA-163

Location:	Edwards Air Force Base Boron vicinity Kern County California UTM coordinates of property line: 11.419140.3872000, 11.419690.3872840, and 11.419690.3873160, USGS 7.5 min Edwards quadrangle, 1973 11.420320.3873760 and 11.421280.3873760, USGS 7.5 min North Edwards quadrangle, 1973 11.421280.3872470 and 11.419970.3872010, USGS 7.5 min Rogers Lake North quadrangle, 1973
Dates of Construction:	1945, with major construction programs in 1957, 1959, 1961, and 1972. Modifications to facilities occurred on a more frequent basis into the 1980s
Fabricator:	1945-1958: United States Army Corps of Engineers; numerous private sector contractors thereafter.
Present Owner:	United States Air Force
Present Use:	Test facility
Significance:	Operated by the California Institute of Technology, the Jet Propulsion Laboratory Edwards Facility was the United States' first university-sponsored research and testing facility for the development of liquid-fueled rocket engines and components. It became a primary national test facility. Experimental liquid propellant combinations were evaluated here, and later solid fuel rocket motors were built and tested here (including motors for the Space Shuttle). It was the site for testing interplanetary space probe engines for noted programs such as *Pioneer, Ranger, Surveyor, Mariner, Voyager,* and *Viking.*
Historians:	Primary: Scott M. Hudlow, Architectural Historian, Computer Sciences Corporation, Edwards Air Force Base, California Secondary: Richard K. Anderson, Jr. Columbia, South Carolina. December 1994-May 1995.

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Historical Background and Context

The Jet Propulsion Laboratory (JPL) dates from 1936. It originated as part of the applied mechanics program at the Guggenheim Aeronautical Laboratory/California Institute of Technology (GALCIT). Six student scientists led by Hungarian emigré Theodore von Kármán conducted the first static tests of uncooled liquid-propellant rocket engines in 1936 in the Arroyo Seco, located at the western edge of the San Gabriel Mountains in Pasadena, California. The Arroyo Seco was chosen for its relative isolation from urban development, lack of foliage, and proximity to the California Institute of Technology (Caltech) campus in Pasadena.[1] GALCIT was an early, amateurish rocket project.[2] Caltech has since received recognition as the first university in the United States to sponsor formal rocket research.

Theodore von Kármán and his six student scientists (Hsue Shen Tsien, Apollo M.O. Smith, John W. Parsons, Edwards S. Forman, Weld Arnold, and Frank W. Malina); Robert H. Goddard; and the exiled German rocket scientists led by Wernher von Braun who worked for the Army after World War II (WWII) at White Sands, New Mexico and later at Redstone Arsenal, Huntsville, Alabama can each claim the seminal roles in America's space program.

Pioneering People

Research into rocketry began well before 1936. The Chinese first used primitive rockets in the twelfth century, probably using black powder as a propellant. Clayton Koppes wrote that in the 19th-century, "Europeans later adapted them [rockets] for warfare—Francis Scott Key scribbled 'The Star Spangled Banner' in the immortal glare of Congreve's incendiary rockets. But these nineteenth-century specimens were inaccurate and dangerous and fell into disuse when improved artillery became available."[3] Although, early examples of interest in rocketry are known, the

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[1] Daniel, Mann, Johnson, and Mendenhall. "JPL Master Facilities Plan 1977". Report on file at JPL, JPL Edwards Facility, Edwards AFB, California, unpaginated; and Clayton R. Koppes, *JPL and the American Space Program: A History of the Jet Propulsion Laboratory*. New Haven, Connecticut: Yale University Press, 1982.

[2] Koppes, 1-8.

[3] Koppes, 1.

modern origins of rocket research and interest in space travel date to the early 20th-century.

In their respective countries, three distinct individuals are most responsible for establishing the theoretical and practical basis for research into rockets and missiles. A Russian, Konstantin Eduardovich Tsiolkovsky, published a theoretical essay on space travel in 1903. Hermann Julius Oberth, a Romanian living in Germany, wrote an important, exhaustive, theoretical analysis in 1923. Robert H. Goddard, an eccentric New Englander, flew the first liquid-propelled rocket in 1926.

Rocketry was first researched by Konstantin Eduardovich Tsiolkovsky, who could be considered the father of rocket science. He was a quiet, studious physics teacher and theoretical philosopher, who never flew a single rocket in his lifetime. Yet, Tsiolkovsky recognized four basic principles of rocket flight. First, reactive thrust is the key by which to achieve motion or acceleration in a vacuum. Second, the measure of thrust is achieved by the exhausted gases. Third, the speed reached by a rocket depends on the temperature of the combusted gases and the weight of the gases' molecular constituents. Last, Tsiolkovsky understood staged propulsion and the understanding of thrust-to-weight ratios.[4] Tsiolkovsky:

> By 1883...was describing the principles of a throttlable rocket motor and, just two years later, wrote a book which prophesied the advent of earth orbiting satellites. After spending more years in defining the concept he finally prepared a paper, at the age of forty, entitled *Exploration of Outer Space with Reactive Devices*. Tsiolkovsky led a peaceful life with little thought for the mechanics of war and to him the great dream of space travel could be transformed into reality. Repeated calculations convinced him of this possibility and in 1903, at the age of forty six he described in detail how a rocket device could be made to transport men beyond the atmosphere using liquid oxygen and liquid hydrogen.[5]

Tsiolkovsky believed that if two liquids could be brought

[4] Baker, David. *The Rocket: The History and Development of Rocket & Missile Technology*. New York, New York: Crown Publishers, Inc., 1991:18-19; 22.

[5] Baker, 17.

together in a chamber and ignited, the resulting gases could be channeled through a narrow orifice at the rear and propel the rocket and a payload in the opposite direction. The gases would expand and be exhausted at high velocity, which would initiate the reaction. Tsiolkovsky was theoretically correct. Moreover, he speculated that to reach a speed of 8 kilometers per second the device must carry propellant weighing four times the empty weight of the rocket and its cargo. Significantly, a velocity of 8 kilometers per second is the speed necessary for orbital flight. Tsiolkovsky recognized the difficulty inherent in this requirement, the huge size and thrust of the rocket necessary to achieve orbital flight. He proposed the use of a staged rocket whereby successive sections could be jettisoned as the propellant was exhausted.[6]

Hermann Oberth, a Romanian, is considered the father of German rocketry. A Versailles Treaty provision prohibited the Germans from developing artillery. The Germans perceived this proscription as an opportunity to develop rocket and missile technology. He wrote a thesis on spaceflight and attempted to publish the text. In 1923, when Oberth agreed to underwrite some of the expenses, *The Rocket into Interplanetary Space* appeared as a book. A second edition of his book appeared in 1929 under the revised title *The Road to Space Travel*, which won Oberth a 10,000-franc literary prize. The award funded his liquid propulsion research.[7]

The Rocket into Interplanetary Space spurred open public interest in rocket transportation. In 1927, amateur German space travel and rocket enthusiasts organized the Verein für Raumschiffahrt (VfR), or the Society for Space Travel. The founding of the Society for Space Travel brought a veritable barrage of interest and enthusiasm in space travel. Membership in the VfR grew to several hundred persons, accompanied by publication of several new books on the subject. In 1928, Max Valier, a popular space writer, eager to exploit the new technology, put solid propellants on the back of a modified automobile. In a series of runs, each one using modifications dictated by the lessons of the preceding test, Valier reached speeds of up to 100 miles per hour, and attracted considerable public interest in the process.[8]

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[6] Baker, 17.

[7] Baker, 27.

[8] Baker, 27-28.

The VfR moved to a suburb of Berlin; an abandoned ammunition dump provided them with a proving ground for rocket tests. Many young enthusiasts were associated with the VfR experiments, including Wernher von Braun, Willy Ley, and Hermann Oberth. By 1929, Oberth was working to prepare his first rocket, which was never launched.[9] The next year, Oberth and the VfR prepared a small liquid-propelled rocket, using gasoline and oxygen as fuel and oxidizer. The combustion chamber protruded into the liquid oxygen tank to facilitate cooling. The rocket, *Mirak 1*, was unfortunately destroyed during ground tests before flight trials commenced. Several months later, its successor, *Mirak 2*, demonstrated 75 pounds of thrust; however, the tiny motor exploded before it could be test launched. Shortly after these abortive efforts, Oberth's concerted efforts paid off. Johannes Winkler launched a liquid oxygen/liquid methane rocket on a successful ascent from Dessau on 14 March 1931, which was the first liquid-propellant rocket flight outside the United States and the sixth in world history.[10]

In the 1930s, Hermann Oberth laid the groundwork for the Nazi missile program. Oberth was one of the principals in establishing Peenemünde, the Nazi Germany rocket testing facility on the Baltic coast. It has been suggested that Oberth helped the Nazis select the site; this section of the Baltic coast contained Oberth's original site for his 1929 rocket test. Peenemünde was also the area where Johannes Winkler wanted to conduct his rocket testing. Oberth has also been credited as leading the Peenemünde facility and developing the German WWII liquid-propelled V-2 rocket.[11]

The primary pioneer of American rocketry was Robert H. Goddard. He received his Ph.D. in Physics in 1911 from Clark University in Worcester, Massachusetts, where he later taught physics. Goddard is considered the father of American rocketry, and was the world's first practical demonstrator of rocket power. Spurred by design progress, he immediately began preparing a set of papers demonstrating the feasibility of liquid propulsion systems. By 1914, Goddard had applied for and been granted

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[9] Ley, Willy. "V.2-Rocket Cargo Ship", reprinted in *Famous Science-Fiction Stories: Adventures in Time and Space*. Raymond J. Healy and J. Francis McComas, eds. New York, New York: The Modern Library, 1946:345.

[10] Baker, 28.

[11] Ley, 345.

patent licenses for a host of devices related to rocket engines, including a combustion chamber design, a propellant feed and control system, rocket nozzles (expansion chambers) and a multistage rocket which would carry a second stage within the upper frame of the first stage.[12]

Goddard typified the scientific efforts in the early twentieth-century, before the advent of government funding and the modern laboratory.[13] He worked alone- a stereotypical eccentric inventor. In many respects, Goddard occupies a place in the history of rocketry similar to that of Samuel Langley, the Wright Brothers, or Glenn Curtiss in the history of flight.[14]

In 1919, the Smithsonian Institution published Goddard's classic paper entitled *A Method of Reaching Extreme Altitude*. It detailed, "...the feasibility of building rockets propelled by successive impulses from powder engines that might reach the moon."[15] This work clarified Goddard's innermost desires and prompted a measure of introspection and withdrawal, which remained with him for much of his life. *A Method of Reaching Extreme Altitude* was based on the work Goddard had undertaken up to America's entry into World War I, including studies conducted in the Arroyo Seco, near JPL's future location. The essay carried definitive values for a rocket design required to perform a limited demonstration and introduced a much more ambitious proposal, reaching the moon.

Goddard recognized the problems associated with accurately measuring the altitude that could be reached by successively higher rocket trajectories. He felt it would be a good idea to set off a small explosion by means of "flash powder" so that ground instruments could register the height reached by the projectiles. Goddard acknowledged this would of course be difficult to accomplish. He noted that the angle of the rocket's

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[12] Baker, 22-23.

[13] Noble, David. *America by Design: Science, Technology, and the Rise of Corporate Capitalism*. New York, New York: Oxford University Press, 1977.

[14] Hudlow, Scott M. *Cultural Resource Evaluation of the North Base Complex (The Muroc Flight Test Base and the Rocket Sled Test Track), Edwards AFB, Kern County, California*. Report on file at AFFTC/EM, Edwards AFB, California, 1995:17.

[15] Koppes, 2.

ascent would be difficult to predict, and that glare from the Sun would compromise satisfactory observation of the flash. To escape this quandary, Goddard suggested that a rocket should fly to the Moon while it was between the Earth and the Sun so that the rocket could impact the lunar surface, set off the powder flash, and provide a visible light source against the darkened background. As David Baker states concerning *A Method of Reaching Extreme Altitude*:

> In one move he [Goddard] had shown that the only way to demonstrate the rocket's potential satisfactorily would be to send it to the Moon, and in doing so ably provide the world with proof of the important developments which could result from such experiments. Concluding the report, Goddard admitted that the plan had little scientific merit, but that the flight could lead to more important tests which would carry scientific instruments into space. This latter possibility was only hinted at and this was undoubtedly because few who were not directly associated with rocket development could see any real long term value in the device. Nevertheless, Goddard had provided an exciting idea for those who had the foresight to see it and the report serves as a reminder that he was ever concerned about the rocket's potential, although the rest of his life would be devoted to engineering developments of more short term interest.[16]

In the mid 1920s, Goddard began experimenting with rockets to implement his theories. In December 1925, he successfully ran a rocket motor for 24 seconds before the rocket expended its propellant supply. Additional tests, in January 1926, had a similar successful outcome; the rocket device rose as high as it could in the restrained test stand. Independent flight was the next stage. Robert Goddard attempted a flight test on a farm at Auburn, Massachusetts, just outside Worcester. Tests began in March of 1926. Goddard was ready to demonstrate a free flight.

Goddard placed the rocket in a 6-foot tall A-frame on 16 March 1926. Four assistants helped him; his wife took notes. The liquid oxygen and gasoline propellants ignited and the rocket lifted into the air. The flight was over in 2.5 seconds, yet in that short interval, the rocket had accelerated to an approximate height of 40 feet with an average speed of 60 miles per hour. The rocket landed approximately 181 feet away from the test stand, in a cabbage patch. The world's first free flight of a

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[16] Baker, 23-24.

liquid propelled rocket had been successful. A second flight, lasting 4.2 seconds, followed several weeks later. Goddard, spurred by his successes, went back to the drawing board hoping to add refinements which would improve the performance of the basic design.[17] Three years later, Goddard tested a second rocket. In 1931, he left Massachusetts for the solitary expanse of New Mexico.[18]

Beginnings of JPL: The GALCIT Project

The GALCIT group, formed in 1936, contacted Goddard to consider joining forces. Not given to teamwork, Goddard developed a paranoid fear of competition. He was especially wary of students, whom Goddard thought were trying to steal his inventions. Homer Newell states:

> Members of the California Institute of Technology Rocket Research Project, established in 1936 by Theodore von Kármán, director of the institute's Guggenheim Aeronautical Laboratory, tried to persuade Goddard [in 1940] to join forces with them. When it was stipulated that a partnership would require mutual disclosure of ideas and projects, Goddard shied away. His reluctance to work openly with others deprived Goddard not only of the opportunity to provide leadership in the field, but also cut him off from the professional assistance that he might have received from experienced engineers who could have helped put his many ideas into practice.[19]

His secrecy and caustic spirit isolated him and deprived him of desperately needed help, whereas the GALCIT/JPL enjoyed the team spirit necessary to modern industrial research and development, which is characterized by the laboratory concept.[20]

As GALCIT made theoretical and financial advancements in the late 1930s and into WWII, Goddard's star sank. Without the engineering expertise necessary to overcome obstacles in pursuit

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[17] Baker, 24.

[18] Koppes, 2.

[19] Newell, Homer E. *Beyond the Atmosphere: Early Years of Space Science*. Washington, D.C.: National Aeronautics and Space Administration, 1980:30.

[20] Noble.

of his dream of spaceflight, Goddard slipped into obscurity during WWII, winding up working at a naval research station on a JATO (Jet-Assisted-Takeoff) project. He died in 1945. National Aeronautics and Space Administration (NASA) posthumously awarded his estate $1,000,000 in 1960 for the rights to the myriad of patents he held. Further, NASA renamed the Naval Research Laboratory (NRL) the Goddard Space Flight Center in his honor.

Hungarian emigré Theodore von Kármán led the GALCIT's rocket program. Von Kármán, a brilliant aerodynamicist and theoretician, received his Ph.D. from Berlin University. He taught briefly in Hungary and Germany, before moving to Pasadena, California. He joined the Caltech faculty in 1926. A Von Kármán assistant reported on Eugen Sänger's rocket-motor experiments in 1936, and stoked the nascent interest of several people, including Von Kármán and a Caltech graduate student, Frank Malina. Malina had always been interested in rocketry, and proposed to write his doctoral dissertation on problems of rocket propulsion and the flight characteristics of sounding altitude rockets, which are used solely for measurements within the atmosphere, including temperature, pressure, density, composition, structure, and movements of the atmosphere.[21]

Under Malina's direction, the GALCIT group, tested its first rocket in October 1936. The first successful test came in January 1937; it brought new financial support and people into the GALCIT fold. Hsue-shen Tsien, a Chinese-born engineer and brilliant applied mathematician, was one of the new people. Tsien returned to China in the 1950s and founded that country's intercontinental ballistic missile program.[22] The GALCIT built its first stationary test apparatus to test rocket engines in 1937. The test apparatus was mounted to a building; however, a test exploded and destroyed the apparatus.[23] Not surprisingly, the noisy and dangerous tests were viewed with suspicion and distrust by the Caltech administration, which prompted discussions about moving the tests out of the facility.

In 1936, the project found a safe site 7 miles away from the Caltech campus in the Arroyo Seco at the foot of the San Gabriel

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[21] Koppes, 3; and Jacob Neufeld. *The Development of Ballistic Missiles in the United States Air Force, 1945-1960*. Washington, D.C.: Office of Air Force History, 1990:42.

[22] Koppes, 5, 31.

[23] Koppes, 7.

Mountains, away from a heavily populated area. The GALCIT group secured a lease with the City of Pasadena and began building small frame and corrugated metal structures during the summer of 1940.[24] A JPL planning study stated:

> Construction of research facilities in the Arroyo Seco began in 1940. Buildings were temporary, based on Caltech's expectation that research would be sustained only as long as hostilities continued in Europe. Neighboring residents tolerated the installation's unharmonious military appearance and noises on the assumption that they were temporary 'war effort' inconveniences. The structures were also considered unpleasant by their inhabitants. The first building, 15 feet square, corrugated metal-clad, and crammed with rocket plumbing, was dubbed the "gas house" by its users.[25]

The troubled political climate in Europe was reflected in a bolstering of U.S. Army Air Corps support of aeronautical research, including rocketry. As such, GALCIT came directly under the aegis of the Army Air Corps in July 1940, although it was initially sponsored by the National Academy of Sciences. The GALCIT/JPL was awarded several federal contracts during WWII for urgent military-oriented research projects. These early rocket tests were conducted during a period of intense research-and-design work and mark the beginning of state-sponsored scientific research which benefitted the military.[26]

The practical demonstration of constant-pressure, long-duration, solid-propellant engines was among GALCIT's early breakthroughs. This technological advancement was the basis of GALCIT/JPL's JATO rockets--liquid-propellant or solid-propellant rocket engines and motors[27] for assisting aircraft takeoff.[28]

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[24] Koppes, 11.

[25] Daniel, Mann, Johnson, and Mendenhall.

[26] McDougall, Walter. ...*The Heavens and the Earth: A Political History of the Space Age*. New York, New York: Basic Books, 1985:78.

[27] In rocket industry parlance, liquid-fueled propulsion devices are called *engines*; the term *motor* is reserved for solid fuel propulsion devices.

[28] Koppes, 11-14.

The development of JATO technology was the first major Army Corps contract that GALCIT/JPL earned. The successful development of JATO became the laboratory's first major technological breakthrough. Jacob Neufeld states that:

> Through his association with Maj. Gen. Henry H. Arnold, von Kármán won the backing of the Army Air Corps for the project at Caltech. The Air Corps was especially interested at that time in developing rockets for use as aids in the takeoff of heavily laden aircraft. Because the term "rocket" connoted something futuristic and impractical, however, it was decided to call them jet-assisted takeoff (JATO) devices instead. In January 1939 the Air Corps provided $1,000 for this jet propulsion research project, nicknamed Project GALCIT, after von Kármán's laboratory. Based upon the promising findings of the study, von Kármán won a $10,000 in July to design and construct small solid- and liquid-fueled rocket engines.[29]

The JATO was a solid-propellant or liquid-propellant motor or engine mounted on an aircraft to assist takeoff. Various ingredients fueled the JATOs including black powder, asphalt mixed with potassium perchlorate as an oxidizer, and a red fuming nitric acid (RFNA)/aniline mixture.[30] The GALCIT group tested liquid-propellant JATOs between August 1941 and April 1947 at Muroc Army Air Base (AAB), and at March Field in Riverside, California. The U.S. Navy used JATO extensively during the last two years of WWII for carrier-based operations in the Pacific.

Aerojet Engineering Corporation, a JPL spin-off company, was created to further develop and market JATO motors during the latter years of WWII.[31]

The JATO was also the propulsion system for Dr. John Paul Stapp's rocket sled between 1947 and 1951. The rocket sled was located east of the JPL Edwards Test Station at the Muroc Flight Test Base, which later became a part of Edwards AFB. Dr. Stapp was a pivotal figure in the development of improved safety restraints for aircraft pilots and in the consequent determination of human endurance limits in extreme decelerations. His work was instrumental in the eventual adoption of seat belts

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[29] Neufeld, 39.

[30] Koppes, 11-14.

[31] Daniel, Mann, Johnson, and Mendenhall; Koppes, 16-17.

by the American automobile industry.[32]

While the GALCIT was actively developing JATO, the Germans developed the pulse-jet V-1 and the V-2 ballistic rocket which attracted the attention of the Americans and the British during WWII. During the summer of 1943, GALCIT scientists studied and commented upon British intelligence reports concerning the V-1 and the V-2. In November 1943, GALCIT scientists concluded that the rockets held great military promise and urged their development by Army Air Force (AAF) Materiel Command. Materiel Command hesitated; however, Army Ordnance expressed a strong interest in rocket development. In January 1944, after the acquiescence of Materiel Command, the Ordnance Department contracted with Caltech's rocket team, GALCIT, to undertake the ORDCIT (Ordnance Department, California Institute of Technology) Project to design and develop a series of liquid-fueled rockets and associated launching hardware. This was the beginning of the Private and Corporal (and Sergeant) rocket programs that JPL developed for the Army. Frank Malina directed the development of the Private and Corporal rockets.

By the end of 1943, GALCIT consisted of about 85 people manning an office building, two laboratories, and several test pits.[33] The GALCIT began formally calling itself the JPL in 1944.[34] David Baker relates:

> that while most of the work embraced by these assignments was centered on rocket propulsion, the word 'jet' was applied in each and every case when an organization was set up to conduct theoretical and practical tests. The popular interpretation of the word 'rocket' had too flippant a connotation to engender the degree of respectability demanded by the work![35]

GALCIT's new name, JPL, brought an additional $3 million in

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[32] Stapp, John Paul. *Interview by Richard Wessel, Linda Stowe, Lewis Hiede, Ted Liveratos, and Frank Kou on 10 December 1992 at Edwards AFB, California*. Transcript on file, AFFTC/EM, Edwards AFB, California; Hudlow, 145.

[33] Daniel, Mann, Johnson, and Mendenhall.

[34] Koppes, 20.

[35] Baker, 72.

funding, and the tripling of the staff to more than 250 people.[36]

By the mid 1940s, population growth in the surrounding communities of Pasadena, Altadena, La Cañada, and Flintridge began to limit the facility's ability to conduct large-scale rocket engine tests.[37] At World War II's conclusion, the area was heavily settled with upper middle-class residences, some of which overlooked the Arroyo Seco. The area's residents "...objected to the noise of static tests, and to the laboratory's unsightliness."[38] For example, the Corporal E liquid engine produced 120 decibels of noise at an altitude of 200 feet.[39] The JPL scientists and engineers were forced to look for an isolated location where it would be possible to conduct noisy and hazardous tests. The JPL had tested JATO rockets at Muroc earlier and was familiar with the Base. Consequently, when JPL searched for a nearby, yet isolated, site for its rocket engine testing facility in 1945, the Muroc Flight Test Base was perceived as a perfect solution. The new JPL facility was known as the ORDCIT test station, until it was renamed the JPL Edwards Test Station in 1951.

Testing Missiles for the Army

Four major Army projects engaged JPL during WWII. In addition to the JATO project, JPL undertook an Army hydrobomb research program for the Materiel Command Aircraft Lab. The JPL also undertook ramjet research and had the ORDCIT contract for research and development of guided missiles.[40] The first projects conducted under the ORDCIT mandate explored different approaches to missile design.

The guided missile project led directly to the development

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36 Daniel, Mann, Johnson, and Mendenhall.

37 Gibbons, John and William C. Tibbitts. "JPL Edwards Facility Historic Overview". Typescript on file at AFFTC/EM, Edwards AFB, California, 1991:1.

38 Koppes, 48.

39 Bluth, John. (Archivist, Jet Propulsion Laboratory, Pasadena, California). Telephone conversations with Scott M. Hudlow, January 1995.

40 Koppes, 21; Neufeld, 42.

of the ORDCIT test station at the Muroc Flight Test Base, which was established in 1945. On 2 January 1945 the Air Technical Service Command, headquartered at Wright Field in Ohio, gave JPL permission to build a test facility at the Muroc Flight Test Base; construction began 16 days later. The test station was staffed and equipped by the ORDCIT Project and considered an extension of the Arroyo Seco facility in Pasadena, California.[41]

The ORDCIT test station was originally conceived as a hydrogen-oxygen liquid propellant test station. The V-2, the successful WWII German rocket used a hydrogen-oxygen liquid propellant mixture as fuel and oxidizer. This prodded the American scientists to emulate the German rocket. Frank Malina, however, stated:

> We did not switch to liquid oxygen after we knew the V-2 was using it and I pointed out in my ORDCIT memoir that I think the U.S. people made a big mistake in switching to liquid oxygen and falling head over heels for the German group. Now no military rocket uses liquid oxygen; it uses in fact storable propellants, the storable propellants that were developed at JPL. I think the V-2 caused a diversion in the military sense. I do point out that it was important later on for space testing.[42]

Discoveries by JPL during WWII led to a successful RFNA/aniline, oxidizer/fuel combination that was the basis of the laboratory's early liquid propellant research. Liquid propellants and oxidizers were the focus of the early rocket testing at Muroc, including hydrazine (N_2H_4) and mono methyl hydrazine ("MMH," or $CH_3HN \cdot NH_2$), which are extremely flammable and toxic, and commonly used as liquid propellants. Aniline ($C_6H_5NH_2$) was an early fuel. Liquid propellant rocket engines possess several important characteristics which make them attractive propellant systems to reach deep space. Liquid propellants are extremely excitable and hypergolic, which means that a small amount will go a long way and fuel and oxidizer will ignite spontaneously upon contact. Liquid propellants offer

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[41] Shoop, Richard L. *Historical Report of Technical Engineering, 4144th Army Air Field Base Unit, Muroc, California, for the Month of May [1946].* Report on file at AFFTC/HO, Edwards AFB, California.

[42] Malina, Frank J. *Interview by James H. Wilson, 8 June 1973.* JPL Archives, Oral History Program. Transcript of interview on file at the JPL Archives, Pasadena, California: 13.

long-term storage capabilities, and unlike a solid propellant, which burns constantly after ignition, liquid-propellant rocket engines can be shut down when propulsion is no longer needed.

The JPL planned a missile series that mirrored the military ranks. To the amusement of the Army Ordnance Department, the JPL planned to have the missile ranks stop at Colonel, because Von Kármán believed that was "the highest rank that works."[43] The ORDCIT test station's first major liquid propulsion project was the Corporal missile. The Corporal missile was the Army's second missile project. It was preceded by the Private A and Private F missile program, which did not lead to a production model.[44]

Private A was an eight-foot tall, 10-inch diameter, 530-pound, unguided, solid propellant rocket. It had a 10.3 mile range, and was JPL's first success in rocket-powered flight. The Private A missile was powered by an off-the-shelf Aerojet asphalt-based, composite solid-propellant JATO motor boosted by an Army Artillery solid fuel motor of 1,000 pounds thrust and a specific impulse of 186 seconds. When the Private A emerged in late 1944, it was seen as the first experimental platform for a series of sequential tests leading to development of the long range missile. Work on the latter aerodynamic design, the Corporal missile, awaited preliminary results from the Private A.[45] JPL's original research on solid propellants led to effective applications of solid propellants in several prominent 1950s and 1960s military missiles. Private A's success during the latter years of WWII brought pressure to improve the missile for use as a strategic battlefield weapon.

Private A's developmental process engendered the Private F missile. The Private F used the same solid-propellant motor as Private A. It was essentially a Private A with wings designed to add stability and increase range. The flight tests, performed at the Hueco Range, Fort Bliss, Texas, were dismal failures. Each Private F missile that was tested achieved a corkscrew flightpath trailing white smoke after a short flight. The JPL realized "...that a missile with lifting surfaces needed guidance

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[43] Koppes, 22.

[44] "JPL Activities at White Sands and Edwards Commence in 1945." *LAB-ORATORY*, May 1953:5.

[45] Baker, 73-4.

equipment for satisfactory performance."[46] With this lesson in mind, the JPL began moving towards the more complex Corporal rocket.

Before JPL developed the successful Corporal E missile, several generations of Corporal missiles were designed, including the "Without Altitude Control," (WAC) Corporal. WAC also stood for "Women's Army Corps" since the WAC Corporal was considered the little sister of the Corporal E.[47] The WAC Corporal was a sounding rocket that was also a test version of several liquid-propelled rockets, including the Corporal E missile. David Baker states that:

> Malina had high hopes that the rocket would play an increasingly successful role in the field of pure science, but recognized the difficulty in getting military funds for a project which had little application to the needs of the armed forces. Yet, there was much that a sounding rocket could provide that would be essential information for the following generation of ballistic and guided missiles and the drive to pursue a more benevolent, scientific, research activity could well find equivalence in the requirements of the services.[48]

The WAC Corporal had been inspired by a U.S. Army Signal Corps requirement, processed through the Ordnance Department, for an atmospheric sounding rocket capable of reaching a height of 1000 feet carrying a small 25-pound payload. Work began in 1944. The Douglas Aircraft Company collaborated with JPL to produce the rocket.

The WAC Corporal had a solid-propellant booster and utilized an aniline and nitric acid, liquid fuel/oxidizer combination. The WAC Corporal could reach a maximum speed of 2,850 miles per hour during ascent, and carried three clipped triangular fins at the booster stage. It later formed part of the Upper Air Research Program. In October 1945, a WAC Corporal flew to a height of 2,150 feet with a 25-pound payload. The WAC Corporal went on to form the design basis for the Aerobee sounding

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[46] Koppes, ?.

[47] Koppes, 23.

[48] Baker, 74.

rocket.[49]

The WAC Corporal rocket engine was probably the first rocket engine tested at the Muroc test station. Its prototype engine was fired on 19 September 1945.[50] The WAC Corporal was a pencil thin 16-foot tall missile; it was fueled by a modified liquid-propellant JATO engine using RFNA and aniline. The JPL reported that "the WAC Corporal, began production in 1945, following conferences with Ordnance Department. Firing tests on the WAC Corporal were held during the month of October, 1945 at White Sands Proving Ground."[51]

Compared to the earlier Private F flight tests, the October 1945 WAC Corporal tests were amazingly successful. The WAC Corporal engine shut off at about 80,000 feet, yet the radar tracked the missile to a height of about 230,000 feet, more than 40 miles. It flew for 7.5 minutes.

The JPL personnel were thinking beyond the somewhat limited capabilities afforded by the WAC Corporal ballistic sounding rocket in 1945. They were looking to the stars. The pressing need for war munitions was over, and it seemed an opportune moment to consider rocketry's future beyond the context of the needs of the armed services. Towards the end of 1945, JPL conducted a brief study on the possibility of launching an artificial earth satellite and concluded that, using the same propellants as those designated for the WAC Corporal it would require a rocket with 3.1 million pounds of thrust to place a 10-pound payload into a path that would reach escape velocity. The rocket would consist of 5 stages, each operating sequentially to achieve the speed of 24,860 miles per hour. The JPL team theorized that even if more efficient propellant combinations could be found and the mass of the rocket decreased accordingly, and even with the most ideal chemistries, the assembly would still be prohibitively large for the technology then in existence.[52]

Four years later, A WAC Corporal missile was the first

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[49] Baker, 259-60.

[50] "Edwards Tests Station Marks 10th Birthday." *LAB-ORATORY*, April 1955:3.

[51] *LAB-ORATORY*, May 1953, 5.

[52] Baker, 76.

manmade object to leave the Earth's atmosphere. On 11 October 1949 at White Sands, New Mexico, a WAC Corporal was attached to a captured German V-2 rocket and launched into the stratosphere. The WAC Corporal/V-2 combination was called the Bumper-WAC; it was also the first successful staged rocket to leave the Earth's atmosphere.[53]

The Bumper-WAC program was implemented between 1948 and 1950 as part of General Electric's (GE) Hermes project. GE needed to study the technical problems of separating rocket stages in flight, determine the possible instability of high altitude flights in the rarefied atmosphere, and evaluate techniques for high altitude ignition. The Army married the V-2 and the WAC Corporal, with the latter mounted on the nose of the V-2, so that WAC Corporal could reach greater altitudes than the single stage V-2.

The WAC Corporal was used without the solid propellant booster normally fitted to the sounding rocket, since it was unnecessary. The V-2 would act as the booster rocket. At liftoff, the Bumper-WAC combination stood nearly 62 feet tall and weighed 13.12 tons. In the Bumper-WAC configuration, the WAC Corporal had a length of 16 feet and a diameter of one foot. The 46-foot-long V-2 provided a first stage boost of 25 tons at liftoff and about 29.6 tons at altitude. In a typical flight, the V-2 would carry the WAC Corporal on its nose for 60 seconds of main engine burn. The V-2 would shut down and separate from the WAC Corporal which would then fire its liquid-propellant engine for 45 seconds with a thrust of 150 pounds. The last two Bumper-WACs were launched from Cape Canaveral in 1950. These were the first flights from what is now known as the Kennedy Space Center, Florida.[54] The Bumper-WAC again anticipated future directions, when JPL would truly begin to look to the stars.

Corporal Rockets and Test Stand "A"

A spartan industrial landscape burgeoned in the high desert to support the vital missile testing. The JPL test station at the Muroc Flight Test Base was developed to static-test the propulsion systems on Corporal missiles. The original complex was 40 acres. Many JPL personnel lived at the station, staying full-time for weeks on end, others traveled from Pasadena to

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53 Koppes, 40-41; McDougall, 99.

54 Baker, 234.

Muroc to conduct tests as needed. John Gibbons and William C. Tibbitts wrote:

> The first major project at the Edwards Test Station (ETS) was the development and qualification testing of the Corporal Missile in the late 1940's. This was a liquid-propellant system, tested on "A" Stand, that produced 20,000 pounds of thrust. At that time, this represented the largest rocket engine test stand in the free world.[55]

Initially, development centered around the Corporal Test Stand (known as Test Stand "A" after 1957) and the associated facilities necessary to support the test stand, which was built in early 1945. A plaque in front of the JPL administrative building commemorates the first firing that was supposedly conducted on 2 April 1945. However, the JPL site log states that the first firing was conducted on 19 June 1945 at 4:30 P.M.[56] The 2 April 1945 date actually honors when the first JPL employees arrived at the test station as it neared completion.

The test stand is a small steel frame anchored to a heavy reinforced concrete foundation. The stand has a vertical atmospheric firing position with a large excavated flame pit to the east into which flames and exhaust were expelled. Rocket engines were strapped into the stand for static testing.

The JPL test station at Muroc recieved its formal name, the JPL Edwards Test Station in 1951. The name change reflected the test station's change in status from a temporary to a permanent station. Nomenclature changes at Edwards AFB affected the JPL name change. During WWII, two distinct facilities had been located on the Muroc Army reservation. Muroc AAB was a training facility for B-24 *Liberator* bomber and P-38 *Lightning* fighter crews; the Muroc Flight Test Base was a top secret flight test base for early Army jets, particularly the Bell XP-59A *Airacomet*. The Muroc Flight Test Base had an identity distinct from Muroc AAB. The JPL test station at Muroc was located at the Muroc Flight Test Base. The two facilities, the WWII training base and the WWII flight test base, were integrated into one Base in 1947, when the United States Air Force was created. In 1949, Muroc AFB became Edwards AFB.[57]

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[55] Gibbons and Tibbitts, 1.

[56] Bluth Interview, January 1995.

[57] Hudlow, 16.

The Corporal E, a surface-to-surface, liquid-propellant missile, was successfully developed for the Army. The program began in 1944; it was the U.S. Army's first generation, short range ballistic missile. The Corporal E was an American response to the German V-2 and adopted several technical approaches reminiscent of the V-2. Graphite vanes in the exhaust nozzle effected radio guidance and control. The first Corporal E was a "...full-size, surface-to-surface liquid propellant missile. The heavy 39-foot long Corporal weighed 4,963 pounds empty and 11,700 pounds when fueled and was designed to carry a 300- to 500-pound payload 62.5 miles."[58] It used a RFNA/ethyl aniline, oxidizer/fuel combination to produce a thrust of nearly 9.1 tons. Four elongated fins were attached to the base of the single stage rocket. This missile was subsequently disparaged, because it was an expensive system, although it met all of the Army's requirements. The Corporal E only had a range of 50 miles.[59]

The Corporal E engine test facilities were completed in June 1945 at Muroc Flight Test Base. They were operated under the direction of Walter B. Powell, the first engineer-in-charge at JPL's Muroc test station. The rocket engines were fired vertically downwards for 1.5 minutes on Test Stand "A." The first engine, Type 1, a regenerative-cooled rocket engine, was ready for testing by 12 September 1945. The Type 2 rocket engine was ready 3 months later. The Type 3 film-cooled rocket engine was not used for the Corporal rocket, and a Type 4 rocket engine with longitudinal cooling, expansion joints, and 20,000 pounds of thrust was discussed. Test data was recorded by cameras photographing the instrument panel in Building 4203/E-4, the Test Stand "A" Control Center, now known as the Test Stand F Monitor, located 60 feet south of the test stand.

The first Type 1 regenerative-cooled rocket engine was tested at Muroc on 10 December 1945. Although the equipment had been thoroughly checked by feeding water through the propellant circuits, the Type 1 regenerative-cooled rocket engine's throat burned out after 15 seconds. However, the Corporal E engine run was not stopped until 48 seconds had elapsed. This was the first

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[58] Koppes, 39.

[59] Caidin, Martin. *Countdown for Tomorrow: The Inside Story of Earth Satellites, Rockets and Missiles and the Race Between American and Soviet Science*. New York, New York: E. P. Dutton and Co., Inc., 1958:235; Baker, 234.

test firing of a Corporal E engine at JPL's Muroc test station.[60] Other engine designs were discussed, including copying the German Wasserfall engine or a Type 5 engine with expansion joints and helical cooling passages. Types 3 and 4 rocket engine development was stopped, and a second Type 1 rocket engine was test run about 9 January 1946. A water-cooled Type 2 engine was tested on 18 January 1946; it ran for 64 seconds and produced 17,600 pounds of thrust.

By January 1946, the Corporal E missile, with conditioned engine requirements, had a range of about 60 miles. A planned January 1946 Corporal E missile test firing date was changed to 15 July 1946. By May 1946, this test date was postponed to 11 October 1946. Scaled down (1/5) test models, "Baby Corporal Es," were test-fired at the Muroc test station on 6 May and 7 May 1946. The Baby Corporal Es were fired vertically on a rail launcher, demonstrating the possibility of zero-speed vertical launch with no jet vanes.[61] By mid-July 1946, engine and tank fabrication difficulties had delayed the Corporal E test firing until 1 December 1946. The JPL successfully launched the first Corporal E on 22 May 1947 at White Sands Proving Ground, New Mexico; its propulsion subsystem had been tested and qualified at the Muroc test station.[62]

The Army pitted GE and JPL against each other in the simultaneous development of the Hermes missile versus the Corporal missile system. In 1947, Army Ordnance decided to make Corporal a weapon; however, from the end of WWII until the summer of 1949, when it became a weapons program, the Corporal was considered an advanced systems development vehicle. Corporal's development and testing provided the overall integration to understand system problems. Meanwhile, GE's Hermes A had a 75-mile range and flew; the Hermes B, which was theorized to have a 150-mile range, never flew. Army Ordnance worried that a tactical missile would not be ready for field deployment by the mid 1950s, if it depended on GE. JPL officials assured Army Ordnance that the Corporal E would be ready. In the mid 1950s, it became the Army's first battlefield ballistic missile.

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[60] *LAB-ORATORY,* May 1953:5.

[61] This rail launcher still survives and appears in HAER photo CA-163-6. It is slated for preservation by the Edwards .

[62] Koppes, 39.

Sergeant Missile

The next planned guided missile in JPL's missile ranks was the Sergeant missile, a solid-propellant rocket, which was tested at Pasadena in the late 1940s and into the 1950s. Solid propellant testing continued at Pasadena until 1962, when it was moved to the JPL Edwards Test Station.

Solid propellants are a combination of fuel and oxidizer, which is brought together and mixed into a single solid mass called the "grain." The fuel is usually prepared in a liquid state; the oxidizer was prepared in a solid state, usually as a powder, and mixed with the fuel. When the grain is prepared, it solidifies to form the propellant. An alternative solid propellant is a double-base type solid propellant. In this combination, each of the two primary constituents could, theoretically, burn on its own accord in a vacuum. The double-base type solid propellant contained a mixture which has the properties of fuel and oxidizer. The two constituents together provide better burn characteristics than either demonstrated alone.

The Sergeant rocket motor overcame theoretical problems that halted earlier attempts to use solid propellants. Solid propellants had power and sustainability problems that were difficult to overcome. The Sergeant emerged as a single-stage, solid propellant rocket with a length of 34 feet and a 30-inch diameter. The forward section was an elongated cone with straight sides that converged to a point; four stabilizing aerodynamic fins were clustered around the base. The XM-100 solid-propellant rocket motor produced a thrust of 20.4 tons; launch weight was around 4.58 tons.[63] The Sergeant was the first ballistic missile to benefit from advancements in solid-propellant technology.

In 1945, a JPL engineer demonstrated that a rubberlike polysulfide developed by the Thiokol Corporation possessed many of the best characteristics of the asphalt solid propellant the JPL was using in its JATO. However, the rubberlike polysulfide developed a burning-rate problem and formed a cone inside the propellant charge. The problem was solved by utilizing the star-shaped solid propellant charge developed by English researchers and scientists at the Allegheny Ballistics Laboratory in West Virginia. Clayton Koppes related that:

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63 Baker, 248.

JPL researchers learned of the star almost by accident, through an appendix to another report being circulated among military laboratories. For the Thunderbird motor [a small, 6-inch diameter rocket designed to test the polysulfide solid propellant] the engineers applied a thin liner to the wall of the combustion chamber, then mounted a ten-point-star-mold core in the center of the chamber. They poured the polysulfide propellant in the chamber and, when the propellant began to harden, removed the star. The design was simplicity itself. When the Thunderbird motor was ignited, the charge burned slowly from the inside, and the star gradually formed a cylinder. The burning-rate problem was solved, and the polysulfide proved it could withstand the acceleration.[64]

The development of an efficient solid propellant is JPL's and America's distinct contribution to rocketry. It opened the doors for the development of large solid-propellant rockets such as Minuteman, Polaris, and Poseidon, which were developed at various laboratories in the 1950s and 1960s.

Although JPL was successful in developing the Corporal and Sergeant missiles, the organization was not comfortable conducting classified military research. The need for secrecy struck many JPL personnel as distinctly at odds with the goals of higher education as exemplified at Caltech and with the desire to conduct scientific research.[65] The JPL ceased military applications after the Sergeant missile's successful development and militarization in 1960. The 20-year association with Army Ordnance was over.

Deep Space: The Next Frontier

The JPL spent the 1950s transforming the Corporal E and Sergeant missiles into effective weapons systems for the Army. However, they were beginning to shift from guided missile research to instrumented deep space exploration.

While JPL was working for the Army on the Corporal and Sergeant missiles, a German group was also working for the Army. The Army brought several hundred German engineers and scientists, including Dr. Wernher von Braun, to the United States during Operation Paperclip after WWII, before the Russians were able to

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[64] Koppes, 37.

[65] Koppes, 30-61.

spirit the scientists away to Russia. The Army also captured a supply of German V-2 rockets. The Army organized a team of these German scientists at Fort Bliss, Texas to conduct studies concerning development of long-range, surface-to-surface guided missiles, including an effort to refine the German V-2. In May 1946, the German scientists began helping the Army test launch the captured V-2 rockets at the White Sands Proving Grounds, New Mexico, which is adjacent to Fort Bliss. Several years later, the German scientists were transferred to the Redstone Arsenal in Huntsville, Alabama, and began developing the Redstone missile. Dr. von Braun and his German colleagues formed the basis of the Army Ballistic Missile Agency (ABMA).

The Navy and Air Force (then the AAF) also began their own missile programs in the late 1940s. It briefly appeared that a single national guided missile program would be established to eliminate duplication of effort among the services. The Army and Navy both favored such a development; however, the AAF strongly opposed the plan. Officials from the AAF feared that a single program would jeopardize their chances of gaining sole responsibility for development and deployment of long range guided missiles. An interservice rivalry over control of guided missiles ensued as each service sought to define its role and mission. The ambiguous nature of guided missiles helped fuel the controversy over control of missile development and deployment. Army officials claimed that ground-launched missiles were merely extensions of artillery and therefore the Army's responsibility. However, Air Force officials claimed that missiles were robot, or pilotless, aircraft and therefore fell under the jurisdiction of the Air Force.

The first foray by JPL into space exploration began modestly in 1954. The JPL embarked on the development of Orbiter, an artificial earth satellite, in collaboration with the ABMA and the Office of Naval Research (ONR). The Orbiter project was planned to help celebrate the forthcoming 1957 International Geophysical Year (IGY). This proposal was competing for the right to build the first American satellite. The Orbiter satellite proposal was composed of a Redstone solid-propellant rocket as a first stage, and downsized Sergeant motors for the second and third stages necessary to place the satellite in orbit around the Earth. This project marked the beginning of a phased program for instrumented deep space exploration involving JPL and the Army.[66]

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[66] Daniel, Mann, Johnson, and Mendenhall; Koppes, 79-87.

The ABMA/ONR/JPL entry into the satellite competition was impressive. Two other proposals were prepared in addition to the Orbiter proposal. The Orbiter proposal's competition came from the NRL's Vanguard proposal, and an Air Force proposal, which entailed the use of an Atlas rocket coupled with an Aerobee-HI second stage to achieve earth orbit. However, President Dwight D. Eisenhower wanted the project to have a non-military focus and desired to have America's first satellite utilized in peaceful and scientific studies.[67]

Faced with the three plans, the Department of Defense organized a special advisory group to review the various proposed satellite programs and make recommendations. Although the special advisory group favored the use of an Atlas missile, the NRL gave Vanguard superior electronic technology to transmit scientific data from space back to Earth. The committee was also concerned about adapting military missiles instead of developing a nonmilitary rocket. The advisory group eventually decided that the Navy program had the best chance of placing the most useful satellite into orbit within the IGY. These factors steered the advisory group to favor Vanguard, which it chose. This decision led to a controversy, over which was the best proposal, Orbiter or Vanguard. The Soviet Union's successful launching of *Sputnik* on 4 October 1957 made the Orbiter-Vanguard controversy a moot point. Instead, *Sputnik* bred a controversy over whether choosing Vanguard was a good decision.[68]

The JPL did, however, find an outlet for its Orbiter project. The ABMA in the mid 1950s was engaged in an interservice rivalry with the Air Force. This rivalry involved developing the Jupiter medium-range ballistic missile before the Air Force finished its Thor medium-range ballistic missile. The Orbiter studies helped the ABMA create the reentry test vehicle (RTV), which became the Jupiter missile's ablation-type nose cone. The JPL also contributed its Microlock electronic technology to the Jupiter missile studies. The Microlock electronic technology is a phase-locked loop tracking system, which later became the foundation of the Deep Space Network (DSN) that tracks deep space vehicles. The first RTV was fired by the Army on 20 September 1956, and attained an altitude of 682 miles and a range of 3,350 miles, new records for American missiles. The ABMA was not allowed to launch a satellite, so the fourth stage was filled with sandbags. However, if the ABMA/JPL RTV had

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67 McDougall, 119-123.

68 Koppes, 78-84.

contained the fourth and last stage, it would have become the first orbiting satellite.[69]

The Soviets launched the first satellite to gain orbit, *Sputnik*, on 4 October 1957. The diverse American groups scrambled to respond to the immediate loss of prestige in the eyes of the American public and the perception that the U.S. was falling behind the Soviet Union.[70] Three weeks after *Sputnik*, Orbiter was given a renewed opportunity, but not before the Vanguard team had its try. Orbiter's name was changed to *Explorer 1*, and it continued as a backup to Vanguard. One month later, on 3 November 1957, the Soviets placed *Sputnik 2* in orbit, which included Laika, the space dog.

Project Vanguard was plagued with technical problems. The Vanguard launch vehicle, which had not been perfected prior to this undertaking, frequently exploded. Vanguard was launched on 6 December 1957. It never left the pad. Instead it sat and burned uncontrollably on national television.

Meanwhile on 8 November 1957, JPL had been authorized to proceed with Explorer launch preparations. The Explorer satellite was launched on 29 January 1958, boosted by a Redstone medium-range rocket developed by the ABMA. *Explorer 1* was a success and America's first artificial satellite. While *Explorer 2* did not achieve orbit because of a structural failure, *Explorer 3* was the second American satellite in orbit on 26 March 1958. *Explorer 3* also discovered the Van Allen belts which circle the Earth. The JPL was now firmly established as the nation's leading space program, as well as a leading missile development agency.

In December 1958, various military space programs and contractors were consolidated into the National Aeronautics and Space Administration (NASA) including the JPL sites at Pasadena and Edwards.[71] The JPL was reluctant to join the new NASA space agency. The JPL felt it had the opportunity to become the lead contractor for the new space agency, a role which NASA did not necessarily endorse. The NASA was created from the National

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[69] Koppes, 80.

[70] McDougall, 132.

[71] Butowsky, Harry A. *Man-in-Space National Historic Landmark Study*. Washington, D.C.: National Park Service, Department of Interior, 1984:19.

Advisory Committee on Aeronautics (NACA); President Eisenhower gave NASA the right to absorb any space-related agency it wanted, such as the NRL, which had developed the failed Vanguard rocket and satellite, and the ABMA, which became Marshall Space Flight Center in Huntsville, Alabama.

By 1959, NASA's primary goal was to land a manned spacecraft on the Moon. NASA was specifically pushing Project Mercury, the first manned space program. However, JPL decision makers decided to develop unmanned rather than manned spacecraft. The JPL would have the primary role in the unmanned program, rather than join the other numerous NASA installations involved in the manned spacecraft program.[72] The JPL Edwards Test Station would play an important role in JPL's unmanned deep space exploration program, according to Gibbons and Tibbitts:

> Under a NASA contract, JPL received its first assignments to lead the nation's unmanned exploration of the solar system. The Edwards Facility has supported JPL in this work from the start and has made significant and vital contributions to JPL's leadership in lunar and interplanetary exploration.[73]

Thus, JPL, including the JPL Edwards Test Station, quietly laid the groundwork for a successful manned space program through its technological breakthroughs and successful scientific missions in the unmanned space program. During this period, JPL established deep space tracking stations at six overseas sites controlled by a 85-foot antenna at Goldstone [Fort Irwin], near Barstow, California which was listed on the NRHP as a NHL in 1985. These installations and the ground communication system linking them constitute NASA's DSN.[74]

The JPL laid out a course of unmanned deep space exploration and proposed it to the new NASA officials in early 1959. The JPL planned to commence with a circumlunar probe and expand outward to planetary exploration. The primary determinant for which planet to visit first was its proximity to Earth; JPL created a 5-year plan to visit or flyby Venus and Mars. The proposal was modified by NASA and JPL, who developed a revised space program in 1960. The new space exploration program coupled NASA's desire for lunar flight with JPL's predilection for planetary

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[72] Koppes, 94-100; Newell, 103.

[73] Gibbons and Tibbitts, 1.

[74] Daniel, Mann, Johnson, and Mendenhall.

investigation. The lunar hard landers were called *Rangers*, and the Venutian, Martian and Mercury orbiters and probes were called *Mariners*.

From 1959 to 1987, every spacecraft launched by JPL had its propulsion subsystems qualified at the JPL Edwards Test Station. This included the *Pioneer* series of interplanetary probes, the *Ranger* lunar series in the early 1960s, the *Surveyor* lunar landers in the mid 1960s, the *Mariner* series of interplanetary landers and probes in the 1960s and early 1970s, the *Viking* Mars orbiters and landers in the mid 1970s, and the *Voyager* series which conducted flybys of Jupiter in the late 1970s. *Voyager 1* departed the solar system in 1980 after conducting a flyby of Saturn. *Voyager 2* is heading into interstellar space also. It conducted flybys of Saturn, Neptune, and Uranus into the 1980s.[75] The liquid propellant propulsion testing for these spacecraft was conducted at Test Stand D, which was built in 1959.

The Ranger Spacecraft

The Ranger series was the first class of deep space vehicles JPL developed. The Ranger vehicle series was developed in blocks of three to five spaceflights that had related missions. The early Ranger vehicles were designed to test spaceflight technology, and to discern whether the Ranger design was satisfactory for reaching the moon. The second block of Ranger missions was designed for science experiments; on these missions Rangers incorporated television cameras, a seismometer, and a gamma-ray spectrometer. The third block of Ranger missions was designed to support manned spaceflight objectives directly.

The Ranger series began inauspiciously on 22 August 1961 after four aborted launches. The launch of *Ranger 1* was successful; however, the second stage of the Agena rocket, which was designed to place it in the moon's orbit, failed. *Ranger 1* tumbled into Earth's atmosphere and disintegrated. Nevertheless, JPL engineers believed they had enough data and readied *Ranger 2* in an optimistic mood. *Ranger 2* suffered the same fate as *Ranger 1*--the Agena second stage burn did not work correctly. The spacecraft was destined for a fiery death. *Ranger 3* overcame the propulsion problems with the Agena rocket; however, it became rapidly apparent that a computer code had been inverted. *Ranger 3* was flying a mirror image of its intended flight path. *Ranger 3's* antenna was not pointing toward Earth; the central computer

[75] Gibbons and Tibbitts, 1.

and sequencer failed. *Ranger 3* tumbled out of orbit and sped into solar orbit. Suffering from a bout of optimism--although privately officials doubted if the mission would be successful--JPL launched *Ranger 4* in 1962. It landed on the moon on 26 April 1962; unfortunately, the spacecraft was dead on arrival. Nothing worked once *Ranger 4* reached the moon, because the master clock and sequencer had failed. A NASA official was quoted as stating, "All we've got is an idiot with a radio signal."[76] While *Ranger 4* was a failure in most respects, it was, indeed, the first American spacecraft to land on the moon.

Following *Ranger 4*, five months elapsed while JPL reevaluated the program. *Ranger 5* was launched on 18 October 1962. Barely an hour into the flight, electric power from the solar panels short-circuited and the craft's temperature soared. *Ranger 5* was switched to battery power, even though the batteries would be exhausted long before the spacecraft reached the moon. A mid-course correction was attempted to ensure that *Ranger 5* hit the moon; however, the spacecraft missed it by 450 miles.

The Ranger program was in shambles. The NASA and JPL responded by completely overhauling the program. Controversial sterilization practices were canceled, excess scientific experiments were ditched, and *Ranger 6* was postponed for a full year. *Ranger 6* launched on 30 January 1964. It had a perfect flight to the moon, except that in mid-flight the television telemetry system activated for 67 seconds then shut itself off. *Ranger 6* landed perfectly on a hard lunar surface, but the television system never reactivated. The NASA reacted bitterly to another Ranger failure, and proceeded to target the Ranger project for cancellation. The JPL's management was desperate to find a suitable solution. A Ranger success was the only item that could redeem JPL. On 28 July 1964, *Ranger 7* sailed towards the moon. It landed three days later on the lunar surface. The cameras came on line and displayed the lunar landscape for the first time. Finally, a Ranger had worked. Now that JPL had a success to build upon, the remainder of the Ranger spacecraft worked wonderfully.

Ranger led from hard landers to the *Surveyor* series of controlled soft landings on the moon which transpired in the mid 1960s in direct support of NASA's manned Apollo program. *Surveyor 1* made the first soft landing on the moon on 2 June 1966 and demonstrated that the lunar surface could support a spacecraft. *Surveyor 6* lifted off from the moon and moved to a

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[76] Koppes, 126.

new location, demonstrating the first engine restart on an extraterrestrial body.[77]

The Mariner Spacecraft

The early Mariner interplanetary probes were developed and launched while JPL was undergoing the Ranger crises. While the early Ranger series was experiencing excruciating problems, the Mariner spacecraft soared fairly smoothly and even exceeded expectations in some instances. Mariner's goals were "...to pass near the planet, to communicate with the spacecraft near the planet, and to perform a meaningful Planetary experiment."[78] *Mariner 1* experienced the worst problems of any Mariner or Ranger spacecrafts; it was destroyed within 5 minutes of launch on 22 July 1962. The launch vehicle and spacecraft veered on a wildly erratic course and was destroyed by the range safety officer: a hyphen had been omitted in the launch-vehicle guidance system equations.[79]

Mariner 2 was launched a month later on 26 August 1962, and seemed destined for a fate similar to *Ranger 1* and *Ranger 2*. However, the guidance problem was solved before the Agena second stage separation. *Mariner 2* soared for Venus and passed it on 14 December 1962, providing scientists with unparalleled scientific data about the planet. Furthermore, *Mariner 2* succeeded in proving that spacecraft could reach neighboring planets with accuracy. *Mariner 2* set a communication record by sending a signal 54 million miles, and lastly, *Mariner 2* functioned perfectly for several months, dispelling several myths about space travel.[80]

After a 2-year hiatus, *Mariner 3* and *Mariner 4* flew in 1964. This time reaching Mars was the goal; Venutian exploration was shelved until more sophisticated spacecraft were built. *Mariner 3* was launched for Mars on 5 November 1964, after designers found innovative means to overcome new problems attendant upon shooting for a more distant target. The spacecraft quickly ran into

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[77] Valerie Neal, Cathleen S. Lewis, and Frank H. Winter. *Spaceflight: A Smithsonian Guide*. New York, New York, W.W. Norton, 1995:135.

[78] Koppes, 127.

[79] Koppes, 128.

[80] Koppes, 129.

problems. A protective fairing, a nose shield, would not eject, creating two major problems: the spacecraft weighed too much to reach its target, and its solar panels would not unfurl. *Mariner 3* was declared dead after nine hours. A team of JPL, Lockheed, and Lewis Research Center personnel found that the fiberglass fairing was not vented; it exploded violently in a heat-vacuum test, revealing *Mariner 3*'s most likely fate. Lockheed, the fairing's manufacturer, quickly cast a vented magnesium fairing. This saved the *Mariner 4* shot, which had a month-long launch window after the *Mariner 3* fiasco. The launch window would be closed for two years, if *Mariner 4* could not be saved. *Mariner 4* was launched successfully on 28 November 1964. It reached Mars on 14 July 1965, and relayed the first television photos of the Martian surface. *Mariner 4* dispelled several myths about the Martian landscape and delivered new information about Mars to scientists.[81]

The important and successful Mariner series of interplanetary flybys continued into the mid 1970s. *Mariner 5*, a modification of *Mariner 4*, was launched towards Venus on 14 June 1967.[82] *Mariner 5* provided data on atmospheric readings, temperature, and magnetic fields. Venus was found to have no significant magnetic field which is probably due to Venus's slow solar rotation, only 243 Earth days, and extremely high surface temperatures.[83] *Mariner 5* used radio signals to probe the Venutian atmosphere.

Mariner 6 and *Mariner 7* were Mars flyby missions launched on 25 February 1969 and 27 March 1969 respectively.[84] *Mariner 6*, which arrived at Mars on 30 July 1969, "took measurements of the structure and composition of the atmosphere, images of the surface, and measurements of surface temperature."[85] *Mariner 6* also carried a infrared spectometer, to sense the spectral distribution of Martian heat energy.[86] *Mariner 7* was an

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[81] Koppes, 165-172.

[82] Bruce Murray. *Journey into Space: The First Thirty Years of Space Exploration*. W. W. Norton, New York, New York, 1989:88.

[83] Neal *et al*, 164.

[84] Murray, 56.

[85] Neal *et al*, 168.

[86] Murray, 55.

identical mission to *Mariner 6*, scheduled to study the polar regions of Mars. However, the radio signal died; a rechargeable battery on *Mariner 7* had exploded and destroyed critical portions of the spacecraft. *Mariner 7* was reprogrammed to bypass the damaged portions of the spacecraft, and resumed its polar mission.

Mariner 8 and *Mariner 9* were designed as a joint mission to fly complimentary polar and equatorial orbits around Mars. However, *Mariner 8* suffered a launch failure, when it was attempted on 8 May 1971, and landed in the Atlantic Ocean. *Mariner 9* survived the launch on 30 May 1971[87] and spent a year conducting the work of two spacecraft mapping Mars using radar and thermal imaging, after encountering an initial dust storm. It demonstrated that Mars had distinct northern and southern hemispheres, volcanic features, dry river channels, lava flows and polar regions comprised of carbon dioxide (CO_2), which suggests that Mars once had a warmer, wetter climate.[88] *Mariner 9* was the last mission to Mars before the Viking missions in the mid 1970s.

Mariner 10 was a mission to orbit Venus and flyby Mercury. Mercury was thought to be a planet that could reveal important information about the Moon. Mercury was thought to have a heavily cratered surface that could have maria (dark plains), "giant scars recording collisions from an extinct family of Earth-circling satellites that once accompanied the moon."[89] Mercury was also interesting as a place to test geologic theories since it was thought that one side of Mercury was perpetually in sunlight and extremely hot, while the other side was in the eternal cold and darkness of the planet's nightside. Before *Mariner 10* Mercury's dark side was thought to be the coldest place in the solar system.[90] *Mariner 10* was launched on November 3, 1973 and underwent several crises, including an electronic glitch that caused its computer to reset. The spacecraft's primary power system fluctuated periodically, its nitrogen attitude-control gas hemorrhaged, and the movable scan platform starting sticking before *Mariner 10* arrived at Venus on

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[87] Murray, 59-61.

[88] Neal *et al*, 168-69.

[89] Murray, 93.

[90] Murray, 95.

5 February 1974.[91] *Mariner 10* arrived at Mercury in March 1974 and found that Mercury resembled the Moon and could be compared to it, vindicating the mission's premise. Mercury was also found to emit excess natural radio noise from the supposedly frigid nighttime side of the planet, which demonstrated that Mercury's nighttime side is not the coldest place in the solar system. *Mariner 10* discovered the planet's magnetic fields and studied the planet's surface and atmosphere during its three flybys. *Mariner 10* was also the first probe to visit two planets and to use a gravity-assist technique for interplanetary travel.[92]

Viking and Voyager

By the mid 1960s and into the early 1970s, JPL had finally begun solving many of the earlier technical problems and was consistently developing successful interplanetary spacecraft. *Mariner* brought plans for a Martian lander. The *Viking* series of orbiters and landers brought these plans to fruition in the mid 1970s. *Viking 1* and *Viking 2* were launched in August and September 1975 to ascertain signs of life on Mars. The Viking landers carried a gas chromatograph/mass spectrometer (GCMS), which was designed to separate and identify organic compounds. The Viking's GCMS could detect a few parts per billion of nearly any carbon-based organic compound in a soil sample. The Martian soil was collected by the Viking lander and subjected to gas-exchange tests and labeled-release tests in which the Martian soil was combined with nutrients that terrestrial organisms commonly consume and a serving of basic, fundamental organic compounds, such as amino acids, respectively. Water vapor and liquid water were combined with the soil in both sets of tests. A third test analyzed the role of CO_2 in the Martian atmosphere and the impact of solar energy on the metabolic processes on any potential Martian organisms. The tests were too strong for the Martian soil to reveal sign of microorganic life. Chemical reactions were created, rather than biochemical. Not a single organic molecule was found, it is a completely sterile environment.[93]

Viking 1 touched down on Mars on 20 July 1976, 7 years after Man first walked on the moon. Its cameras revealed a dry, barren, rocky, and rust-colored surface. Mars was found to be

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[91] Murray, 113-14.

[92] Neal *et al*, 174.

[93] Murray, 69-73.

rust- or red-colored due to the amount of oxidized iron in the soil and due to the dry, arid nature of the desert-like planet. Water is possibly restricted to a permafrost layer below the surface and the polar ice cap. *Viking 2* touched down on the side of Mars opposite to *Viking 1* and combined with *Viking 1* to map nearly 100 percent of the planet's surface over the next three years. *Viking 1* expired in 1980 and *Viking 2* terminated in 1982. The Viking landers hopped from location to location using their rockets to maneuver. The Vikings studied the gravitational field and atmospheric water vapor. A thermal map of Mars was also created. The landers transmitted more than 4,500 images and conducted biological soil and atmospheric tests. The *Viking Orbiters* lasted until 1980 and transmitted over 52,000 color and stereo images of Mars.[94]

The late 1960s brought the initial planning for Voyager, which was conceived as proceeding on a "Grand Tour" of the solar system.[95] The Grand Tour was canceled in 1972 due to budgetary concerns, since it was planned as an expensive flyby project through the entire solar system. JPL responded by formulating a cheaper project called Mariner/Jupiter/Saturn (MJS), which was approved and transformed into Voyager. The Voyagers were scheduled to encounter Jupiter and Saturn, and possibly Uranus. Voyager had an enhanced computer which drove the attitude control system.[96]

The identical *Voyager 1* and *Voyager 2* were launched in 1977. *Voyager 2* was launched on 20 August 1977, sixteen days before *Voyager 1*, which was launched on 8 September 1977. *Voyager 1* is was the first Voyager probe to encounter Jupiter, hence the name. *Voyager 1* was on an easier, faster trajectory to Jupiter, while *Voyager 2* was a longer trajectory which could be retargeted to reach Uranus. *Voyager 1* would encounter Jupiter in March 1979 four months before *Voyager 2*, and then flyby Saturn, 20 months later in November 1980. The Voyager 2 launch was smooth, however, the spacecraft experienced several bouts of robotic "vertigo." The disoriented spacecraft alarmed the JPL controllers, who subsequently discerned a slight mis-setting of computer parameters.[97] The spaceflight was uneventful once the

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94 Neal *et al*, 170-71.

95 Koppes, 186.

96 Murray, 140-1.

97 Murray, 145-46.

initial problems were corrected.

Voyager 1 discovered a thin ring around Jupiter, studied the planet's magnetic field and the Great Red Spot, a permanent storm which moves in a counter-clockwise rotation. *Voyager 1* used Jupiter's gravity to fly a trajectory on to Saturn. Studies of Saturn's rings revealed that the rings are composed of "thousands of ringlets made up of countless ice and dust particles."[98] Several Saturnian moons were discovered, bringing the total to 20. *Voyager 1* also studied Titan, a Saturnian moon, which was found to have a thick, smoglike atmosphere, before heading out into the solar system.

After *Voyager 2* encountered Saturn in August 1981, it continued on to Uranus and Neptune. In January 1986, *Voyager 2* made its closest flyby of Uranus. *Voyager 2* studied Uranus's ring system, photographed its surface and moons. *Voyager 2* revealed 10 additional undiscovered Uranian moons, bringing the total to 15. *Voyager 2* proceeded on to Neptune, which it encountered in late 1989. It studied Neptune's ring system and its largest moon Triton, and discovered 6 new Neptunian moons.[99] The Voyagers continue to transmit data in the 1990s as they speed towards the edges of the solar system.

The JPL reached an apogee in the early 1980s with the Voyager projects. Its focus changed as JPL tackled new and different projects, in the face of the success and the budget of the Space Shuttle, and the enormous distance to the unexplored outer planets. The work at the JPL Edwards Test Station slowed considerably as NASA reevaluated its programs in the wake of declining budgets, and the perceived success of the Space Shuttle program, which was developed by the North American Aviation division of Rockwell International, an aerospace company. The Space Shuttles were reusable, an important characteristic deep space landers and probes lacked.

Closure of JPL Edwards Facility

Today, deep space continues to bring new challenges for JPL to overcome, due to the great distance from earth of the unexplored outer planets in our solar system. The Cassini and Mars Pathfinder projects, which were first conceived in the mid 1970s, and Pluto flyby projects bring new opportunities for JPL,

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[98] Neal *et al*, 178.

[99] Neal *et al*, 178-79.

as it once again attempts to make discoveries that stretch the boundaries of knowledge and experience.[100] However, the JPL is currently closing its Edwards Facility and will return the administration of the property to the Air Force Flight Test Center (AFFTC) at Edwards AFB, effective 1 October 1995. The closure plan includes demolishing 13 buildings, mothballing 37 buildings, cleaning 18 buildings, leaving 9 buildings as is, removing all equipment from 2 buildings, and performing 1 Resource Conservation and Recovery Act (RCRA) closure. The disposition of two buildings has yet to be determined. JPL records located at the Edwards facility will be transferred to JPL archives in Pasadena, California.

JPL Test Stands and the Industrial Cultural Landscape

The JPL Edwards Facility in 1994 is a complex composed of 83 structures, including 80 industrial structures (7 of them test stands), one commercial structure, one administrative structure, and one security facility. The complex dates from 1945 and grew throughout the entire Cold War period. The rocket engine test stands dominate JPL Edwards Facility's industrial cultural landscape and are its focal point.

The JPL Edwards Facility ceased building activity in 1992. By that time, the facility had developed an extensive complex dedicated to the testing of liquid and solid propulsion systems for guided missiles, deep space probes, interplanetary landers, and commercial satellites. Building campaigns revolved around the diverse spacecraft propulsion systems and their peculiar project requirements. Historical events had a profound influence in shaping the JPL Edwards Facility's cultural landscape.

A cultural landscape is the communal sum of the built environment, including technology, vernacular architecture, and the social and experiential webs that bind a community, including work communities. Technology, vernacular architecture, and the cultural landscape are reflectors of conscious and unconscious ideas and concepts; they are historical products that reveal intent and define social and cultural relations. A cultural landscape also reflects choices of and adaptations to the natural landscape and its ecological systems. Technology is viewed as "an expression of our culture, encoded with our dreams, purposes,

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100 Murray, 245.

environment, insights, and limitations."[101] In a 1985 article, Dell Upton stated "artifacts of every scale are physical expressions of the continuous articulation of space that we all carry in our heads."[102] Integration of different types of artifacts can be achieved by studying the built environment as a holistic entity--a cultural landscape.

The term "cultural landscape" arose from cultural geography. It allows an investigator to integrate individual components of a community into a general context of related building types, time periods, and places. The cultural landscape reflects the manner in which a place is the product of its own unique history; a cultural landscape is a growing and evolving entity. The JPL Edwards Facility cultural landscape is spare and organized around requirements focused on either liquid or solid propellant engine and motor testing in a desert setting. The JPL Edwards Facility's built environment reflects these unique requirements and attests to the rigors of testing advanced technology. The exacting standards and unique construction underscore the inherent ecological and human safety concerns and the uncommon requirements of testing advanced technology.

The JPL faced increased local pressures in Pasadena, California as WWII drew to a close. It was realized that the laboratory was not simply a wartime operation; JPL was becoming an integral component of a new post-World War II political, military, and social order. Although JPL had an important future role in missile development and deep space exploration, upper middle-class residents of nearby La Cañada and Pasadena thought that the laboratory was unsightly, noisy, and kept strange hours. They intimated that the laboratory was incompatible with their quiet upper middle-class neighborhoods.

It was also beholden upon JPL to move its test facility to a sparsely populated area to prevent damage to neighbors in the event of an accident. Rocket engine testing utilizes highly

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[101] Pursell, Jr., Caroll W. "The History of Technology and the Study of Material Culture" in *Material Culture: A Research Guide*. Thomas J. Schlereth, ed. Lawrence, Kansas: University Press of Kansas, 1985:113.

[102] Upton, Dell. "The Preconditions for a Performance Theory of Architecture," Comment on "Time and Performance: Folk Houses in Delaware," by Bernard Herman in *American Material Culture and Folklife: A Prologue and Dialogue*, Simon Bronner, ed. Ann Arbor, Michigan: UMI Press, 1985.

combustible and excitable materials and compounds that are dangerous to handle and use. Subsequently, Army Ordnance found JPL an isolated, secret site to test Corporal rocket engines: the Muroc Flight Test Base.

Site Characteristics

The climate at Edwards AFB is a mid-latitude desert type with hot, dry summers and cool, slightly moist winters. Average precipitation is less than 12.7 centimeters (5 inches) per year, with most occurring as rainfall during the winter months. Temperatures range between 38 and 43 degrees Celsius (100 and 110 degrees Fahrenheit) in summer and drop to well below freezing in the winter. The climatological regimen dictates a reliance on subsurface water for contemporary permanent human habitation. Prevailing winds are from the west south west and southwest; calm presides only 15 percent of the time (see the wind rose on Sheet 1 of the HAER drawings).

The Base occupies portions of the alluvial floors of several intermontane valleys in the western Mojave Desert. The JPL Edwards Facility is located between 1.5 and 10.7 meters (5 and 35 feet) below the fossil shoreline of Pleistocene Thompson Lake[103] at an average altitude of 701 meters (2300 feet) above sea level.

Edwards AFB is located within the geologic structure known as the Mojave Block, and is bounded by the Garlock and San Andreas Fault zones. The faulting and uplift associated with the Mojave Block has created a region which is geologically complex, with both Tertiary and pre-Tertiary geologic formations as well as later Quaternary alluvial sediments. The JPL Edwards Facility is located in an area of recent Quaternary alluvium composed of alluvial sand and gravel, playa clay, and wave-deposited sandbars.[104]

The JPL Edwards Facility is located within the xerophytic phase saltbush scrub community. The dominant shrubs represented in the project area include allscale (*Atriplex polycarpa*), cheesebush (*Hymenoclea salsola*), golden cholla (*Opuntia echinocarpa*), creosote bush (*Larrea divaricata* var. *tridentata*),

[103] Dibblee, Thomas W. "Geology of the Rogers Lake and Kramer Quadrangles, California." USGS *Bulletin 1089-B*, U.S. Department of the Interior, Geological Survey (USDI-USGS), Washington, D.C.: U.S. Government Printing Office, 1960:127.

[104] Dibblee, 127.

boxthorn (*Lycium* cooperi), rice grass (*Oryzopsis hymenoides*), spinescale (*Atriplex spinifera*), and wolfberry (*Lycium andersonii*).[105] Elm trees (*Ulmus spp.*) at the JPL facility were planted to provide shade and relieve some of the visual starkness of the natural landscape.

While JPL was located at Muroc AAB, the Muroc Flight Test Base was not part of the Base until 1947. The Muroc Flight Test Base was a separate, autonomous base, under the auspices of Materiel Command (later Air Technical Service Command), dedicated to testing experimental aircraft, particularly the Bell XP-59A *Airacomet*, the first American jet aircraft.[106] Construction began in January 1945 on the JPL's Muroc test station. The JPL quickly built the Corporal Test Stand (Test Stand "A") and additional buildings to support the vital testing at Muroc. The Muroc test station was remotely operated; JPL personnel from Pasadena managed the station and drove to it to perform engine testing. The JPL's missiles were test launched at White Sands, New Mexico, Fort Bliss, Texas, and Cape Canaveral, Florida.[107]

The planned, institutional landscape of the JPL Edwards Test Station evolved episodically between 1945 and 1992. Planning decisions were reactionary and geared toward meeting challenges and solving problems. The JPL's dynamism underscores the importance ascribed to technological advances during the Cold War, and demonstrates how rapidly technology and corresponding social and cultural changes occur. The JPL's cultural landscape reflects the changing needs of the burgeoning post-World War II missile industry and a modern deep space research and development facility. The commonplace architecture of most structures at JPL belied the importance and the radical nature of the guided missile and space probe testing conducted at the JPL Edwards Test Station during the second half of the 20th-century.

Building sites were chosen as needs were identified. The JPL did not have an initial master plan; construction decisions were made on an individual, building-by-building basis as various missile and space probe programs were implemented by the military

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105 Vasek, Frank C. and Michael G. Barbour. "Mojave Desert Scrub Vegetation," in *Terrestrial Vegetation of California*. Michael G. Barbour and Jack Major, eds. New York, New York: John Wiley and Son, 1977:835-867.

106 Hudlow, 16.

107 Koppes, 23-24, 39; Baker, 234.

services, NASA, and Congress. The Army Corps of Engineers (ACE) built, planned, and laid out the ORDCIT test station in 1945; however, they did not assist in locating the test site. The AAF and JPL chose the test station's location at the Muroc Flight Test Base for its proximity to Pasadena, lack of human habitation, clear weather, and the fact that the land was already under military ownership and security.

The JPL Edwards Test Station was designed for maximum economic and spatial efficiency (consistent with safety and climatic factors). Robert Kreger notes that "Utilitarianism ... plays a role in shaping planned landscapes. It is characterized by the absence of waste. It is an uncomplicated, no frills, landscape management philosophy. ... It affects architectural design and styling standards, and serves to prohibit the construction of unnecessary and cost-prohibitive facilities which might be deemed luxurious."[108] Indeed, the JPL Edwards Test Station was small, compact, and had a minimum of buildings when it was originally established. The ACE initially utilized temporary architecture, construction techniques, and materials. The test station only grew when the mission expanded or changed its focus and new construction (or alteration) was necessary to meet changing mission goals. Some of the new missions introduced new planning factors to the evolution of the JPL site. The majority of later construction was designed by Austin, Field, and Fry of Pasadena, California, various contractors, and the JPL Plant Engineering office. The test station's architecture and cultural landscape continued to reflect those initial needs and goals; it eventually became a complicated, planned industrial landscape coexisting with a desert ecology.

The ACE designed the early test station complex with ease and speed of construction in mind. The ACE drew on its vast experience with simple prefabricated temporary wooden buildings, and the cultural landscape at the JPL Edwards Test Station consciously and unconsciously reflects these architectural and economic values. The architecture of the JPL Edwards Test Station constitutes a form of vernacular or folk architecture based upon

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108 Kreger, Robert David "The Making of an Institutional Landscape: Case Studies of Air Force Bases, World War I to the Present." Ph.D. diss., University of Illinois, Champaign, Illinois, 1988:17-18.

the repetition of building forms and types.[109] The military vernacular nature of the JPL Edwards Test Station makes it a powerful place evocative of spartan living and serious purposes.

The architectural design criteria embodied by the temporary buildings at the JPL Muroc test station were as follows:

> Ease and speed of construction ... Framing remained simple. Anticipated manpower shortages made it necessary to use unskilled labor. Only a portion of those employed on building crews would be experienced carpenters, so framing techniques were intentionally designed to be uncomplicated. Platform framing, in which floors are framed separately (as opposed to balloon framing), had been in practice since the turn of the century. Second-story floors obtained greater stability and load-bearing capacity. Dimensioned lumber and stock items such as doors and windows were used throughout. The concrete foundation piers of most company buildings were 8 x 8 in. posts of 5 ft. height, set on 16 in. square concrete footings installed 3 ft. below grade. Anchor bolts set in the middle of each pier fastened a composite sill made up of three 2 x 8s spiked together. The sills carried 2 x 8 joists that spanned 10 or 13 ft., depending on the building.[110]

Prefabrication was not new, having become an important part of the building industry in the late 19th-century.[111] The U.S. military began using prefabricated building units in the early 20th-century. Temporary building types constructed during World War I included barracks, warehouses, messhalls, etc. To the extent that prefabrication was normally "...used in the construction of U.S. military bases, it was in the use of

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[109] Vlach, John. "The Concept of Community and Folklife Study" in *American Material Culture and Folklife: A Prologue and Dialogue*. Simon J. Bronner, ed. Ann Arbor, Michigan: UMI Research Press, 1985.

[110] Garner, John S. *World War II Temporary Military Buildings: A Brief History of the Architecture and Planning of Cantonments and Training Stations in the United States*. USACERL Technical Report, CRC-93/01, Champaign, Illinois, 1993:39.

[111] Bishir, Catherine, Carl Lounsbury, Charlotte Brown, and Ernest Wood III. *Architects and Builders in North Carolina: A History of the Practice of Building*. Chapel Hill, North Carolina: University of North Carolina Press, 1990.

prepared materials such as ready-cut lumber delivered to site, and in the assembly-line manner in which buildings were erected."[112] Despite its availability, prefabrication was not a common civilian building technique until after WWII. Temporary buildings were numerous and important intrinsic elements of the cultural landscape of WWII military installations, including the JPL Muroc test station, which was sponsored by Army Ordnance and unconsciously modelled after a military installation, particularly in the utilization of temporary architecture.

Initial Construction: Test Stand "A"

The Muroc test station was initially arranged on a central north/south axis (approximately 344° azimuth). The original entrance to the JPL test station is located directly south of Building 4200/E-1.[113] Originally, the JPL test station was a dense cluster of support buildings centered on the Corporal Test Stand, (or Test Stand "A," as it was known after 1957). The original 40-acre site was planted with elm trees, which provided shade in the hot desert sun; Fig. 1 shows the location of trees in the original Corporal Test Stand area (as well as the "Short Snorter," Test Stand "B") ca. 1972. The roads were asphalt-paved and the building lots were scraped of native vegetation. A security fence was erected around the test station to thwart unwanted visitors.

Building 4202/E-3 is on the east side of the original north/south axis and is located at the northern edge of the test station complex away from the majority of the complex (its UTM coordinates are 11.420500.3872400). The Corporal Test Stand was constructed to test liquid-propellant rocket engines for the Army's Corporal guided missile program. In the late 1940s, Test Stand "A" was the largest test stand in the Western world. It is possibly the country's and the world's oldest permanent rocket engine test stand. This test stand was the cornerstone of the JPL Muroc test station in 1945.

Test Stand "A" consists of a small, steel I-beam framework

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112 Garner, 14.

113 The dual numbering system for JPL structures reflects the heritage of JPL and NASA facilities management systems. The "E" (for Edwards) numbers were originally assigned by JPL. The 4200 series was assigned by NASA in 1958 when the JPL Edwards facilities were transferred from ORD/Army Corps of Engineers to NASA under executive Order No. 10793.

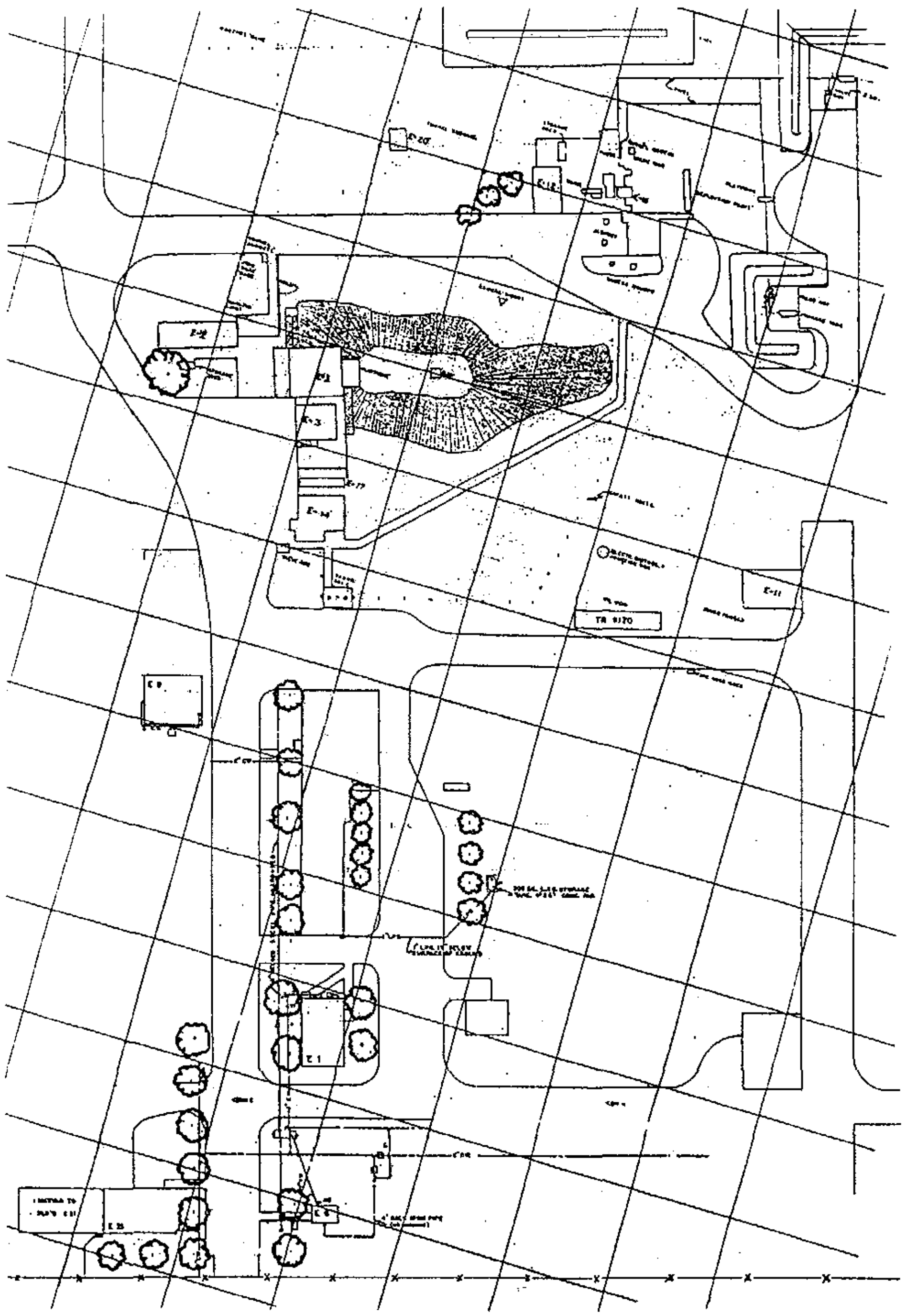

Fig. 1
Trees shown heavily outlined in this site plan were planted ca. 1945 (see Illustration Sources for citation); 50-foot grid.

and the associated tanks and plumbing necessary to test missile engines. The test stand rests on a poured-in-place concrete foundation anchored deeply in the ground with its east facade facing a flame trench excavated to the east. The poured concrete was laid in wooden shuttering (see HAER photo CA-163-A-1). The bottom of the flame trench immediately to the east of the stand is lined with concrete and has a drain (see HAER photos CA-163-A-3,-4). The flame trench has partially filled with earth as its sides have slowly subsided from lack of maintenance. Test Stand "A" has a single atmospheric vertical firing position: engine exhaust was vented downward directly into the atmosphere. At the bottom of the central channel in the foundation was a "flame bucket" or deflector designed to direct the exhaust into the flame trench. The flame bucket was originally lined with refractory brick, laid in stretcher bond, later shielded with steel plate (see HAER photo CA-163-A-5). Atop the foundation, a rectangular steel frame supported a light travelling hoist for the transport of engines and equipment between engine mounts and delivery trucks. A pyramidal steel tower was added to the top of this structure within a year of initial construction to provide a single lifting point for a block and tackle over the flame channel centerline. (In later years a 3-ton hoist running on an I-beam rail was erected around the south, east, and west facades of the travelling crane tower.) Steel stairs to the upper levels of the test stand are on the north facade, and were constructed at the same time as the tower. Catwalks on the east side of the test stand access the flame trench and the flame bucket. Stainless steel tanks for distilled water, fuel, and gaseous nitrogen (GN_2) are *in situ* in reinforced concrete bays on the north facade of the test stand (see HAER photo CA-163-A-16). All oxidizer tanks such as an oxidizer storage tank ("A"), oxidizer scrubber tank, and smaller tanks designated "B" through "E" were decontaminated and removed before this writing (see Fig. 2 for schematic of "A" Stand propellant systems). Interconnecting piping, valves, tubing and monitoring devices were all removed in decontamination procedures several years ago.[114]

For tests, a rocket engine was secured in the middle of the test stand with the nozzle pointed down into the flame bucket, directing the flames and exhaust into the flame trench. Maximum

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[114] Decontamination involves draining all remaining propellants from tanks and plumbing, flushing the systems clean with distilled water, and then removing all items (primarily tanks and plumbing) normally associated with a specific test program. After tanks and plumbing are removed from a test stand, all that is left is a bare structural steel framework.

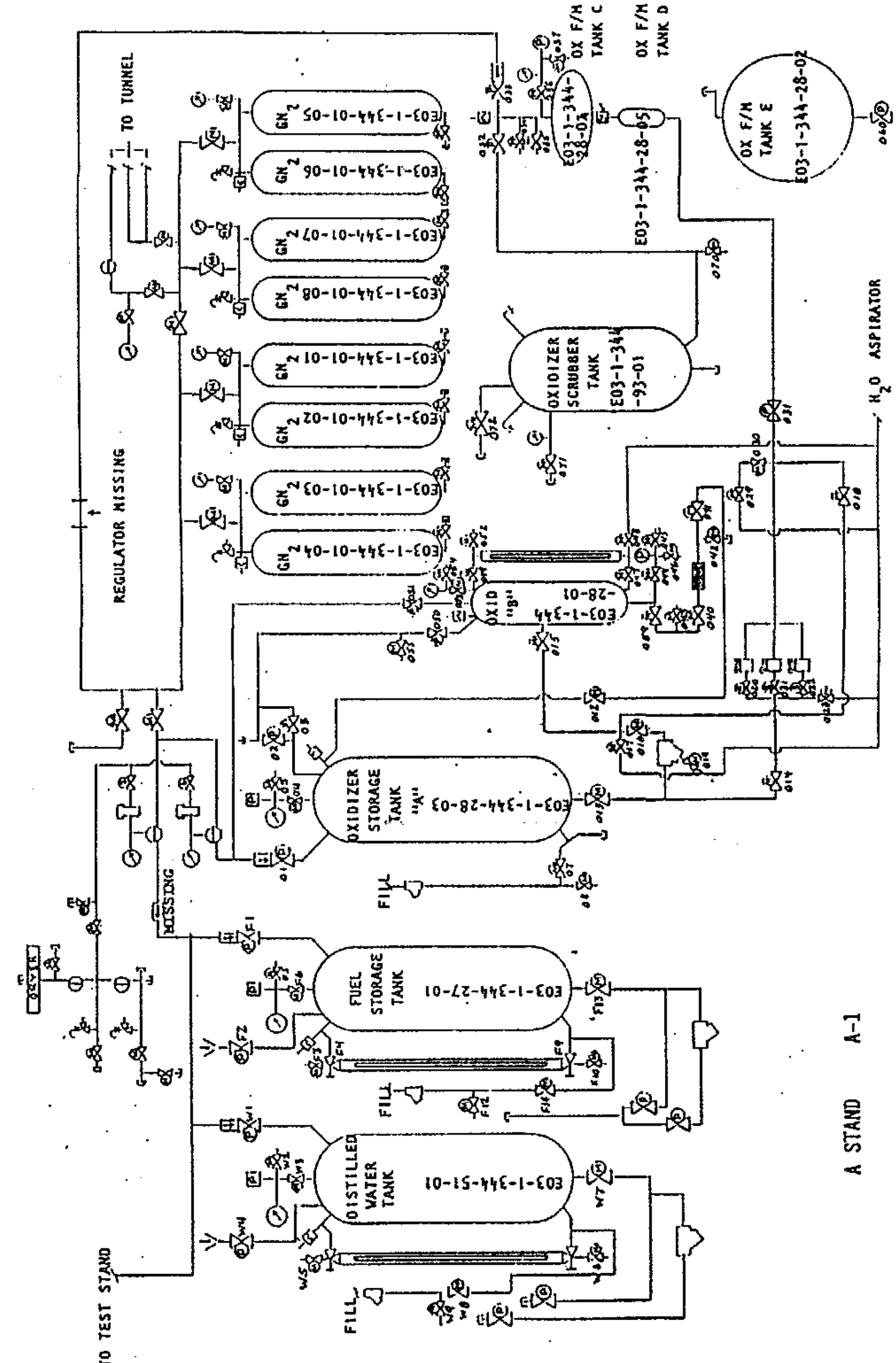

Fig. 2
Test Stand "A" Fuel and Oxidizer Schematic

test firing capability was possibly 80,000 pounds of thrust.[115] Liquid fuels and oxidizers, such as white fuming nitric acid (WFNA), RFNA, and aniline were piped to the engine from stainless steel tanks using GN_2 to "pump" the fluids and remotely operate the necessary valves. The tanks were perhaps located on the north facade to keep sunlight from unduly affecting the temperature and pressures of propellants and/or to shield the control center or "blockhouse," Building 4203/E-4, from any accidents involving the tanks.

Over the years, additions and modifications were made to the original "A" Stand structure. A reinforced concrete machinery room was built onto the south side in 1955, to provide space for refrigeration equipment. When the interstand tunnel system was built in 1957, access to "A" Stand was created on the west side of the "A" Stand foundation (see HAER photos CA-163-1; CA-163-A-7). The test stand was later used as a non-firing, propellant flow stand for testing component hardware, such as valves, pumps, and tanks during the 1960s and 1970s.

Test Stand "A" has been abandoned for 10 to 15 years; it became evident that it was too small to test large modern rocket engines and could not be economically modified to house high-altitude simulation apparatus.

Test Stand "A" Ancillary Structures

Seven temporary buildings were built in 1945 to complete the initial test station complex (see HAER photo CA-163-1):

4200/E-1: an administration building/photo lab
4201/E-2: Test Stand "A" Work Shop
4203/E-4: Test Stand "F" Monitor (historically the Test Stand "A" Control Center) UTM 11.420480.3872440
4204/E-5: Storage Building
4205/E-6: Guardhouse
4206/E-7: Observation Post
4212/E-13: Paint Storage Shed

These temporary buildings were constructed on poured-in-place concrete slabs, with wooden frame walls covered by stuccoed gypsum board. They were designed to remain serviceable for a period of 15 to 30 years, and all wooden structures were placed

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[115] Koebig and Koebig. *Master Plan for Edwards Test Station 1974-1979-1984*. Report on file at JPL, JPL Edwards Facility, Edwards AFB, California, n.d., unpaginated.

to the west or south of the test stand to avoid engine exhaust plumes and any wind-borne propellant fumes. Only two original buildings, in addition to Test Stand "A," survive from the initial construction period: Buildings 4200/E-1 and 4203/E-4. The remaining five structures were demolished after 1981: Buildings 4201/E-2, Test Stand "A" Work Shop; 4205/E-6, Guardhouse; 4206/E-7, Observation Post; and 4212/E-13, Paint Storage Shed.

The Test Stand "A" workshop, Building 4201/E-2, was a small, one-story, one-room structure with a gable roof of composition roofing materials. The interior workspace was 6'-0" x 16'-0", and contained a 9'-6" long workbench in the northern end. Outside, an emergency shower was attached to the east facade facing the test stand, near an off-center door. A door and small window were on the south facade. An addition was added to the west facade.[116]

The Storage Building was demolished in 1983. It was a 12'-0" x 16'-0" two-room shed of the same construction as the workshop. The rafter butts of its overhanging roof were cut in a decorative pattern. The shed had two doors on the northern facade: the eastern one was for equipment and the western for personnel. A slatted casement window pierced the west facade. Building 4212/E-13, Paint Storage Shed was a 48-square foot, one-story shed located on the western edge of the complex. Building 4205/E-6, Guardhouse, was approximately 13'-0" x 8'-0" and located south of Building 4200/E-1, adjacent to the perimeter fence. This one-story shed had a single centered entrance on the east facade on the opposite side from the traffic flow into the test station.[117]

The Observation Post, Building 4206/E-7, was a three-sided, poured-in-place concrete structure open to the south. It was 13'-0" long, 3'-6" wide, and 8'-3" high and located 200 feet southeast of Test Stand "A." Its 8-inch thick walls had three 1-1/2" thick bulletproof plate glass windows centered on the north facade facing the test stand; each window was about 16" x 21". Personnel and visitors watched the Corporal engine tests from this observation post, prior to 1959, when the Control and

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[116] JPL. *Control and Energy Conversion Division, Facility Utilization ETS, Edwards Test Station, Edwards, California*. Unpublished Manuscript on file at JPL/Edwards Facility, 1981, unpaginated.

[117] JPL, 1981.

Recording Center (4221/E-22) was constructed.

The Test Stand "F" Monitor, Building 4203/E-4 (historically the Test Stand "A" Control Center or "blockhouse"), is a one-story, one-room, flat-roofed, poured-in-place reinforced concrete structure situated 60 feet south of Test Stand "A" at UTM 11.420480.3872440. Only 22'-0" x 16'-0" in size, it had walls and ceiling one foot thick to shelter test personnel and their control and recording equipment (no original equipment remains inside). Test personnel observed events through five 16" x 21" windows made of 1-1/2" thick bulletproof plate glass set in the north facade, facing the test stand. Bulletproof plate glass windows also pierce the east and west facades, each sheltered by a small, vestigial concrete hood. Entrance was gained on the south side via a three-foot wide gas-proof steel door. The view towards Test Stand "A" is now obscured by the Test Stand "A" Barricade (Building 4216/E-17), an earth-filled wooden structure erected in 1957 to protect the control center from shrapnel in the event of an explosion at the test stand (UTM coordinates 11.420480.3872420). Several additions have been made to the old control center, including a one-story, plywood shed telephone junction booth that has been attached to the west facade and a one-story wrap-around shed on the south and west facades. The building has not been used as a control facility since 1959, when Building 4221/E-22, the Control and Recording Center, was built; today it is simply a storage facility.

Building 4200/E-1 was the original administration building/photo laboratory (see HAER photo CA-163-1), and utilized the same construction as the other temporary buildings. It was 20'-0" x 32'-0", a size and form identical to the lavatories erected at the Muroc Flight Test Base during WWII.[118] As an example of pre-fabricated, temporary WWII construction, these small building forms could be adapted for diverse uses. The east half of the building contained administrative offices, and the west half housed a work and storage room and a photographic darkroom. Building 4200 has been extensively modified over the last 50 years to serve different functions. It was the test station's main administrative office until 1963. In the mid 1960s, it was utilized as an office and photo laboratory; it was the standards and chemistry laboratory in 1981, currently it is the safety equipment repair shop.[119]

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[118] Hudlow, 49.

[119] JPL, 1981.

Building activity quieted until 1953, except for the construction of one new building. Building 4207/E-8, Shop and Living Quarters, was erected in 1949 to support the ongoing Corporal rocket engine testing. Building 4207/E-8 was a one-story, frame and stucco, gable-roofed shop building that was later transformed into an instrumentation repair and storage building. Building 4207/E-8 rested on a poured-in-place concrete foundation and probably had 12-light casement windows. Originally, the building had a machine shop and a welding shop on the northern end. The southern end of the building contained a living area arranged on a center passage. Toilets, a darkroom, an office, and a coffee room completed the structure. The building was 116 feet in length and 20 feet wide. A 16'-0" x 36'-0" one-story shed wing was attached to the north end of the east facade; it contained the welding shop and the toilets. Building 4207/E-8 was demolished in 1987 as an extreme fire hazard; portions of the roof and ceiling had collapsed.

Test Stand "B"

In the early 1950s, JPL's focus began to change. The JPL disliked conducting classified military research, and resented becoming an Army "job shop."[120] Space exploration always interested JPL, but its work primarily came from Army guided missile contracts. In 1954, JPL was given the opportunity to work on a space-related project. Project Orbiter was a satellite project which used downsized 6-inch diameter, solid-propellant Sergeant motors as a booster. Orbiter was later renamed *Explorer 1*. In January 1958, it became the first American satellite to reach orbit.

In 1953, to help facilitate this shift in research from guided missiles to deep space exploration, JPL built a new test stand at the Edwards Test Station to support exotic and hazardous fuels testing. This signalled an important new phase of JPL's research: the study of exotic[121] fuels and oxidizers, particularly hydrazines (like MMH and UDMH), boranes, and fluorinated compounds. The JPL newspaper, *LAB-ORATORY*, reported that:

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[120] Koppes, 25-77.

[121] "Exotic" was a term that came to signify fuels containing boron compounds; H. Bennett, *Concise Chemical and Technical Dictionary*, 3rd ed. New York, New York: Chemical Publishing Company, 1974:486.

JPL's installation, now called Edwards Test Station (ETS) has added several buildings, including a second test stand, propellant storage docks, office space, a dark room, sleeping quarters, storage buildings, etc. At the present time there are sixteen structures manned by a permanently assigned crew of twelve, backed by various personnel at JPL who devote part of their time to ETS. Half of the permanent crew now have their homes near Lancaster, the nearest large residential district, approximately 35 miles from the station, and several more are in the process of relocating in the area.[122]

The test station began to be formally called the JPL Edwards Test Station in 1951, and was known as such until the mid 1980s, when the name was changed to JPL Edwards Facility. The initial name change reflected the station's change in status and the 1949 name change of Muroc AFB to Edwards AFB; the test station became a permanent operation, focused on testing propulsion subsystems.

In the mid 1950s, the JPL Edwards Test Station had enough work to merit a permanent crew to operate the station. The sleeping quarters were in Building 4200/E-1, the administration building/ photo lab, and later in Building 4207/E-8, living quarters and shop. The buildings were cramped, however; only two to three people lived at the station, including the photographer. The remainder of the station's personnel lived off-base in the surrounding communities.

The focus of the new construction was Building 4215/E-16, Test Stand "B," originally known as the "Short Snorter" (at UTM coordinates 11.420540.3872460); the letter designations were not assigned to test stands until Test Stand "C" was built in 1957. Like the Corporal Test Stand, the "Short Snorter" consisted of a heavy, reinforced concrete foundation surmounted by a rugged steel frame. Test Stand "B" could support engines that generated upwards of 20,000 pounds of thrust. Engines were fastened to the frame on an upward incline; during tests, their exhaust vented directly into the atmosphere towards the east (see HAER photo CA-163-C-2). Liquid propellants and oxidizers such as WFNA, aniline, nitrogen tetroxide, (N_2O_4), unsymmetrical dimethyl hydrazine (UDMH, or $(CH_3)_2N \cdot NH_2$), hydrazine (N_2H_4), and mono methyl hydrazine, (MMH, or $CH_3HN \cdot NH_2$) were used.[123] Propellant tanks were located at or very near the test stand, continuing the

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[122] *LAB-ORATORY*, April 1955:3.

[123] Koebig and Koebig.

pattern begun at the Corporal Test Stand. A pivoting one-ton hoist atop the frame lifted engines and equipment into place. A shallow, concrete-lined flame trench was built to the immediate east of the stand, with steps leading down into it. This flame trench was fitted with various means to protect it from the heat of engine exhaust plumes. HAER photo CA-163-C-2 shows a water spray device made up from standard steel plumbing fixtures lying in the flame trench bottom. Other engine installations at "B" used water spray rings, as can be seen in a 1961 aerial photo of Test Stands "C" and "B" (see HAER photo CA-163-D-4); this photo also shows that a steel deflector plate was added at the east end of the pit. HAER photographs CA-163-D-4 and CA-163-5 show that by 1961 outdoor storage tanks for fuel and oxidizers had been moved behind earthen barricades (built in 1960) to the east of Test Stand "B." This change protected tanks from shrapnel; vented propellants blew to the east, away from personnel in the test stand area. Propellants were delivered to the test stand via tubing in above-ground racks supported by "Unistrut" poles. (The above ground routing provided numerous advantages over a buried installation: ease of monitoring for leaks or damage, and ease of change or repair.) The propellant delivery lines were run on a dogleg well to the north of any engine exhaust plumes so that heat or shrapnel from an accident would be unlikely to damage the lines and cause a propellant spill. (See the upper right of Fig. 1, in which delivery lines are labeled "pipes.")

Portable equipment, instrumentation, tubing and piping changed radically at Test Stand "B" depending on the engines to be tested and the nature of the tests to be performed. A photograph taken in 1972 (see HAER photo CA-163-C-3) shows how complex the web of equipment, wiring and tubing was at times involved.

After the construction of Building 4221/E-22, stationary closed circuit television cameras, such as one shown in HAER photo CA-163-D-4 situated south of the test stand, recorded the engine tests. By the late 1970s and early 1980s, engine tests at Test Stand "B" had long since ceased in favor of more modern equipment at Test Stands "C" and "D," however, a special shock tube was installed at Test Stand "B" for a Coast Guard fuel dispensing program in 1980[124]; the project's mission was to find less spill-prone ship-to-ship fueling connections for vessels at

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[124]Control and Energy Conversion Division, Facility Utilization ETS, Edwards Test Station, Edwards, California. Jet Propulsion Laboratory, California Institute of Technology, June 1981, entry for Bldg. No. E-16.

sea (see HAER photo CA-163-C-4). In 1994, all that remained of the shock tube installation are two poured concrete tiedown areas, including one forming a cross pattern to the north of the test stand. Test Stand "B" itself has not been used for a number of years and is in a poor state of preservation in 1994.

Test Stand "B" Ancillary Structures

In addition to Test Stand "B," five temporary buildings were constructed during the 1953 building phase to support the test programs:

4208/E-9: Shop (Instrumentation Building)
4209/E-10: Oxidizer Dock
4210/E-11: Fuel Dock
4211/E-12: Test Stand "B" Work Shop
4213/E-14: (later reassigned as Test Stand "C" Shop)

The two docks (Buildings 4209/E-10 and 4210/E-11); Building 4208/E-9, Shop; and Building 4213/E-14, Test Stand "C" Shop still stand. The Test Stand "B" Work Shop was demolished in the mid 1980s. All these structures were located to the south, west, or north of Test Stand "B." The need to keep personnel and equipment upwind of engine exhaust plumes and any propellant fumes emerged as a major planning factor in laying out the Test Stand "B" complex and all other JPL test stand complexes.

In addition to the factor of prevailing winds, fire and explosion safety zones became planning determinants because of the exotic and excitable fuels intended for use at Test Stand "B." Buildings and structures containing propellants, cryogenics, or high-pressure gases were separated from each other by safety zones, depending on the quantity and volatility of the substances stored. Distances and limitations on the weights of various propellant classes at JPL Edwards Test Station were displayed in a 1974 report by Koebig & Koebig on a sheet titled "Intraline Quantity-Distances."[125] This landscape pattern is standard for storing explosive materials. The greater the number of buildings that housed explosives, the larger the complex. This resulted in a geographically extensive complex at JPL Edwards, due to the need to provide space between buildings so that a potential explosion could be isolated to a single structure. Where intraline quantity-distance limits cannot be achieved by mere separation, barricades surround buildings that are inhabited on a regular basis or are located in immediate

[125] Koebig & Koebig.

proximity to buildings that are regularly inhabited.

Building 4210/E-11 is located 180 feet southeast of Test Stand "B," and Building 4209/E-10 over 380 feet south of Test Stand "B"; the two structures are separated from each other by 190 feet. The fuel and oxidizer docks are raised one-story, poured-in-place concrete sheds with corrugated sheet steel walls and roofs mounted on steel frames. They are open to the south, away from Test Stand "B" itself. A large metal-sheathed container is located in Building 4210/E-11, and a large two-celled, metal-sheathed wooden oxidizer storage box is located at Building 4209/E-10. Building 4209/E-10 also has a porte cochère on the south facade to allow personnel to unload oxidizers in the shade.

Building 4213/E-14, known at present as the Test Stand "C" Shop, was probably built originally to support Test Stand "B" since it was built in 1953, four years before Test Stand "C" was constructed. Since it is currently used to support Test Stand "C," further description can be found under Test Stand "C."

Building 4211/E-12, Test Stand "B" Work Shop was demolished in 1982 to facilitate the construction of Building 4288/E-89, the present systems assembly building. The workshop was a one-story 20'-0" x 12'-0" building of typical temporary materials and design. It had one room with opposing doors on the east and west facades.

Building 4208/E-9 was the original instrumentation building; it is now a shop. Though located across the road, south-southwest of Test Stand "A" (upwind of both test stands), it is part of the Test Stand "B" construction package. Building 4208/E-9 is a one-story 24'-0" x 28'-0" gable-roofed structure of typical temporary construction. Two doors are on the east facade, a pair of two-over-two sash windows are on the north facade, and an eight-light sliding casement window pierces the west facade. A centered, frame and stucco, one-story shed wing was added to the west facade for a telephone juncture box. A large non-reflective sliding window was added to the south facade, and one to the west facade which overlooks the test area for the short-lived JPL solar power project for which it was the operations center in 1981.[126] Building 4208/E-9 is currently vacant and in a poor state of preservation. Workbenches probably lined both sides of the interior wall, when the building was an instrumentation laboratory. The floor is covered with a

[126] JPL, 1981.

rubberized material and the walls are covered with celotex tiles.

The Tunnel System

The JPL Edwards Test Station began building at a tremendous rate in the late 1950s. The lure of deep space exploration coupled with the formation of the National Aeronautics and Space Administration (NASA) spurred JPL to begin building new facilities at the Edwards Test Station to handle larger liquid propellant rocket engines. Before the expansion, JPL planned to move the test station to a larger piece of land in order to test liquid engines as large as 1.5 million pounds thrust. JPL officials sought large parcels of land at Camp Cooke (which became Vandenburg AFB), Camp Pendelton, Fort Irwin, and Edwards AFB, but their plans did not come to fruition. Instead two additional test stands were built in 1957 and 1959, Test Stand "C" and Test Stand "D," respectively at the existing JPL Edwards Test Station. (The alphabetical designations were given to the test stands after 1957, when a new naming system became necessary due to the growing number of stands.)

In addition to the new test stations, an extensive tunnel system was installed to interconnect all test stands with a new computerized central Control and Recording Center, Building 4221/E-22. The 7-foot diameter tunnels were constructed economically of #8 gauge (approximately 3/16ths inch thick) galvanized corrugated steel pipe of the kind used for highway drainage culverts--easily fabricated and quickly laid in trenches cut by bulldozers (see HAER photo CA-163-I-3). The tunnel system yielded numerous advantages: in addition to giving speedy and unhindered all-weather access between test stands and Building 4221/E-22, the tunnel system also provided shelter to personnel from wind, fire, and fumes. The tunnel system was also designed to carry electrical power, instrumentation and communications cables; water; and non-flammable high-pressure nitrogen and helium (He) lines--all of which would be protected from above-ground damage and could be easily modified or serviced in the tunnel environment (see Fig. 3 and HAER photo CA-163-J-12). Small portions of the tunnel system were modified at future dates (see HAER photo CA-163-D-11), but the tunnel system itself maintains most of its original integrity. Concrete was laid in the tube bottoms to create a level surface for people and equipment to move through the tunnels. Work stations, remote firing stations, telephone lines, an intercom system, and emergency lighting are present throughout the system, as are air vents and tunnel access points.

Building 4266/E-67 is the tunnel entrance servicing the

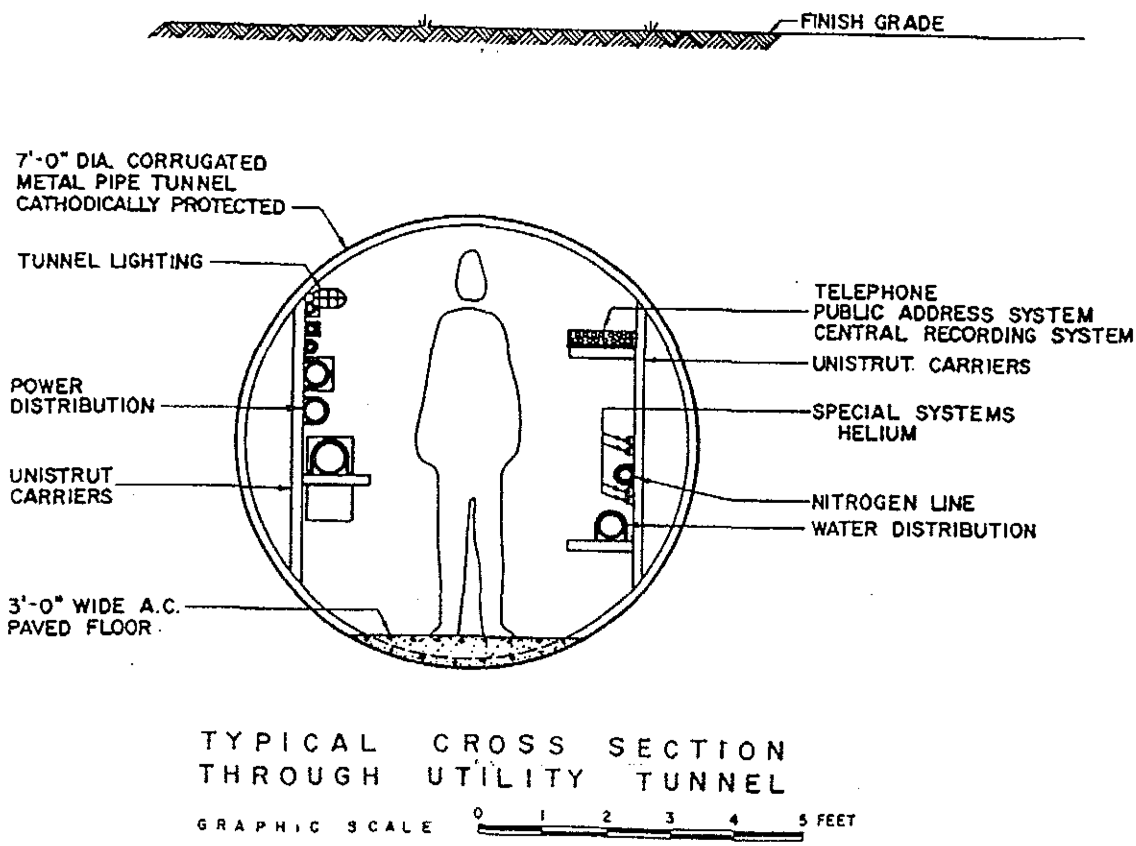

Fig. 3
Schematic cross section of typical tunnel at JPL Edwards

Solid Assembly Building (4260/E-61) and the Igniter Magazine (4261/E-62), but its size, form, and construction is typical of the tunnel houses, including those not assigned building numbers, such as at test stands "D" and "E." The typical entrance house is a 9'-0" x 7'-0" one-story, concrete block, flat-roofed structure that accesses the tunnel system from the east or west. Tunnel blower houses, such as Buildings 4219/E-20 and 4225/E-26, are located directly over underground tunnels and contain compressors to provide ventilation.

No master plan appears to have been prepared by 1957 for constructing Test Stands "C" and "D" or the Control and Recording

Center.[127] However, engineering drawings for Test Stand "C" and the tunnel system in 1956-57 reveal clearly that JPL engineers were expecting future additions.[128] The tunnel at Test Stand "C" was designed to overrun the test stand branch to the north and to provide for a westward tunnel connecting the Control and Recording Center, which was built (along with Test Stand "D") shortly after Test Stand "C" was finished. The two major planning principles driving the test station's layout to this time played a prominent role in the 1950s building campaigns. Test Stands "B," "C," and "D" (as well as future stands "E" and "G") all lie along the north-south axis of the easternmost tunnel. All their inhabited support structures and monitoring systems (including the Control and Recording Center) lie to the west of this axis to take advantage of prevailing winds, for removal of engine exhaust plumes, vented fumes, or smoke and dust from accidents. In addition, test stands and potentially dangerous support structures are widely separated, reflecting scrupulous observance of intraline quantity-distance safety measures.

Test Stands "C" and "D" and Their Complexes

Test Stand "C," or "Charlie" Stand, as it is known colloquially, was constructed in 1957 to conduct atmospheric liquid-propellant engine testing. Its construction was completed mere months before the Russian satellite *Sputnik I* was successfully launched on 4 October 1957, inaugurating the "Space Race" in the international public eye. Test Stand "D" (or "Dog" stand[129]) was begun two years later as testing programs

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[127] At least, no such plan existed in drawings or reports reviewed for this history. There may be JPL correspondence alluding to considerations for future growth that could be looked upon as an informal master plan.

[128] Project field notes contain numerous electrostatic copies of JPL engineering drawings of these stands that were not included in the HAER large format photography record.

[129] "D" is usually for "delta" in Air Force parlance, but J.R. Bonner indicates "D" Stand was referred to as "Dog Stand" at JPL Edwards; the origin of the term at JPL is obscure. Humorously, one of the authors (Anderson) recalls seeing JPL technical photographs in the course of research in which rocket engine nozzles are capped with protective plastic covers from cans of dog food ("They fit, too!" says Bonner). Occasionally a cover bears the likeness of a collie, "Lassie" of television fame, along with the slogan "Eat the

expanded. "D" Stand construction drawings were underway in November 1958, just before the formation of NASA and the official transfer of the JPL property from ORDCIT to NASA on 3 December 1958. Drawings labeled for a formal request for construction approval were dated 29 January 1959. In many ways, what was built at one stand complemented or assisted the other, so the following account interweaves the development of these two sites chronologically rather than treating each stand as a separate entity.

Test Stand "C" was the primary research and development test stand at the JPL Edwards Test Station. Operational equipment was not tested here. The poured-in-place concrete base for the original stand survives surrounded by a conglomeration of tanks, scrubbers, and other accoutrements at UTM coordinates 11.420600.3872440. Test Stand "C," Building 4217/E-18, as it was constructed in 1957 was relatively the same size as test stands "A" or "B." It was built initially to test the liquid propellant propulsion system for the Vega engine, and had somewhat the same engineering as Test Stand "B" (compare HAER photos CA-163-D-2 and CA-163-C-2). Unlike Stand "B," however, Test Stand "C" was integrated with the tunnel system, and took advantage of the tunnel system for centralized power, communications, and gas supplies. A large bunker in the south side of the stand foundation (accessed by a trap door seen in HAER photo CA-163-D-2) contained manifolds and small tanks for the distribution of high-pressure GN_2 to the valves and systems used in tests. Another bunker or bay was designed into the north side of the stand to house propellant tanks (HAER photo CA-163-D-3). A ramp to the west permitted forklifts and other vehicles to deliver equipment to the top of the foundation. Test Stand "C" saw the advent of a third planning principle for the test stand layouts: segregation of fuel and oxidizer storage tanks and equipment. The fuel storage tanks and fuel management equipment were segregated to the south of the test stand, and oxidizer tanks and equipment were located to the north. (Location of fuel and oxidizer tanks behind separate barricades at Test Stand "B" took place after "C" Stand was built.)

Like Stand "B," Test Stand "C" sported a small, robust steel tower designed to fire engines down into a concrete flame pit cooled with water. Homer Newell writes: "...the first year [NASA's first year-- 1958] produced both progress and wasted motion. It was a period of learning. At the request of the JPL leaders, the Vega upper stage intended for deep-space missions

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food that Lassie eats!"

was assigned to the laboratory in the first months, only to be canceled within the year in favor of the Centaur stage."[130]

With its original mission canceled, Test Stand "C" was adapted for propulsion research aimed at finding excitable and safe liquid propellants that could make the trip to deep space with a minimum of volume and weight for propellant storage. In the 1950s and early 1960s, boron compounds were considered for widespread application to space exploration, missiles and military aircraft. A large industry was expected to materialize. Clifford Hampel, writing about boron compounds, states:

> The hydrides of boron are colorless solids, liquids or gases and are easily oxidized, with consequent large energy liberation. These compounds have been extensively studied by government agencies because of desirable characteristics as rocket fuels. The highest jet velocities are attained with elements of low atomic weight, and, although hydrogen is probably the "tops" theoretically as a propellent fuel, it is extremely difficult to contain, and so must be combined with other elements, such as boron or lithium. It is generally agreed that, for many reasons, boron is the likeliest candidate for this role. For a propellent fuel of reasonably high bulk density, very high jet velocities may be expected from reacting boron hydride [B_2H_6] with fluorine oxide of water [OF_2]; boron hydride is a water-reaction fuel, being highly explosive when exposed to moist air or traces of water.
>
> It is interesting to compare the energy release of boron with other fuels: 1 cu[bic] f[oot] of boron releases 3,603,986 Btu [British Thermal Units] upon combustion; the same amount of kerosene, 946,000 Btu; and gasoline, 790,000 Btu. Boron-derived fuels to be used in the reaction motors of jets and rockets yield half again as much heat per pound as the best hydrocarbon fuels, and it has been said that such boron fuels will develop into a billion-dollar industry in a decade. These fuels, in a general way, are conveniently made by reacting lithium hydride [LiH] with boron trichloride [BCl_3] or boron trifluoride [BF_3]. Such reactions, when modified in various ways, can yield diborane (B_2H_6), pentaborane (B_5H_9), and decaborane ($B_{10}H_{14}$).
>
> Although there still remains much to be learned

[130] Newell, 263.

> about the various boron compounds, it appears that, as far as the investigations have proceeded, new industries are in the making in which boron, in some form or other, will play an important role.[131]

Fluorine has long been known as the most energetic oxidizer of the halogen family (which includes fluorine, chlorine, bromine, iodine and astatine), and fluorinated oxidizers (fluorine compounds including other halogens or oxygen) were expected to release more energy per pound than pure oxygen. Indeed, JPL photographs show that in 1958, the oxidizer chlorine trifluoride (ClF_3) was in use at Test Stand "C"[132] and in HAER photo CA-163-D-11 a tank marked for oxygen difluoride (OF_2) is in place on the north side of the stand. Chlorine pentafluoride (ClF_5) was used in the 1970s.[133] Liquid fluorine (LF_2) was also employed, as well as a mixture of liquid oxygen (or "LOX") and liquid fluorine known as "FLOX." By 1961, insulated in-ground cryogenic tanks were in place for fuel and oxidizer on the stand's south and north sides (see HAER photo CA-163-D-4). Many combinations of fluorinated oxidizers and boron compounds were tried in various engines to determine an optimum combination of engine design, materials, and propellants. Because of the highly reactive nature of these substances, inert helium gas was used to propel them from tanks through tubing to engines rather than electrically driven pumps. In 1958, a helium "tank farm" consisting of 13 horizontal cylinders was installed west of Test Stand "C," and the Helium Compressor Building 4226/E-27 was built in 1959 to help maintain pressure at 6000 pounds per square inch (psi). Figures 4 and 5 diagram the fuel and oxidizer systems at "C" Stand in the early 1970s.

Due to the turbulent nature of combustion in a rocket engine, some propellants present may not react due to engine wall temperatures, propellant injector patterns in engine combustion chambers, or other factors. Hence the stochiometric quantities

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131 Clifford A. Hampel, *Rare Metals Handbook*. 2nd ed. London: Reinhold Publishing Corporation, 1961:76-77.

132 JPL negative number 383-3287-C, 1 October 1958, shows a detail of a clearly labeled drum of chlorine trifluoride.

133 Bonner interview, 12 January 1995; telephone conversation, 27 June 1995. Chemist Cliff Moran, Member of Technical Staff, JPL Pasadena, California indicated in a telephone conversation with Anderson on 27 June 1995 that ClF_5 was much more difficult and hazardous to handle than the hydrazines or nitrogen tetroxide.

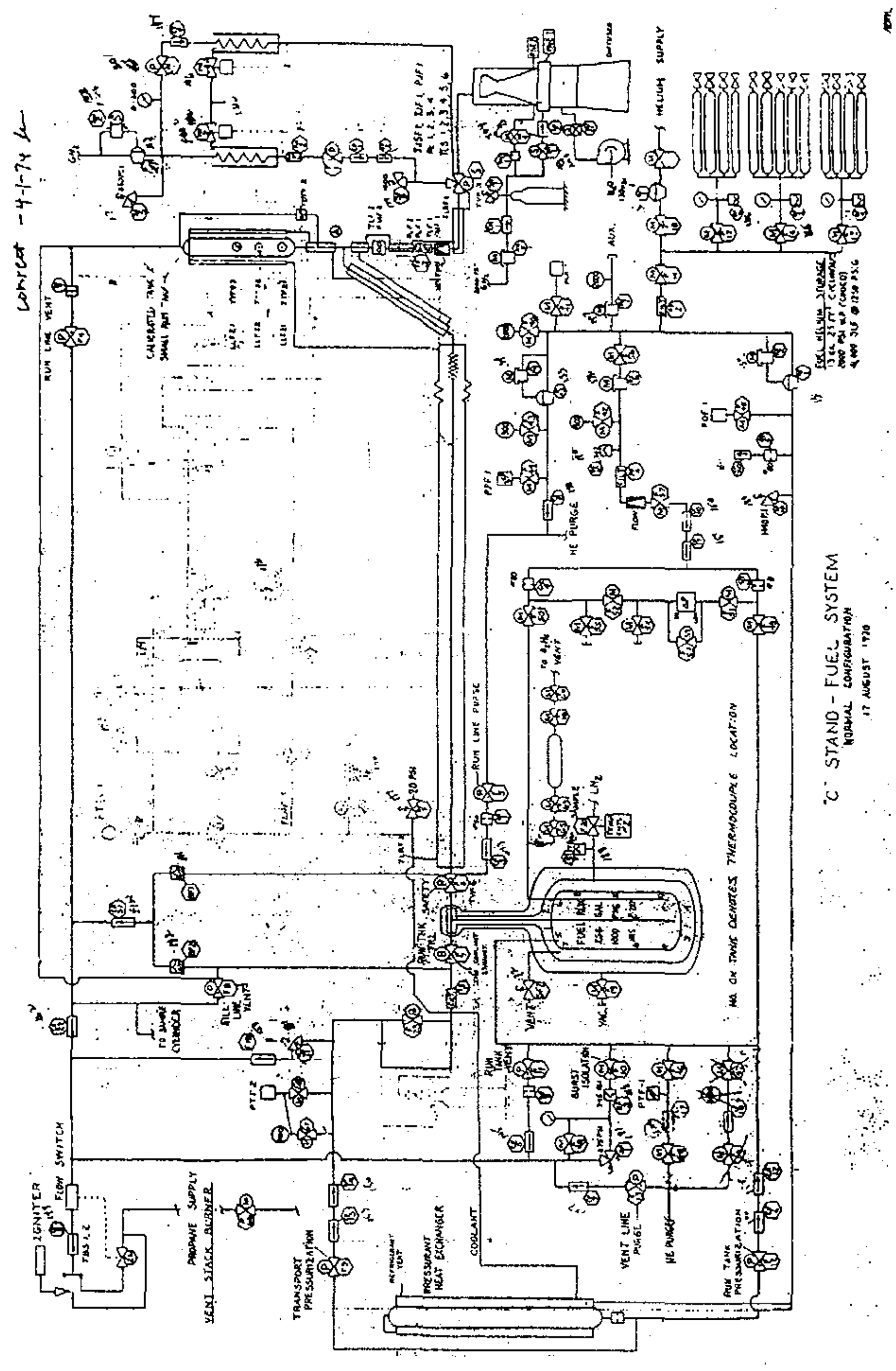

Fig. 4
"C" Stand fuel system, normal configuration in 1970; note helium supply and vent stack burner.

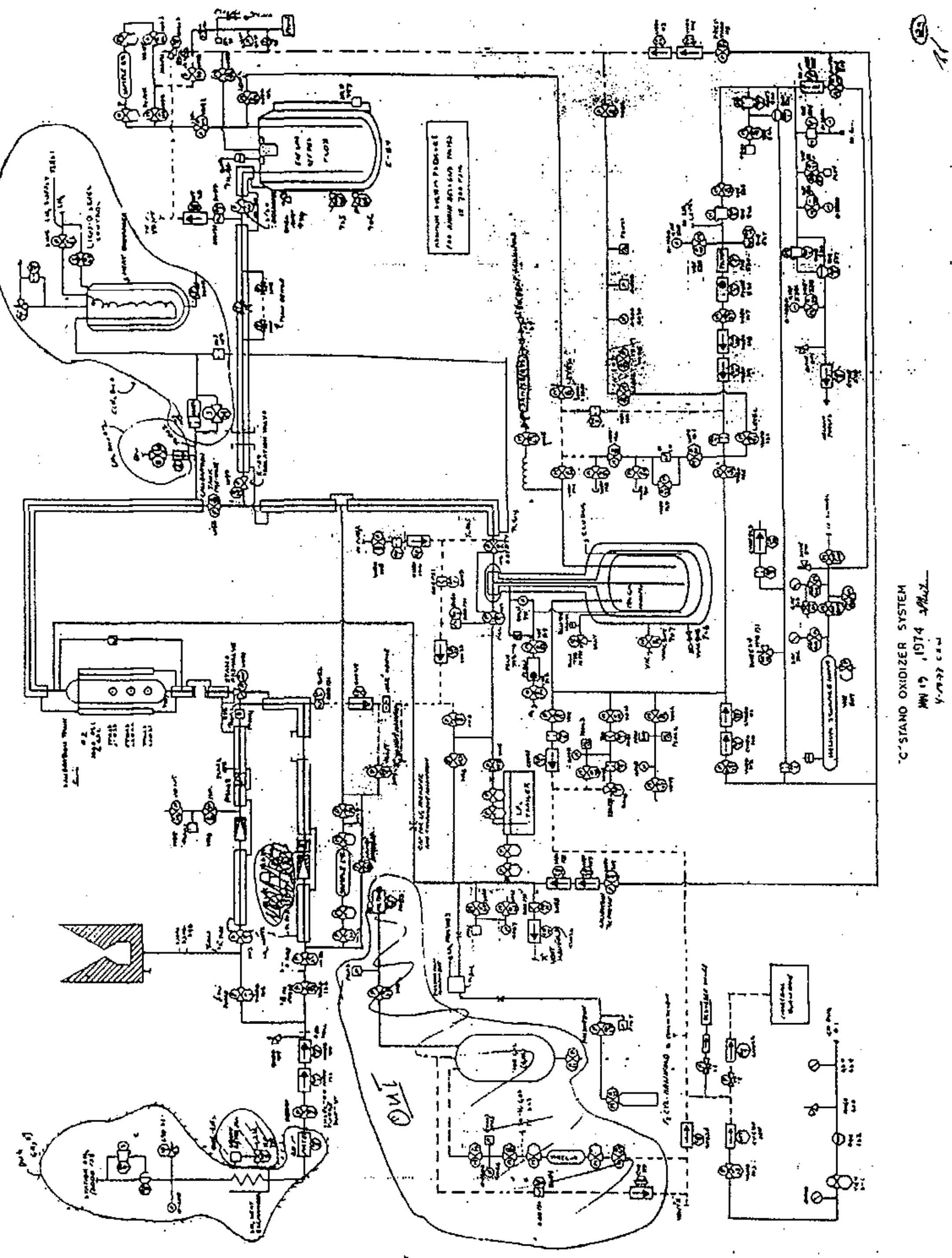

Fig. 5
"C" Stand oxidizer system, 1975-1977, using F_2 and FLOX; note pressurization and vent subsystems.

(balanced to consume all propellants completely in an exact ratio) one might expect in an ideal laboratory setting were not necessarily the most optimal. Years of tests were required to develop data that would aid combustion chamber, injector nozzle, and engine designs and choices of materials. Ideally, the propellants diborane (B_2H_6) and liquid fluorine (LF_2) would produce the highest specific impulse--or energy per unit of mass--but according to JPL test stand engineer John Richard Bonner, "we could never get it to work right."[134]

Problems using cryogenic liquid fluorine (maintained under pressure at -310°F) also had to be overcome. JPL personnel found that bends in the stainless steel tubing used for liquid fluorine had to have long sweeping radii, not sharp bends, or the fluorine would quickly corrode the tubing and cause leaks. Sharp edges and burrs likewise had to be removed from tubing and any passages conducting liquid fluorine.[135]

The combustion products of fluorinated oxidizers had their own hazards in earth's atmosphere. Fluorine combines with the hydrogen in diborane or other hydrogen-containing fuels (like MMH or UDMH) to produce hydrogen fluoride (HF), a highly corrosive gas. Dissolved in water (or the moisture in air), hydrogen fluoride creates hydrofluoric acid, which unlike nitric, sulfuric, or hydrochloric acids, attacks even glass. Tests using these propellants continued from the early 1960s through the 1970s. The diborane tank at Test Stand "C" was replaced in 1969 with one having a 256-gallon capacity; the present oxidizer tank (marked "FLUORINE"), also built in 1969, has a 186-gallon capacity[136]. Both these heavily insulated and jacketed tanks were built by the Cryoquip Corporation of Lynwood, California. Evidently the quantity of propellants expended and byproducts produced was not high. No obvious lasting effects were noticeable on surrounding vegetation or structures in 1994 from the years of atmospheric testing conducted until the fluorine scrubber facility was installed in 1970.

A site plan from JPL Edwards files dated 21 September 1976 shows a 525 gallon FLOX tank at Building E-64 (but no nitrogen

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[134] John Richard Bonner, interview with Richard Anderson, 12 January 1995 at Test Stand "C".

[135] Bonner interview, 12 January 1995.

[136] Dates for both tanks were obtained from their builder's plates.

tetroxide tank) and an 80 gallon FLOX gas storage tank adjacent to the 186 gallon LF_2 tank (see Fig. 6). To the east of the 256 gallon diborane tank was a 100 gallon hydrazine (N_2H_4) "tank package," to the west was a 1265 gallon liquid nitrogen tank. The plan includes six drums labeled "charcoal disposal system" at the end of a fluorine vent line northeast of the caustic pond. The tank behind the barrier east of "C" Stand Tower was replaced by Building E-65 (Compatibility Test Building) in 1971; various metal alloys and components were placed into long-term contact with propellants to determine their compatibility on long space journeys.[137]

In addition to facilities for exotic fuels, Test Stand "C" was provided a complement of support buildings in 1957, constructed in the vernacular manner of military temporary structures. Building 4213/E-14, Test Stand "C" Shop was built in 1953, most likely for support to Test Stand "B"; it was reassigned to Test Stand "C," and is reported to have been identical in form and plan to the Test Stand "A" Shop.[138] It is located at UTM coordinates 11.420560.3872420. Building 4213/E-14 is 24'-0" x 27'-0" and enclosed three rooms. The north facade double doors provide entrance to the large workspace on the north half of the structure; machine tools and a large workbench dominate the workspace. The room on the east half of the south facade is an office space; a closet for housing work clothes, especially protective gear is on the west half of the south facade, accessible from the office. An emergency shower and eyewash station is attached to the east facade; a chemical hood also is installed on the east facade.

Building 4217/E-18, Test Stand "C" Barricade, was constructed in 1957 to the immediate south of the test stand. Made of heavy timbers and backfilled with earth, the barricade protected Test Stand "B" from mishaps at the fuel tanks or stand at Test Stand "C." For a few years, a small plywood hut perched on top of the barricade housed motion picture cameras (See HAER photo CA-163-D-4). The original "C" stand barricade was later replaced by a concrete-parged earth barricade designed to deflect shrapnel upward in the event of an explosion.

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[137] It is interesting to note that even drawings done by the test stand engineers themselves still took account of the trees growing on the site (extreme lower left of Fig. 4 near the "High Press. Cyl.")!

[138] JPL, 1981.

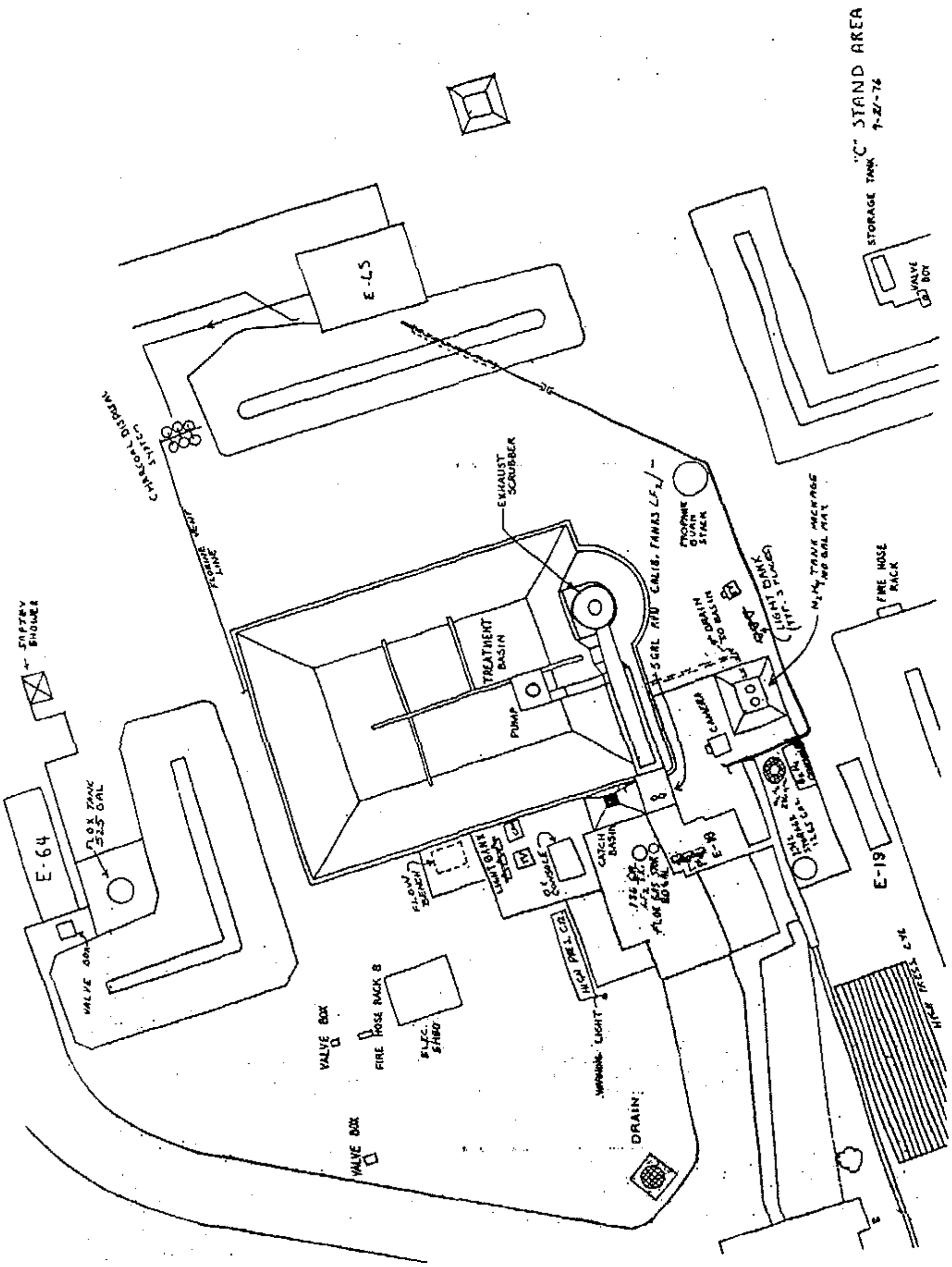

Fig. 6
"C" Stand Area, 21 September 1976

Test Stand "D," Building 4223/E-24, was the first test stand constructed at the JPL Edwards Test Station following NASA's accession of JPL in 1958. As Test Stand "D" rose during 1959, NASA, JPL and other organizations began active planning to reach the moon, and JPL Edwards focused on reaching the Moon, Venus and Mars with unmanned craft. Test Stand "D" began as a distinct, self-contained complex with an individual location on the cultural landscape (UTM coordinates 11.420700.3872440). Its tower centerline was situated 430 feet north of the centerline of Test Stand "C." It followed the three cardinal planning principles that had emerged in JPL Edwards' evolution: response to prevailing winds, attention to intraline explosive quantity-distance limitations, and segregation of fuels and oxidizers. In the JPL newspaper *LAB-ORATORY*, it was reported that:

> They're building a new test stand with a water-cooled flame deflector for the static testing of the 6K propulsion system to be used in the upper stages of our space probes. Height of this test stand is about 43 feet. It is referred to as the "D" stand and its completion will give ETS a total of four test stands.[139]

The 6K liquid-propellant rocket engine placed probes and orbiters in parking orbit around a heavenly body, such as the moon, Mars, or Venus and maneuvered probes and landers, once they had achieved orbit. Test Stand "D" was the primary test stand where operational liquid- and solid-propellant propulsion systems for the *Ranger*, *Surveyor*, *Mariner*, *Viking* and *Voyager* spacecraft were tested.

Also built at the same time was the Control and Recording Center (Building 4221/E-22, UTM coordinates 11.420600.3872360) and tunnels necessary to connect it to the two-year old test stand tunnels. The new Control and Recording Center was a necessary safety precaution due to the hazardous nature of the testing conducted at the JPL Edwards Test Station.[140] The Center contained television monitoring equipment, recorders, and a computerized data acquisition and reduction system, some of which is still partially intact (see HAER photos CA-163-J-10, -

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[139] *LAB-ORATORY* April 1959:2.

[140] Gibbons and Tibbitts, 4.

11).[141] It was reported in *LAB-ORATORY* that:

> This system contains analog recording equipment and a flexible transistorized digital recording system, the MicroSADIC, with an initial capacity of 60 channels and a maximum sampling rate of 6666 samples per second. Output is a magnetic tape suitable for entering into the IBM 704 digital computer at JPL. Use of digital computing will speed up data processing by a considerable degree. This building will eventually house all control and instrumentation equipment for the three existing stands as well as the new "D" stand.[142]

The Control and Recording Center is a 52'-0" x 52'-0" blockhouse built of reinforced concrete by JPL and the Dilworth Construction Company. It has approximately 2500 square feet of air-conditioned interior space on two floors. The interior is composed of two primary areas: an office and workspace with bathrooms and storage rooms on the west half, and a large control room on the east half. The control room has a false or dummy floor to provide access to concealed cables (see HAER photo CA-163-J-9), and in the southeast corner is a stairway leading to the tunnel system. The north, east, and west sides of the center are banked with earth, its only access above ground being from the west (opposite to the test stands) for vehicles. A stair on the north embankment leads to a flat-roofed, polygonal observation booth located on the northeast corner of the roof, from which Test Stands "A," "B," "C," "D," and "E" are visible. The observation booth windows are bullet-proof plate glass. The entrance into the observation booth is on the west facade, opposite from the test stands (see HAER photos CA-163-J-7, -8).

Test Stand "D" was initially constructed by the Structural Engineering Company of Azusa, California, along with the Test Stand "D" Workshop, Building 4222/E-23, located to the west of the test stand at UTM coordinates 11.420720.3872420. In the ensuing 18 years, five test cells were built at "D" stand, including the Dd horizontal test cell and Dj atmospheric test station in 1960-61, the Dy horizontal test cell in 1963, the Dv vertical test cell in 1969-70, and the Dpond atmospheric test station in the 1970s. The 24'-0" x 24'-0" workshop has a

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[141] National Aeronautics and Space Administration and Jet Propulsion Laboratory. *The Edwards Facility*. JPL 400-304. Pasadena, California: Jet Propulsion Laboratory, November 1987:6.

[142] *LAB-ORATORY* April 1959:2.

five-room plan, which is still intact with minor alterations. Two workspaces, an office, a bathroom, and a storeroom are present. The northern workspace has a large workbench on the north facade (see HAER photo CA-163-G-4).

The original Test Stand "D" tower contained two 170-gallon propellant tanks; engines were mounted beneath the propellant tanks and fired downward. A water-cooled steel deflector, or "flame bucket," at the tower base directed the exhaust gases eastward where prevailing winds carried the plumes away from the stand complex (see HAER photos CA-163-F-4 and -6). In keeping with site layout principles established at Test Stand "C," fuel storage tanks were located south of the tower, and oxidizer tanks to the north of the tower for safety (see Fig. 7). Only MMH ($CH_3HN \cdot NH_2$) was used as a fuel at Test Stand D, and nitrogen tetroxide (N_2O_4) was the sole oxidizer. The waste products from these propellants are water (H_2O), carbon dioxide (CO_2), and nitrogen (N_2). Hence, no exhaust scrubber was ever necessary. Unused MMH vented from tanks and lines was neutralized in a tank of "Perchloron" [$Ca(ClO)_2$ or calcium hypochlorite, in diluted form used as common household bleach] ; vented N_2O_4 was eliminated by a natural-gas fired burner.

In 1960, almost immediately after testing began at Test Stand "D," the Dd (d=diffuser) horizontal vacuum cell and Dj (j=injector) atmospheric test stand were constructed on the east side of the "D" stand tower. The Dd cell with its steam-driven ejectors allowed JPL to test engines up to 1,000 pounds of thrust at simulated altitudes from sea level to 120,000 feet. Unlike the Corporal E and Sargeant missles which were fired only once in the earth's atmosphere, space probe engines were liquid-fueled engines intended to be restarted numerous times in deep space. It became necessary to simulate the extremes of the outer space environment as well as possible in order to test engines and propellants for functionality. The Dj stand was a small steel table on which engine injector designs were tested. Construction of these two stations began in April 1960 and continued into early 1961. *Ranger* spacecraft had been under development since 1959, and JPL was signatory to a contract with Hughes Aircraft to build the moon-lander series Surveyor. *Surveyor* was intended to soft-land on the Moon, and development of a suitable vernier (throttlable) engine took nearly 5 years owing to numerous technical and managerial problems.[143]

Test engines were installed or removed from the Dd cell via

[143] Koppes, 173-179.

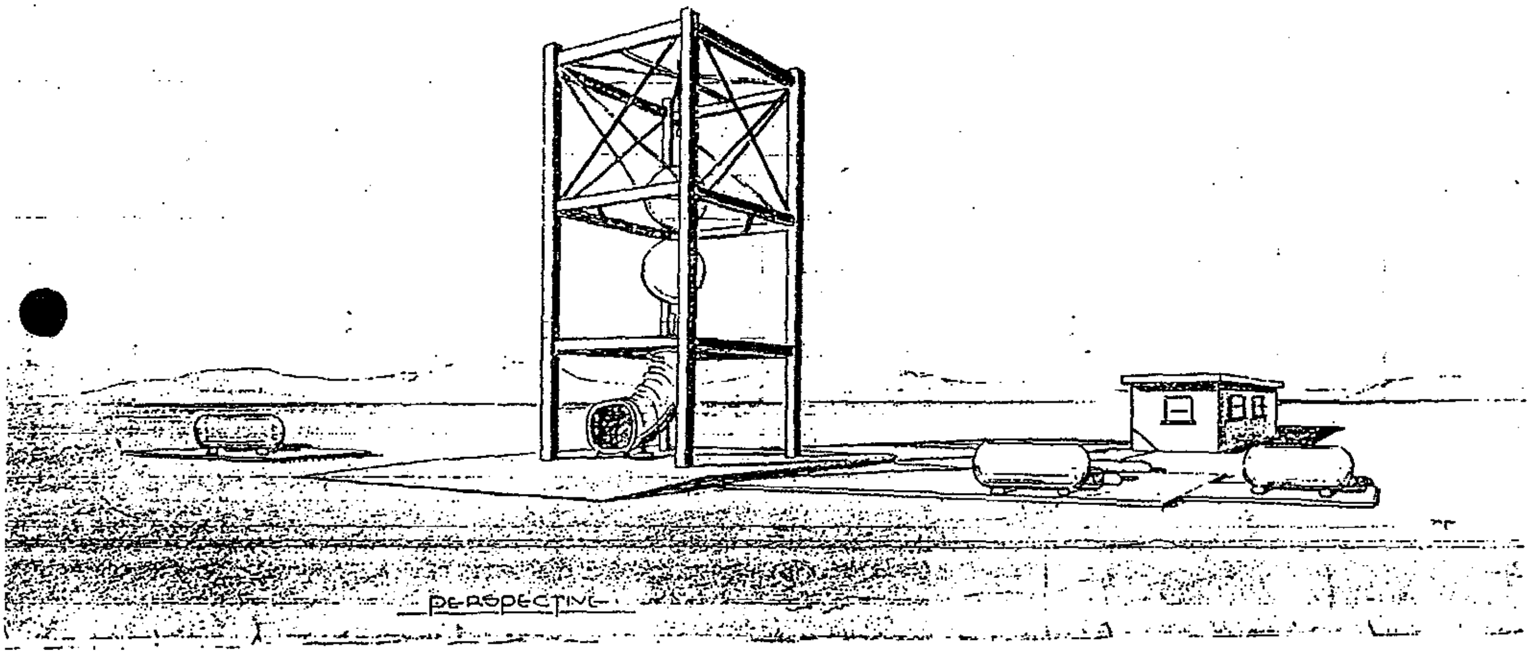

Fig. 7
Conceptual drawing of Test Stand "D" from cover sheet of original drawing set, 29 January 1959.

a top hatch, using a fixed crane (see HAER photos CA-163-F-10 and CA-163-F-16). Propellant lines, instrument wiring, and fire suppression systems passed into the chamber through vacuum-tight flanges. Figures 8 through 11 present diagrams of "D" Stand fuel and oxidizer storage systems, the fuel run system and the helium system which "pumped" propellants to the test engines. Figs. 12a and 12b show the complexity of the nitrogen system which activated valves of the other systems. Vacuum-tight viewing ports in the Dd cell permitted test personnel to monitor tests via closed circuit television cameras. Attached to the east end of the Dd cell was a diffuser, a water-jacketed exhaust gas cooling chamber with internal water injection cooling jets, and two steam-driven ejectors powered by a "Hyprox" steam generator (see HAER photos CA-163-F-14, -15). The diffuser and water jacket consumed domestic water at 1000 gallons per minute (gpm). The generator was fueled by a 360 gallon tank of hydrogen peroxide (H_2O_2), mobile tanks of hydrogen (H_2), and a 1500-gallon water tank--the exhaust from the generator was simply water vapor (see Figs. 13 and 14). A steel barrier wall was built along the north side of the Dd station; two N_2O_4 run tanks were on the north side and two fuel run tanks were on the south side. The test chamber "train" was mounted on rails, permitting it to expand and contract with changing temperatures or the installation of different sized diffusers. The test train was aligned eastward so that the prevailing winds would carry exhaust gases away from the complex. A concrete-lined "neutralization pond" was built; however, it was never needed for neutralizing engine exhaust products or waste propellants.

Perhaps as a result of the Ranger program, the difficulties with the Surveyor engine, and the initiation of the Mariner program, a "Y" branch and second horizontal vacuum cell were added to the Dd cell ejectors in 1963 (see HAER photo CA-163-F-17). The branch was "Custom built by C.E. Howard Corporation" (South Gate, California) according to its builders plate, and with it The Dd and Dy cells could be isolated from each other and sealed off from the atmosphere after evacuation by butterfly valves installed between the cells and the ejector system. This permitted JPL to "soak" engines--subject them to long periods in vacuums--in order to ascertain restart reliably in the depths of space. The Dy cell was equipped with a jacket through which LN_2 could be pumped, cooling the chamber interior down to better simulate the frigid depths of outer space. Undoubtably, many designs were tested in the Dd and Dy cells before the successful launches of *Mariner 1* on 22 July 1962 and *Surveyor 1* on 30 May 1966. Mariner launches continued until 1973, while work on *Viking*, *Voyager*, and *Pioneer* spacecraft continued. One diagram discovered in the JPL files indicates that a solid motor test

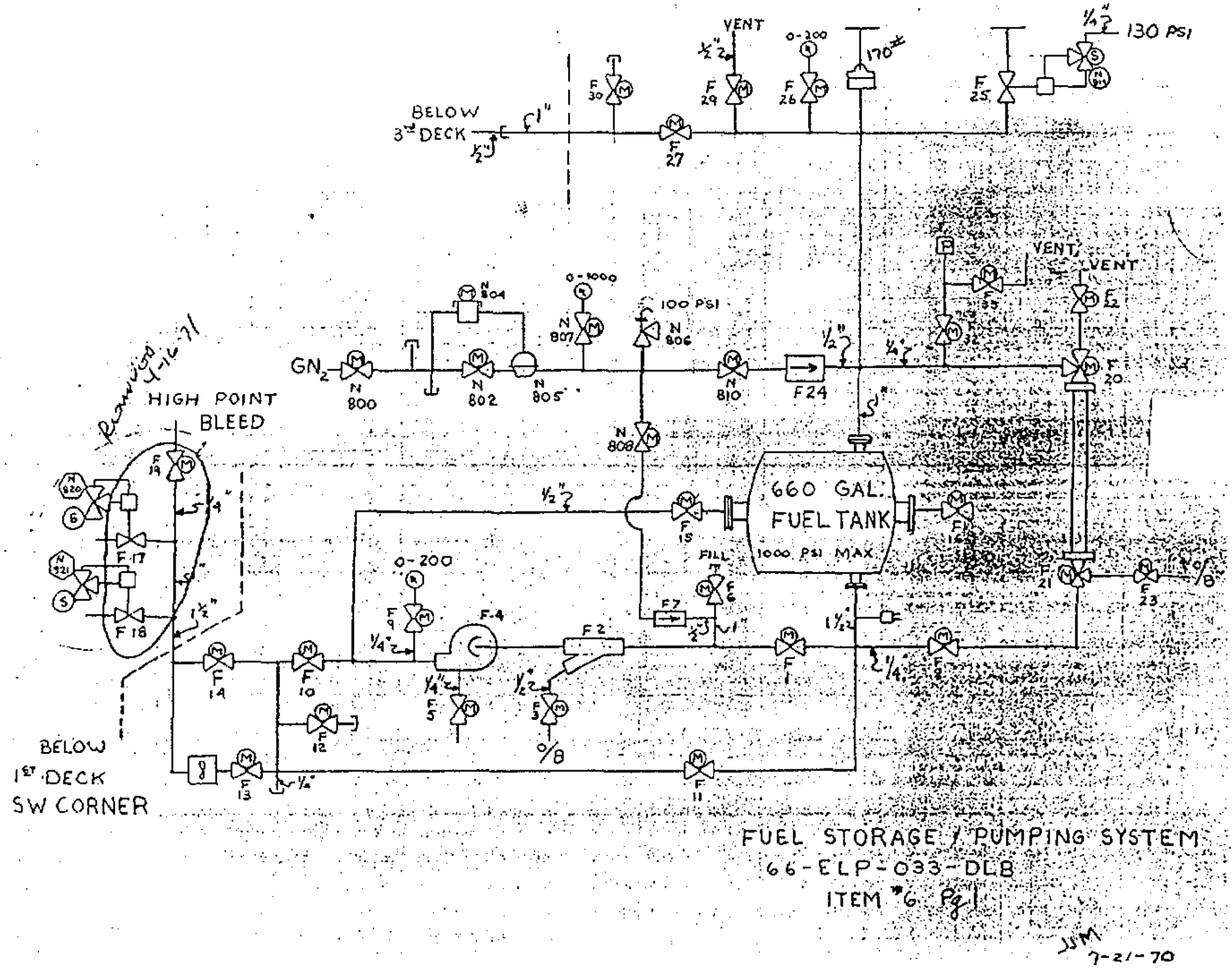

Fig. 8
Fuel storage and pumping system diagram at "D" Stand in 1970.

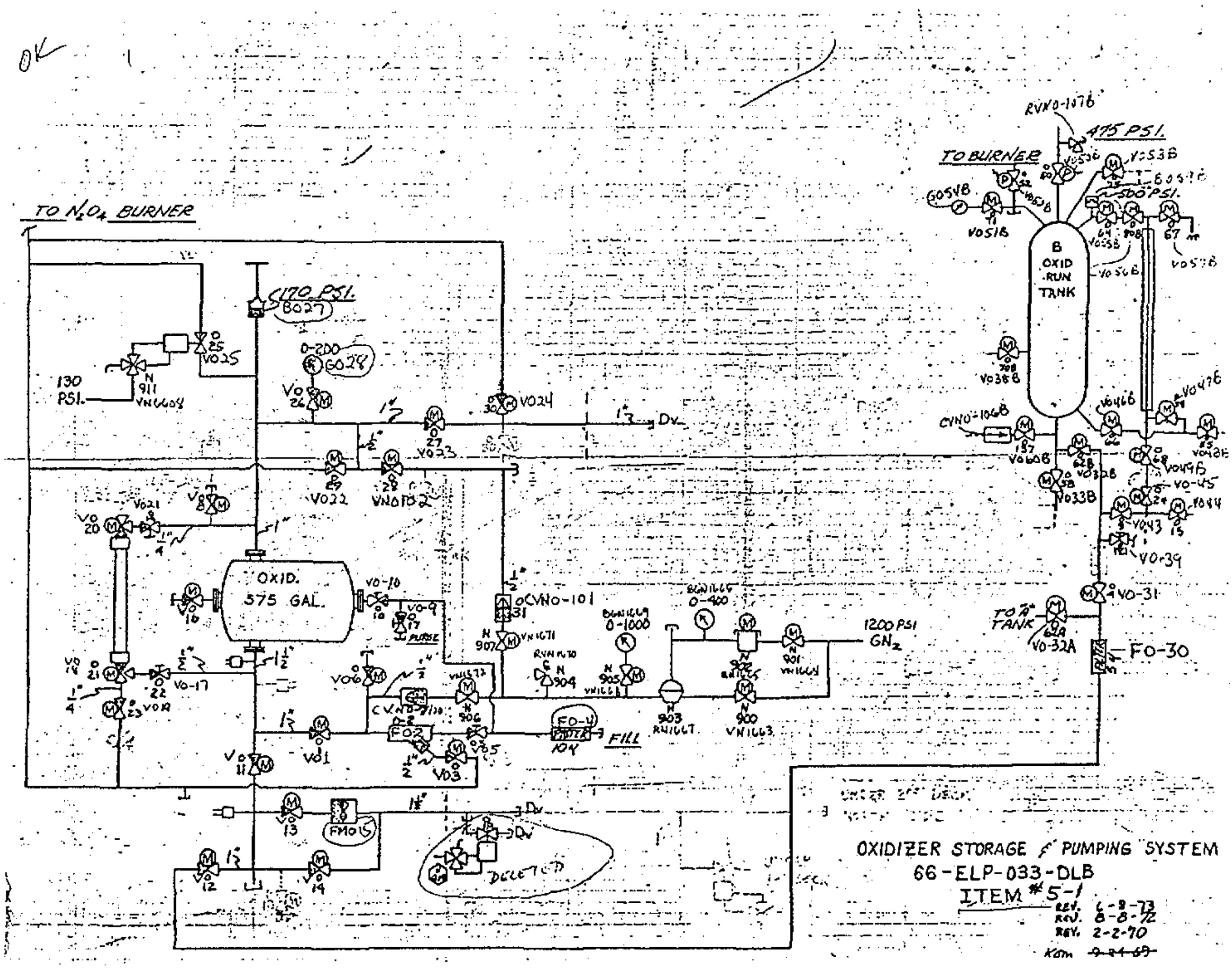

Fig. 9
"D" Stand oxidizer storage and pumping system diagram in 1970-1973.

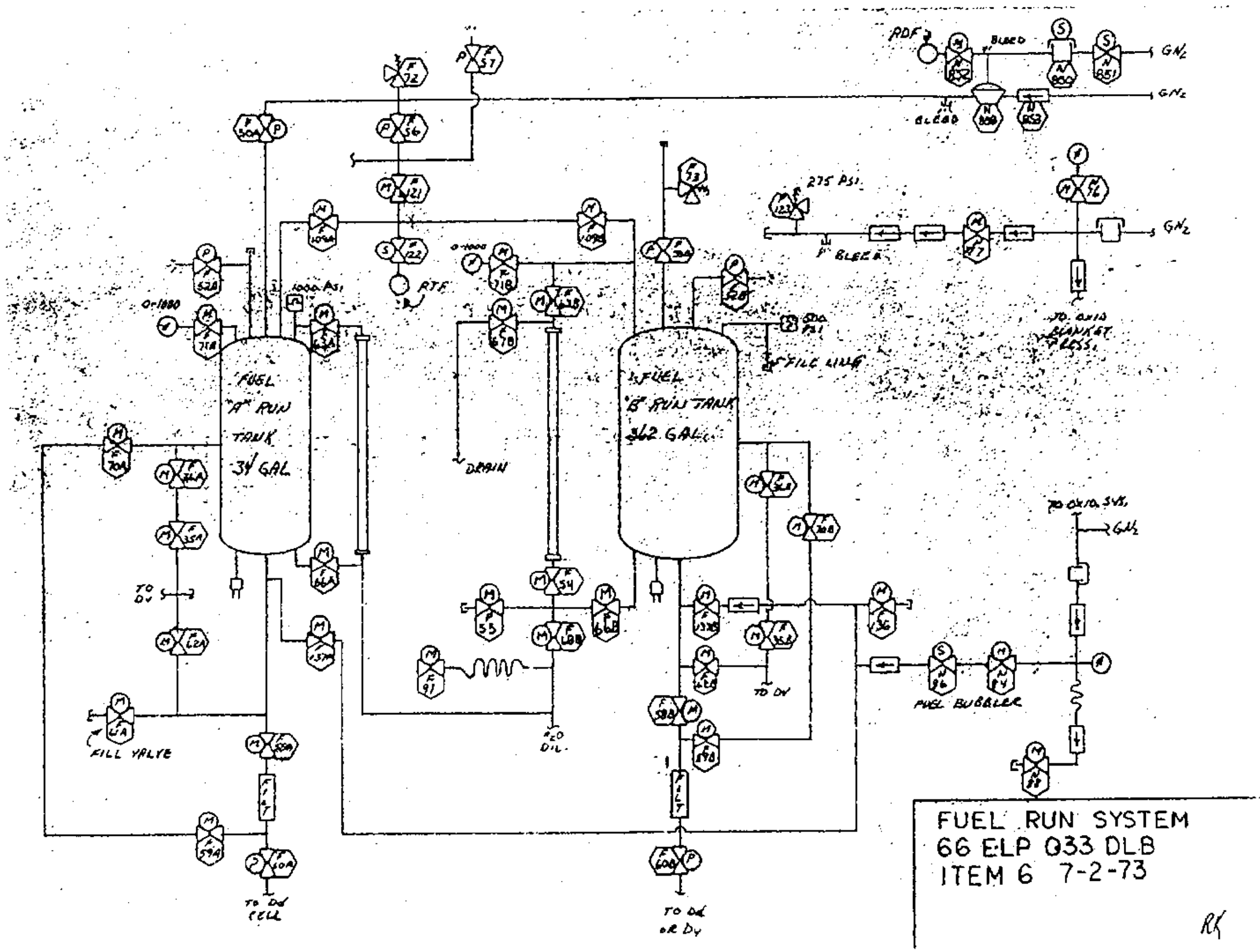

Fig. 10
"D" Stand fuel run system diagram in 1973;
the oxidizer run system is similar in outline.

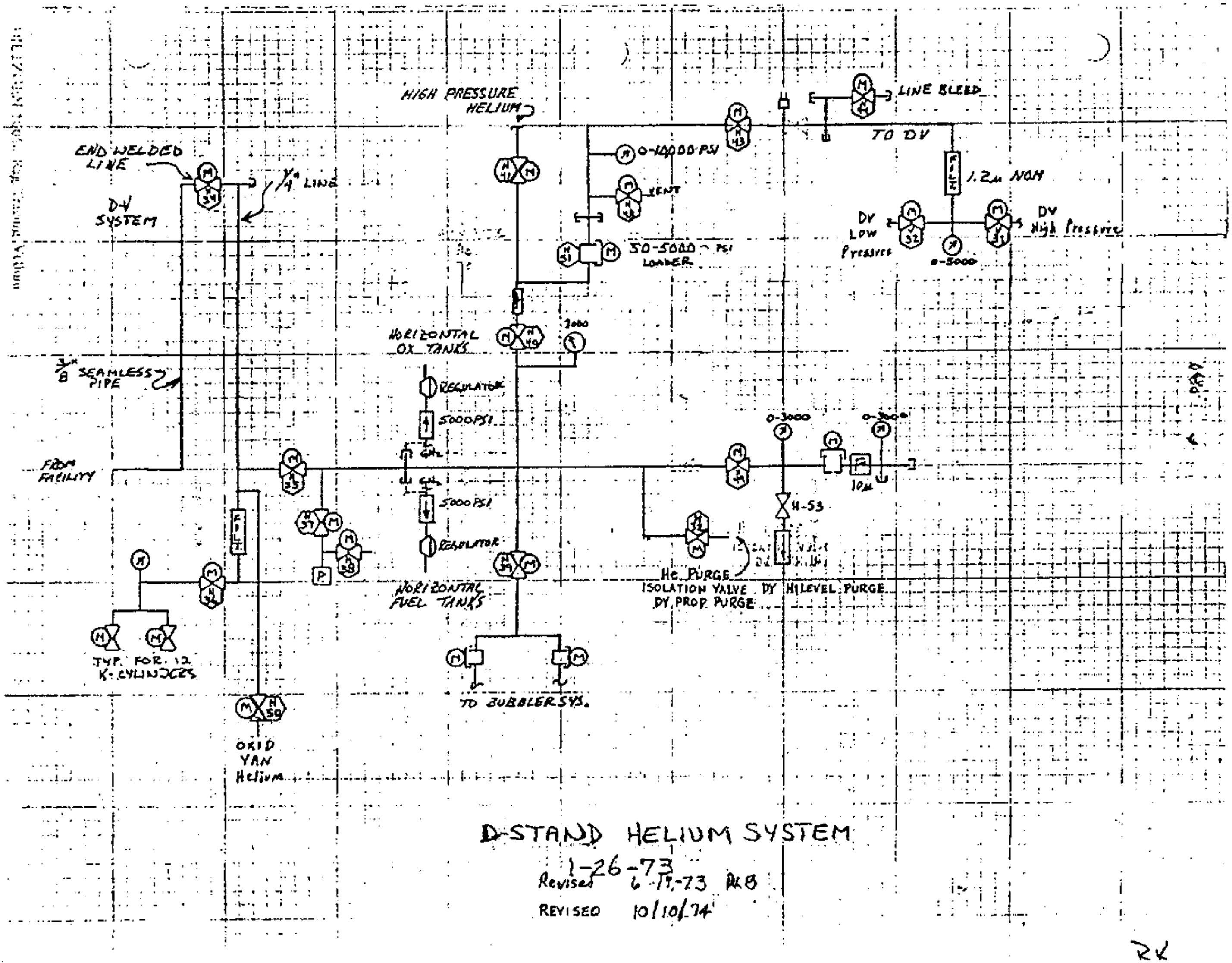

Fig. 11
Diagram of helium system at "D" Stand in 1973-1974.

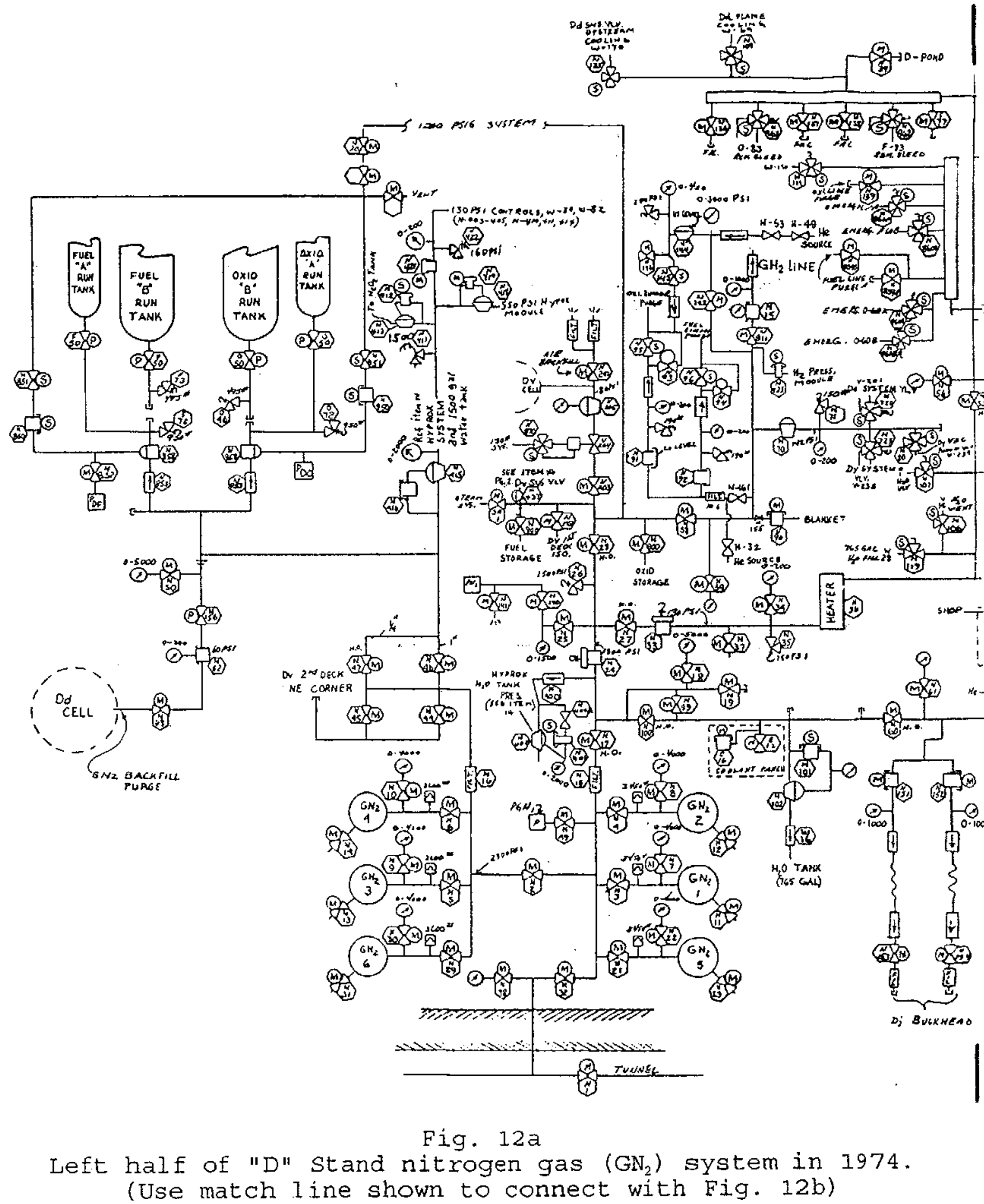

Fig. 12a
Left half of "D" Stand nitrogen gas (GN_2) system in 1974.
(Use match line shown to connect with Fig. 12b)

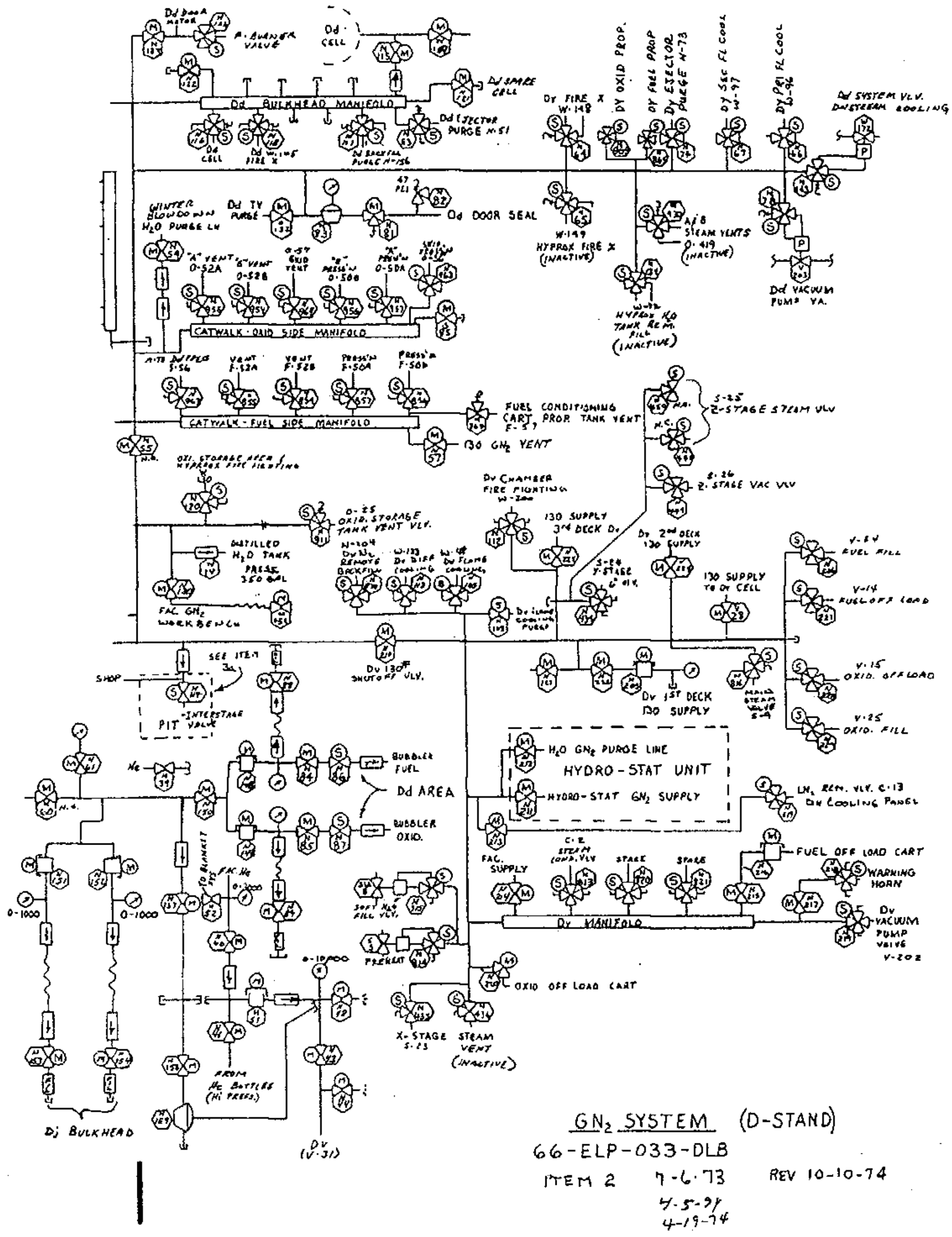

Fig. 12b
Right half of "D" Stand GN_2 system diagram in 1974.
(Use match line to connect with Fig. 12a)

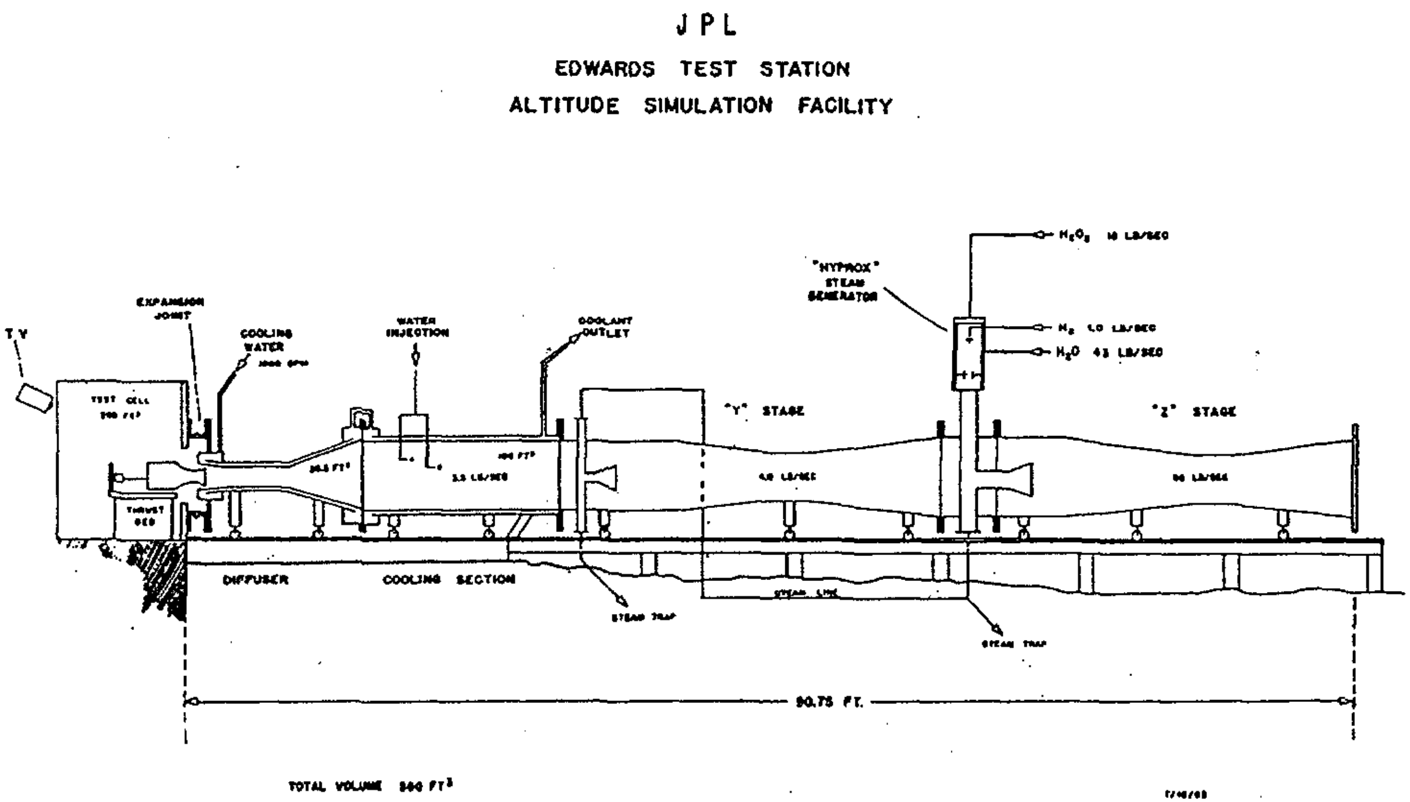

Fig. 13
Diagram of Dd station "Altitude Simulation Facility"

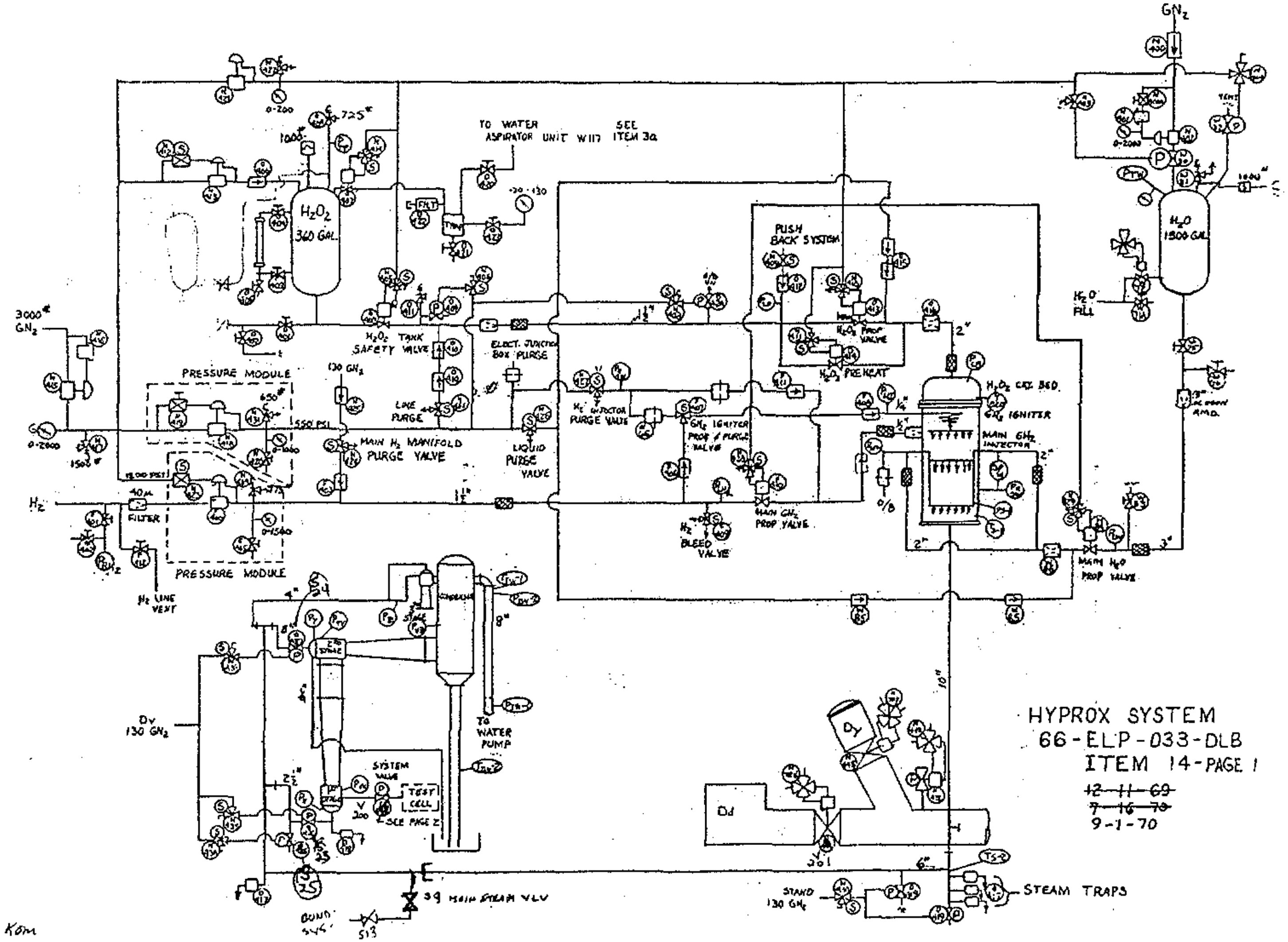

Fig. 14
Diagram of "Hyprox" system fuel and steam lines in 1970.

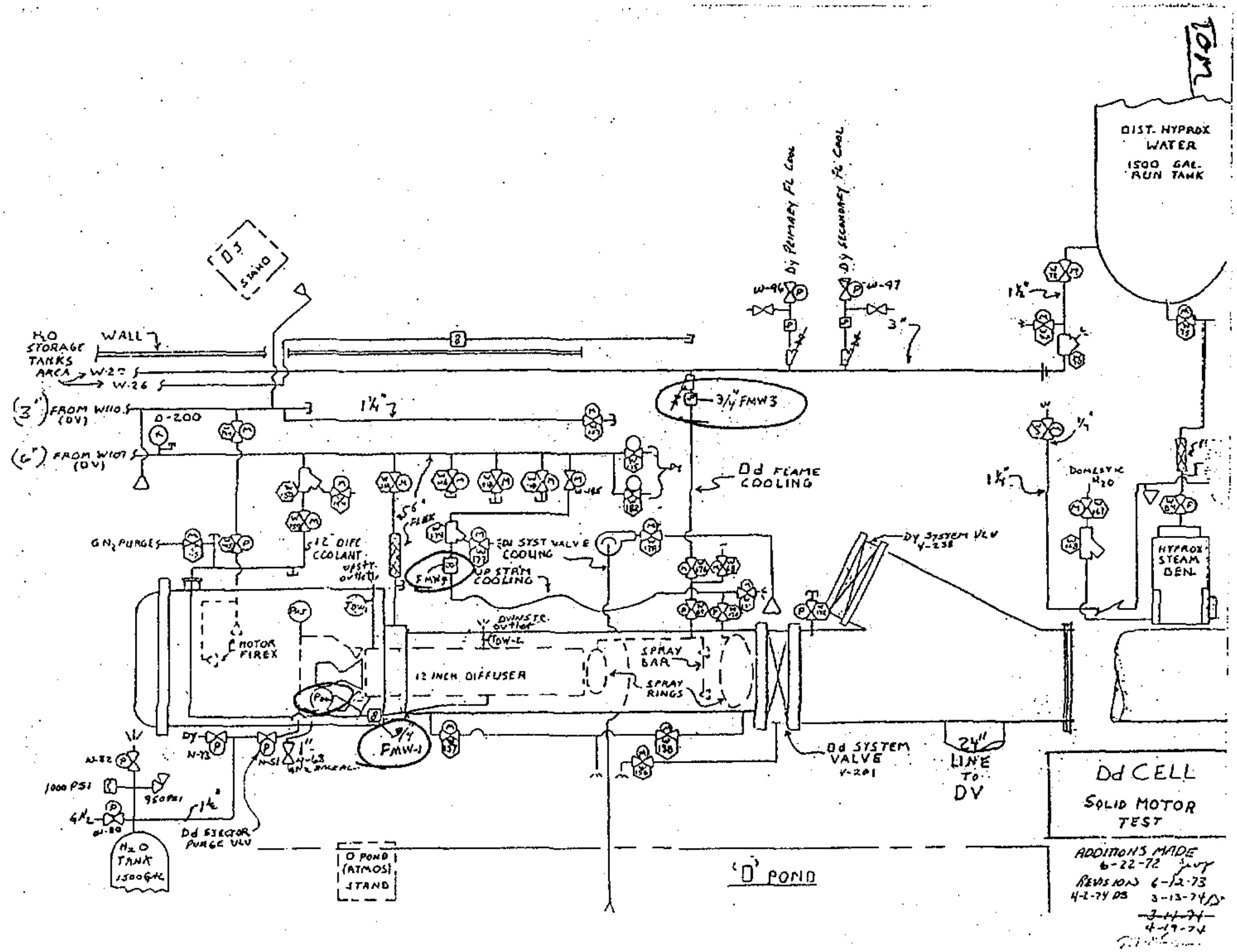

Fig. 15
Diagram of Dd Cell solid motor test set-up from 1973-1974.

setup was planned for the Dd Cell in 1973-74 (see Fig. 15).

During JPL Edwards' concentration on the development of liquid-propelled engines, JPL headquarters decided to move its solid-propellant testing facilities from Pasadena to JPL Edwards in 1961. Plans were drawn accordingly for Building 4259/E-60, Solid-propellant Test Stand "E," which was built in 1962. Test Stand "E" was located further north of Test Stand "D" along a third-phase tunnel extension, following the industrial land-use design principles outlined earlier. More discussion of the mission and design of Test Stand "E" follows later.

During 1964, the construction program at JPL Edwards suggests that the facility was preparing for a still higher volume of test programs. Building 4262/E-63, a 250,000 cubic foot liquid nitrogen storage facility built to the west of Test Stand "C" in 1960, was augmented by the addition of a mammoth 480,000 cubic foot liquid nitrogen "Driox" tank built by the Linde Company of Union Carbide. This addition to the JPL site came within months of the completion of the new Dy cell at Test Stand "D" (which was equipped with an LN_2 cooling jacket), and the construction of Building 4270/E-71, a liquid propellant storage facility. The build-up of capacities for nitrogen (essential to propellant controls) and propellants was prodigious. In 1966, JPL converted Building 4270/E-71 to Test Stand "F," extending foundations and erecting a tower reminiscent of Test Stand "D"; however, Test Stand "F" was never used for engine firings.

The year 1969 brought the first manned landing on the Moon, two successful Mariner missions to Mars, and major expansion projects at Test Stands "C" and "D." However, the National Environmental Protection Act and the Clean Air Act were working their way through Congress, and public attention to manned moon-landing spectaculars began a multi-year decline. Plans were drawn for a third vacuum cell ("Dv") at Test Stand "D," including a large three-stage ejector system. A toxic exhaust scrubber facility was designed for Test Stand "C." Construction at both stands appears to have overlapped, though a voucher for work completed at Test Stand "D" was paid on 24 April 1970; work was continuing on the scrubber system in photos dated November 1970 (see HAER photo CA-163-D-6).

In 1970, the original Test Stand "D" tower was enlarged and its fuel tanks and original flame bucket were removed. The basic four-story, braced, steel I-beam structural framework with a metal stair on the north facade was retained. An 8-foot diameter stainless steel vacuum chamber built in 1955 by Capital Westward, Inc. of Paramount, California was modified and installed vertically in the tower to test engines up to 400 pounds thrust. It was capable of simulating outer space conditions (vacuum, extreme heat, and cold) between sea level and 120,000 feet of altitude. Similar to the Dd and Dy stations, the Dv cell permitted test personnel to "soak" engines. After removing the chamber top, a Shepherd-Niles hoist (Crane & Hoist Corporation, Los Angeles, California) of 15,000 pounds capacity extending from the top story of the framework, lowered spacecraft engines into the vacuum chamber for vertical firing. Instrument wiring, stainless steel fuel, oxidizer, and control lines were connected to the rocket engine through vacuum-tight flanged ports in the chamber walls. Figure 15 shows the piping diagram for a "V.O.-75" (Venus Orbiter) engine in the DV Cell in 1973. Test personnel entered the chamber via a large flanged opening with a cover secured by multiple bolts. Personnel could not open the cell until it contained 19 percent oxygen. The cell was enclosed by an insulated air plenum by which it could be heated externally; internal panels circulated fluids near test engines to simulate extremes of heat and cold.

A three-stage air ejector system with an interstage condenser was built by Croll-Reynolds Co. and erected on the east facade of the tower to evacuate the Dv cell for simulated high altitude tests (see Fig. 17). The system was driven by steam at 300 psi; however, the steam and engine exhaust which carried over from the first two stages (X- and Y-stages) met with counterflowing sprays of cold domestic water in the condenser. This not only resulted in a less spectacular cloud of steam (such as could be seen when the Dd train was in action), the condenser was of considerable help to the X- and Y-stage ejectors. As steam was condensed, a vacuum was created in the condenser, helping to draw in the engine gases and ejector steam, since they were not resisted by normal atmospheric pressure (as at the Dd and Dy ejectors). The condenser removed the steam from the gas flow, leaving only the non-condensible engine exhaust gases to expel into the atmosphere. Normally, one of the two small Croll-Reynolds Z-stage "Evactors" on top of the condenser would be sufficient to this task. The second, or "Z-1," ejector could be turned on if needed. The condenser was referred to as an "interstage" device because it operated between the Y- and Z-stage ejectors. Condensates drained into a hotwell at the base of the "D" stand tower via the condenser's "tailpipe," and from there into the pond. Because of the vacuum created, the condenser was mounted high on the Test Stand "D" tower, so that its lowest point was at least 35 feet above the water level in the hotwell. This prevented the atmosphere from forcing water into the ejector system from the hotwell (average atmospheric

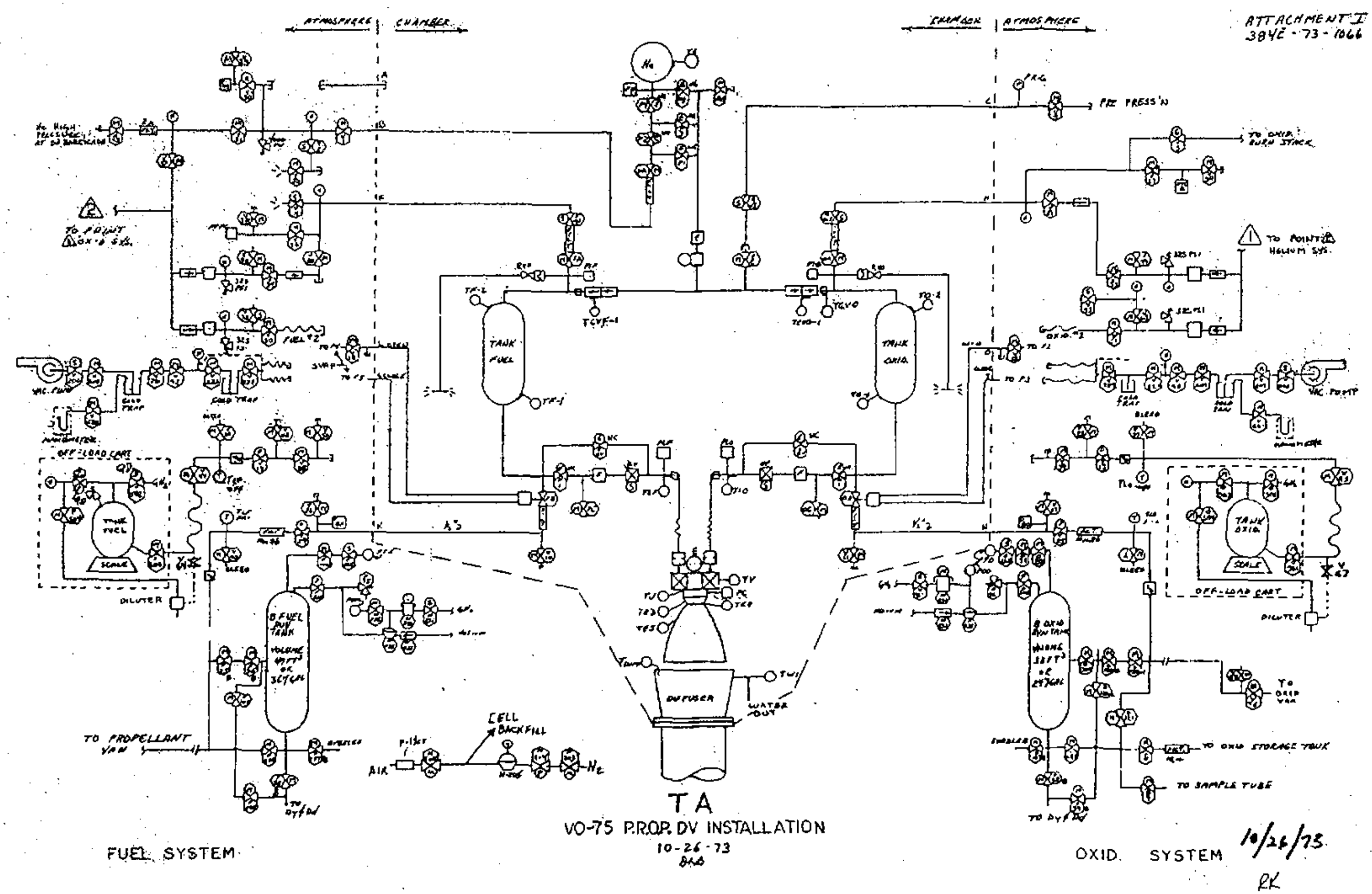

Fig. 16
Diagram showing fuel and oxidizer line installation in the Dv Cell for Venus Orbiter engine test in 1973.

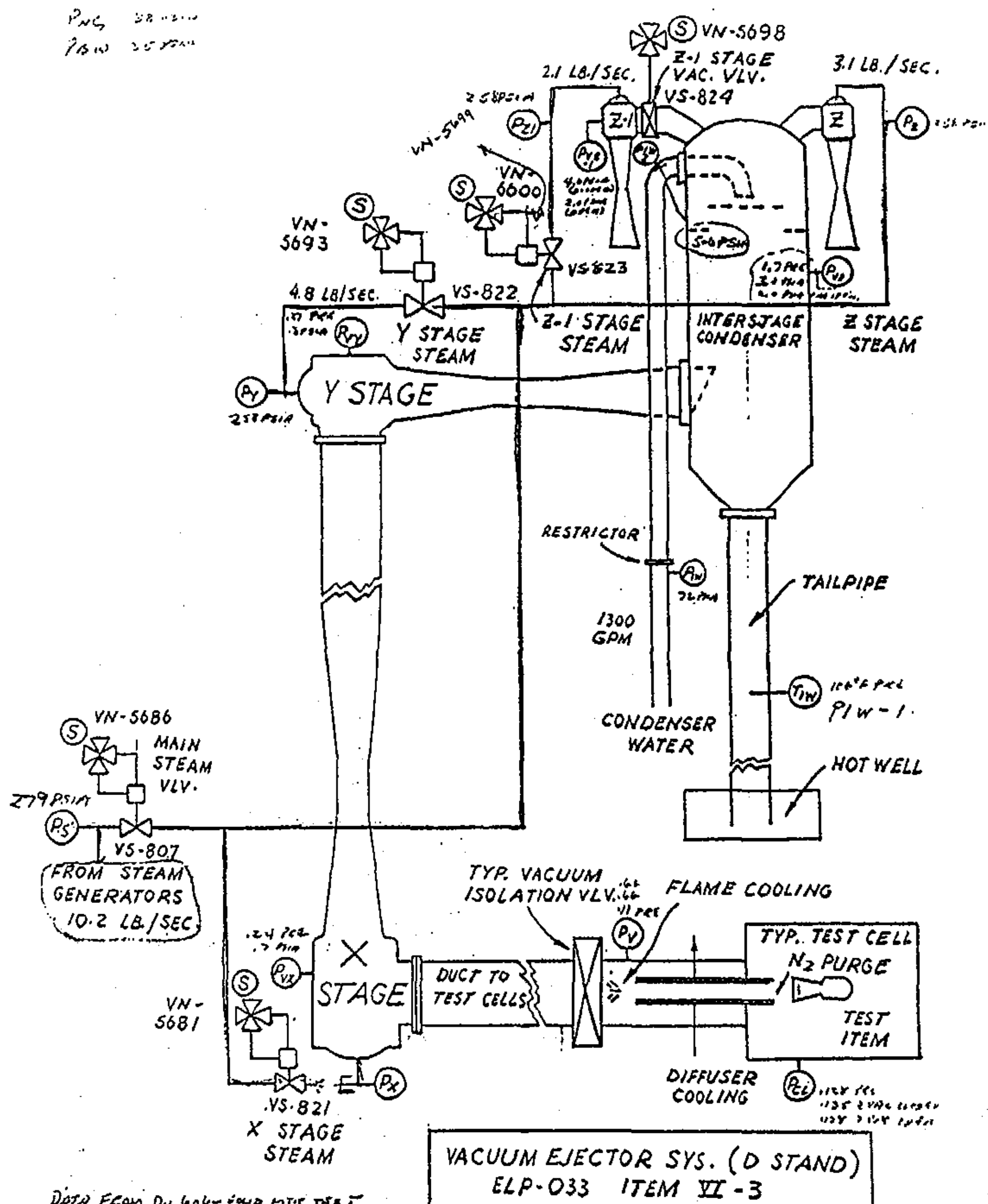

Fig. 17
Schematic of 3-Stage Ejector System for Dv Test Cell.

pressure will support a 32-foot column of water). (HAER photo CA-163-F-25 shows the Z-stage ejectors in operation during a test.)

At some point shortly after the Dv cell was erected, the 24-inch diameter vacuum line at the bottom of the cell was extended and connected to the "Y" branch on the Dd train, ahead of the Dd ejectors. In addition, a large GN_2 actuated gate valve was installed between the Dv Cell bottom and the junction between the vacuum pipes to the tower ejectors and the Dd ejector. The vacuum line extension allowed the Dv cell to use the Dd ejector system for tests (or add in the tower ejector system as well), while the gate valve could isolate the Dv Cell for lengthy vacuum "soak" tests.

Over at Test Stand "C," the imminent national air quality laws seems to have spurred JPL to find means of eliminating HF, HCl, and boron compounds from exhaust gases released into the atmosphere, in order to continue testing for longer times on larger scales. Accordingly, Frank C. Brown & Company, Inc. was called on to upgrade the atmospheric test station with a design for a "Toxic Exhaust Scrubber Facility." This equipment was installed in 1969-1970 at Test Stand "C" (see HAER photos CA-163-D-5, -6). Known facetiously as "Flushing Meadows" at JPL Edwards, this scrubber is claimed to be the first of its kind in the United States.[144] Included with the scrubber was a large reinforced concrete "Treatment Pond" designed to contain between 100,000 and 170,000 gallons of 1.5 percent (by weight) sodium hydroxide (NaOH) solution. A schematic of the equipment process appears in Fig. 18. The scrubber tower was made of mild carbon steel, as well as the cooled and uncooled ducts which conducted corrosive exhaust from a test engine to the scrubber tower. A test engine would be mounted on a securely anchored table near the western end of the scrubber's intake duct, and the engine nozzle would be inserted into a diffuser, somewhat like a funnel, that directed all exhaust products into the duct. Air from the surrounding atmosphere was also entrained, and temperatures of the subsonic exhaust gases reached approximately 6400° Fahrenheit. The first 15'-0" segment of the 3'-0" diameter duct, cooled by a double-walled steel jacket, injected NaOH solution into the exhaust plume through 24 stainless steel nozzles at a rate of 1200 gpm after the NaOH circulated through the jacket. In addition to cooling the exhaust gases, the NaOH was intended to absorb HF (and/or HCl), as well as uncombusted fluorine and boranes. The NaOH reacted with the uncombusted fluorine and

[144] Gibbons and Tibbitts, 1; "Flushing Meadows" is stencilled numerous places on the scrubber and Cv Cell tower.

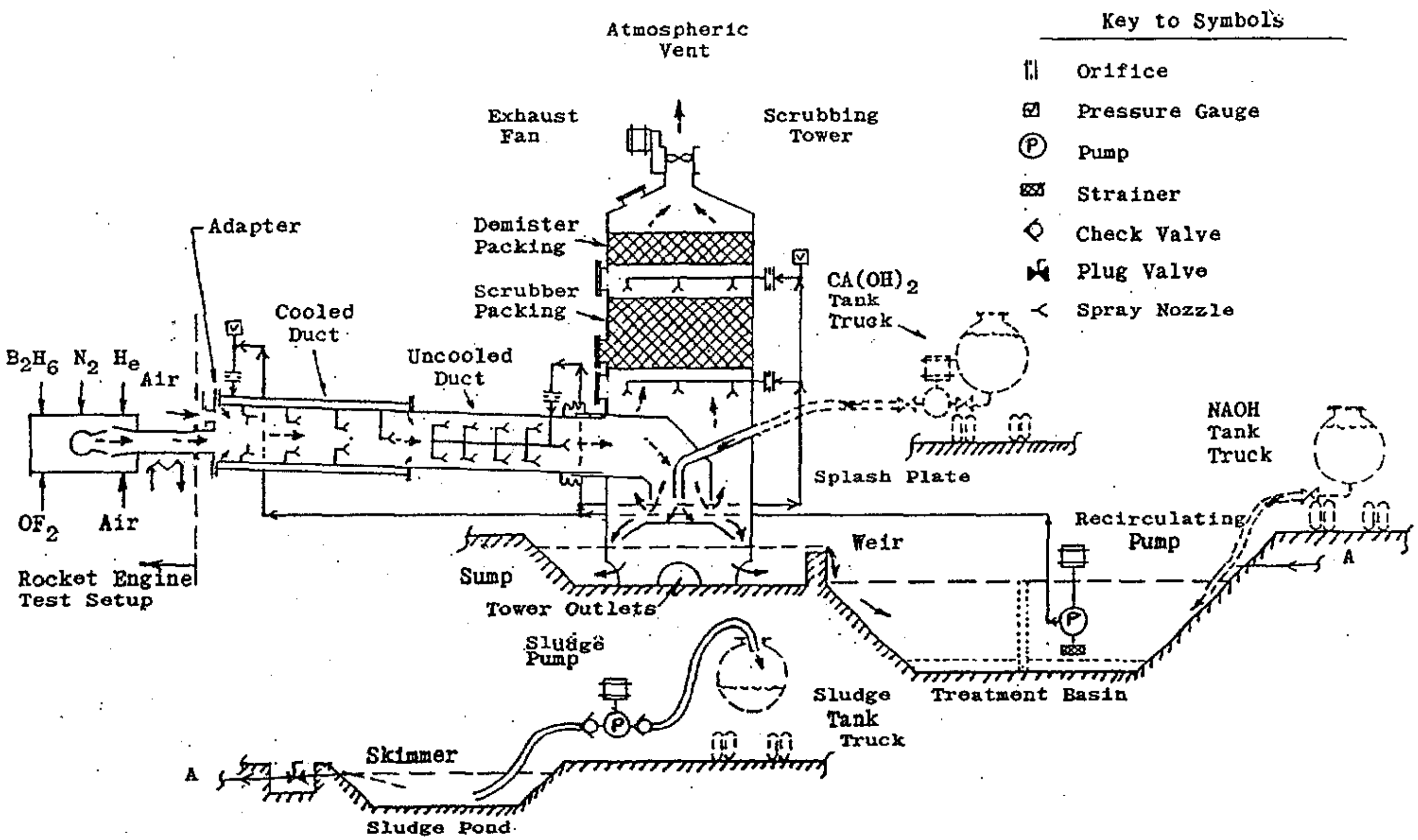

Fig. 18
Schematic Process Diagram of Toxic Exhaust Scrubber Facility

boranes to produce more benign compounds like sodium fluoride (NaF) and sodium borate ($Na_2B_4O_7$) in aqueous solution (or even common table salt, NaCl, when chlorine pentafluoride was used). The second 15'-0" duct segment did not need a cooling jacket; instead it contained 24 PVC (polyvinyl chloride--a common late 20th-century plastic plumbing material) nozzles arrayed in a "Christmas tree" fashion to inject 1200 gpm of NaOH from a supply pipe centered at the duct axis. The duct was inclined so excess NaOH solution would drain into the scrubber tower by gravity.

The scrubber tower was a mild carbon steel tank 10'-0" in diameter and approximately 25'-0" high. At its top was an axial fan that drew scrubbed gases from the inclined duct through the unit and blew them into the atmosphere; the cleaned gases consisted of carbon dioxide (CO_2), nitrogen (N_2), and water vapor (H_2O). Counter to the gas flow, NaOH solution was sprayed at a rate of 500 gpm over an 84-inch deep bed of polyethylene spirals called "Tellerettes" at the bottom of the tower, through which the exhaust gases had to pass on their way up the tower. The tellerettes helped provide an extensive surface-area-to-gas-volume ratio for the last traces of toxic compounds to be absorbed. NaOH solution flowed by gravity into the bottom of the tower, which opened to the treatment pond beneath the pond's surface, at once providing fluid circulation while sealing off any gas leaks. The tower contained an upper level of dry "Tellerettes," 12 inches deep, designed to deflect entrained droplets of NaOH out of the gas stream before gases left the tower. The scrubber facility and "caustic pond" (as the treatment pond came to be called) were designed to handle up to 5.12 pounds of propellants per second for as long as 1000 seconds. This was equivalent to firing an engine of 2000 pounds' thrust. Further neutralization of the absorbed reactants was accomplished by adding slaked lime solution--calcium hydroxide $Ca(OH)_2$--to the contents of the bottom of the tower from the hose of a tanker truck. What resulted from this stage of treatment was an insoluble, nontoxic sludge of calcium fluoride (CaF_2), calcium tetraborate (CaB_4O_7), and reconstituted NaOH solution suitable for recycling in the process. According to John Richard Bonner, a test stand engineer at the Edwards Facility since the 1960s, the pond was "mucked out" twice in his career by hand, and it had about 8 inches of sludge in it each time. This atmospheric test station continued to operate with no major modifications. If NaOH was needed in the "caustic pond," JPL personnel simply added it by hand in dry form from cardboard boxes, rather than by tanker truck as illustrated in Fig. 18.

The NaOH concentration was monitored with a pH meter.[145]

In part as a result of JPL Edwards research, the rosy future anticipated by advocates of boron fuels in the 1960s darkened, and finally collapsed. Research revealed a bevy of problems: many combustion products from diborane, dihydrotetraborane (B_4H_{10}), pentaborane, and hexaborane (B_6H_{10}) were found to be toxic to the human nervous system, or systemically poisonous, and cumulative in their effects.[146] In addition, the boranes were discovered to "disproportionate"--within the same propellant tank, pentaborane (a disagreeable, spontaneously flammable gas condensing at 0°C/32°F) would convert spontaneously to decaborane (a solid melting only at 100°C/212°F or higher) while in storage.[147] This characteristic made it highly unreliable and unsuitable for long space missions. The U.S. Congress funded a $100 million plant for the production of hydroborane fuels for use in aircraft, only to cancel the project as it was nearing operational status.[148]

The present atmospheric test station at Test Stand "C" is the final evolutionary phase of the original Test Stand "C" installation. It came to be used primarily to test propellant injector designs and patterns. As is apparent from the volume of facility photographs, the JPL Edwards photographer[149] was kept busy constantly photographing the effects of various tests on injectors, engines, equipment, and specially engineered materials. Detailed piping and equipment schematics were

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[145] Bonner interview, 12 January 1995.

[146] Moran, Cliff, JPL Pasadena, California, telephone interview with Richard Anderson, 20 March, 1995.

[147] Moran interview, 20 March 1995.

[148] Moran interview, 20 March 1965.

[149] The JPL photographer from 1945 to 1946 was George Emmerson; between 1947 and July 1957, the JPL Photography Department was responsible for coverage (the individual photographers were not identified on JPL images); from July 1957 to the present, William C. Tibbitts was the facility photographer, and he estimates that 90 percent of the photos taken at JPL Edwards during this time period were made by him.

recorded for all test set-ups.[150] Tests were also conducted in separate structures on the long-term effects of propellants on various materials that might be used in spacecraft.

Normally, four JPL employees maintained and operated the test stand. After 1959, the personnel were stationed in 4221/E-22, Control and Recording Center, for safety purposes during test firings, which were observed via television and remote-controlled photography. Electrical systems for instrumentation ran at 28 volts direct current (DC), relying on a battery in Building 4213/E-14 for power; 120/220 volts alternating current (AC) was used for lighting, and small pumps; the 100-horsepower caustic solution pump, which delivered 4,000 gallons per minute, ran on 460 volts (3-phase alternating current) at 117 amps.

Set-up time and costs for a test varied depending on the quantity of pre-existing tubing and equipment that could be reused. Stainless steel alloys 321 and 347[151] were used for propellant lines to resist corrosion from propellants at room or cryogenic temperatures. Stainless steel tubing was also used for high-pressure GN_2, LN_2 and helium (He) lines. After tubing was bent to shape and coupling fittings attached, interior surfaces had to be thoroughly cleaned of all lubricants, dirt, and other contaminants. Not only could such substances react explosively with propellants, dirt particles could clog tiny orifices used to control propellant flow rates. Fuel lines (such as MMH) were cleaned with a mixture of isopropyl alcohol and de-ionized water, then dried in a vacuum. Oxidizer lines were cleaned with freon (a refrigerant, dichlorodifluoromethane, CCl_2F_2). A service cart containing these cleaners was devised for cleaning lines already in place on the stand (see Fig. 19). Once cleaned, parts were

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[150] The authors presume that equally detailed extensive data were retained on all tests, but in-depth analysis of test history and results was beyond the scope of this documentation project. Such an analysis would no doubt yield a more thorough history of each test stand as well as the specific engines, programs, personnel and other subjects of interest.

[151] Alloy 321 (American Iron and Steel Institute numbering system) contains 0.08 percent carbon (maximum), 17.00 to 19.00 percent chromium, 9.00 to 12.00 percent nickel, and titanium at a minimum of 5 times the carbon content, the balance being iron; alloy 347 contains 0.08 percent carbon (maximum), 17.00 to 19.00 percent chromium, 9.00 to 13.00 percent nickel, and columbium and tantalum at a minimum of 10 times the carbon content, the balance being iron. Both alloys are austenitic.

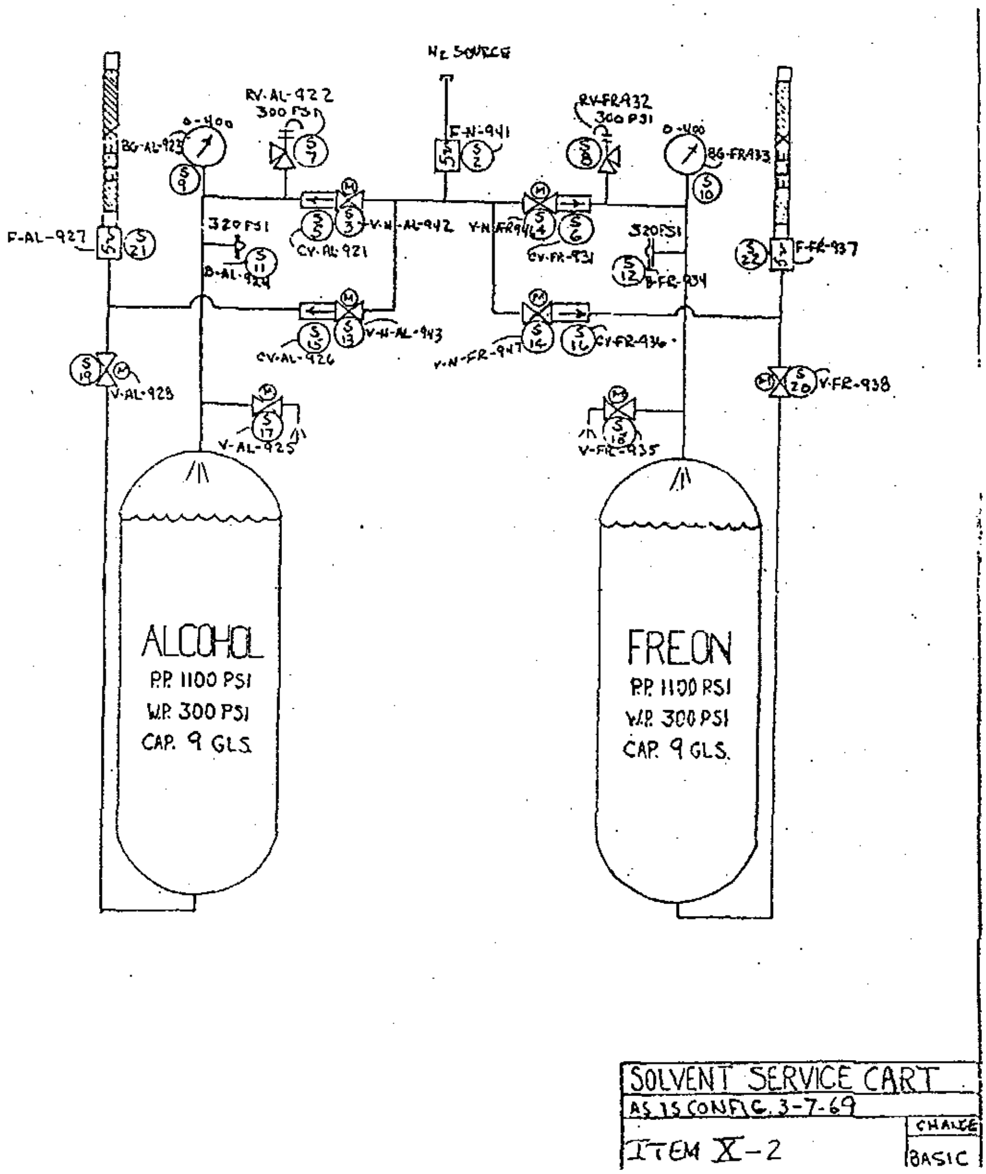

Fig. 19
Schematic of Solvent Service Cart
used for cleaning propellant lines.

bagged (ends of tubing and fittings) for transport to their installation points. Once assembled, the air in tubing, valves and ancillary fittings was flushed out with GN_2 and the system pressure-tested for leaks. A gas-detecting liquid designed to produce telltale bubbles at leakage points was brushed onto joints. Propellant lines were not only flushed with GN_2, the escaping nitrogen was tested with a hydrocarbon analyzer for the presence of solvents, and a "dewpointer" was used to check for the presence of any moisture. Tubing was then capped off (or a valve closed) until propellants were introduced. Fluorine was introduced to passivate the walls of oxidizer tubing before the tubing was filled and pressurized for use in a test[152]. All valves for propellants were actuated with high-pressure GN_2, not electricity, for safety and reliability. Nitrogen is used because it does not react with the propellants, and is non-toxic and non-corrosive to equipment and personnel (the earth's atmosphere is 80 percent nitrogen). Propellants (especially cryogenics), however, were driven by high-pressure helium gas, which is chemically inert and does not liquify except at extremely low temperatures (-269°C/-452°F), well below those of any cryogenic propellants. Because helium is used to pressurize spacecraft propellant tanks and "pump" propellants to engines, fittings called "bubblers" were fitted to each propellant line to saturate the propellant with helium gas. This affected propellant and engine performance, but in a way that reproduced conditions aboard spacecraft in deep space. Most tests were very short duration--5 to 15 seconds, but set-up time could run into the hours or days. Evaporated propellants (as from warming cryogenics), fumes, etc. were vented from tanks and propellant lines to various disposal mechanisms. Boranes were vented to a natural-gas fired burner that rendered them harmless. Fluorine and FLOX were vented to the scrubber facility, or in emergencies, to 55-gallon "burn barrels" filled with activated charcoal. Other oxidizers like nitrogen tetroxide (N_2O_4) were vented to natural-gas fired burners also. Mono methyl hydrazine was absorbed in reaction tanks filled with Percholoron ($Ca(ClO)_2$). Liquid nitrogen and liquid oxygen were vented to the atmosphere. Lines were flushed with GN_2 if test facilities were to be idle while extensive changes were made. A test installation could become a maze of tubing, wiring and devices (see HAER photo CA-

[152]Passivation produces an anti-corrosive coating on a metal surface as a result of exposure to a gas- or water-borne chemical; after passivation, the chemical causes little or no further corrosion. In the oxidizer tubing, fluorine created a thin coating on the stainless steel tubing wall surface which prevented further corrosive action by fluorine.

163-D-7). To confound the visual confusion for laypeople, disused tubing was usually left in place--"they gave us the money to put it up, but never any to take it out."[153]

The 1969-1970 modifications to Test Stands "C" and "D" seemed adequate for several years. During the coming years, testing continued for the development of Viking and Voyager spacecraft engines, and JPL seems to have gone on a quest for higher vacuums or better simulations of deep space environments. The steam supply at Test Stand "D" was augmented in 1972 by four natural-gas-fired Clayton Steam Generators (water-tube flash boilers) which provided 10.2 pounds of steam per second to the Dv ejector system. The steam generators were housed in Building 4280/E-81 (UTM coordinates 11.420680.3872440), a steel frame structure with corrugated metal walls and roof--perhaps a more up-to-date equivalent of the inexpensive temporary military construction used for earlier ancillary buildings (see HAER photos CA-163-H-1 to 4). The building was supplied by Soulé and erected by E.C. Morris & Son, Inc. (Lancaster, California). Plans were also laid for a second large horizontal test chamber and ejector train at Test Stand "D" in 1973. This facility retained the designation "Dy" because it reused the 10-year old jacketed Dy vacuum cell. Similar to the Dd train, the new Dy train was set on rails so it could accommodate changes in length caused by temperature fluctuations or different diffusers. Added to the Dy cell were a water-jacketed diffuser, a 25'-0" cooling section containing water injection nozzles built by Croll-Reynolds, followed by a single large steam-driven "Evactor Air Pump", also built by Croll-Reynolds. This station was intended for testing solid fuel motors, but it was reportedly rarely or never used.

In 1976, following the successful Viking missions to Mars and two Pioneer missions to Jupiter, JPL embarked on a second campaign to upgrade and increase the capabilities of Test Stands "C" and "D." Plans were drawn up in August 1976 for a substantial addition to the Test Stand "D" steam supply, followed closely by the addition of a vertical vacuum cell to Test Stand "C." At 10'-0" in diameter, the Cv (v=vacuum) cell was larger than its predecessor at Test Stand "D" in order to accommodate larger engines, and was connected to the Test Stand "D" ejector system via an underground duct.

At Test Stand "D," a concrete pad was poured in the summer of 1977 for a 12-foot diameter sphere--an insulated steam

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[153] Bonner interview, 12 January 1995.

"accumulator" with three 100-kilowatt Chromalox electric heaters ordered from Capital Westward, Inc. of Paramount, California. Designed to provide a 100-second, 300 psi steam supply for the ejector systems at Test Stand "D," the accumulator was cross-connected to the Clayton flash boilers in Building 4281/E-81 so that either steam source (or both together) could be used at any test cell. The "Hyprox" steam generator was removed. Installation of the steam system addition was completed by early 1978.

To complement other spacecraft test programs, JPL personnel built a small test table, "Dpond," in the 1970s on the north side of the "neutralization pond."[154] Small altitude thrusters (5 pounds thrust or less) and various non-firing components were tested there. A small flame bucket directed engine exhaust into the pond.

Like its predecessor at Test Stand "D," the vertical Cv test cell permitted JPL to "soak" engines. They were maintained in a vacuum at various temperatures for extended periods in order to test their operational reliability. The vacuum chamber was a flight simulator for flights from sea level to 100,000 feet under simulated outer space conditions (vacuum, extreme heat, and cold) using fluorinated and non-fluorinated oxidizers. After removing the chamber top, a 10-ton hoist, extending from the top story of the framework, lowered spacecraft engines into the vacuum chamber for vertical firing. Usually a diffuser was connected beneath each engine nozzle and the bottom duct of the tank to collect exhaust gases. Instrument wiring, stainless steel fuel, oxidizer, and control lines were connected to the rocket engine via vacuum-tight, flanged ports in the chamber walls. Engineers and test personnel entered the chamber via a 48-inch diameter flanged port on the west side.

A 36-inch diameter steel vacuum duct connected the Cv firing station to a new scrubber-condenser tower erected on the eastern edge of the caustic pond. The scrubber-condenser was built by Croll-Reynolds of Westfield, New Jersey. Before firing an engine in the Cv cell, the cell and its vacuum ducts were evacuated by air ejectors at Test Stand "D" via a 30-inch diameter underground duct. The ejectors, which emptied the system of exhaust gases, remained in operation during firings. The scrubber-condenser was essential to removing fluorinated exhaust compounds before the remaining gases were drawn to the Test Stand "D" ejection system,

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[154]Dpond and the vacuum systems at "C" and "D" stands were designed by J. Richard Bonner. Bonner interview, 12 January 1995.

which had no means to absorb and neutralize toxic byproducts. Most firings lasted between 5 and 15 seconds, with some lasting as long as 30 seconds. Mono methyl hydrazine (MMH or $CH_3HN \cdot NH_2$) was used as fuel in conjunction with N_2O_4 or F_2. The waste gases from non-fluorinated propellants are water (H_2O), carbon dioxide (CO_2), and nitrogen (N_2); hydrofluoric acid (HF) was a byproduct when fluorinated oxidizers were consumed.

Exhaust gas heat from Cv Cell tests was dissipated in several ways; first, domestic water was sprayed into the bottom duct of the vacuum chamber through hundreds of small holes in the deflector at the vertical duct bottom. The double-walled steel deflector elbow was cooled by circulating domestic water. Seventy nozzles sprayed 1.5 percent NaOH solution from the caustic pond onto the exterior of the 36-inch diameter horizontal steel duct to the condenser tower. A 4,000 gallon-per-minute Borg-Warner Byron Jackson vertical pump delivered the NaOH solution, which returned to the pond under the duct by gravity. A 100-horsepower Holloshaft pump motor built by Emerson Electric of Los Angeles, California drove the pump at 1770 revolutions per minute. The scrubber-condenser tower scrubbed exhaust of raw propellants and fluorine compounds by passing a shower of NaOH solution through the condenser against the gas flow. Absorbed compounds and NaOH solution returned to the caustic pond via a 12-inch diameter vertical drain pipe while CO_2 and N_2 continued to the Test Stand D ejectors. The condenser is elevated over 35 feet above the pond surface in order to prevent the atmosphere from forcing the NaOH solution up the drain pipe and into the vacuum system. To soak an engine, a butterfly valve near the condenser scrubber was closed, and the vacuum in the Cv Cell maintained by a 15 horsepower Beach-Russ rotary vacuum pump at the "C" stand tower. Two 6-inch diameter 10'-0" long lime (CaO) tanks purged fluorinated compounds before they could contact and corrode the pump. At the conclusion of a test, GN_2 from a purge tank flushed the chamber of any exhaust gases before personnel opened and entered the system. As at all other test stands, propellant valves were operated remotely by high pressure GN_2 lines and propellants were "pumped" by pressurized helium. Cryogenic fuel and oxidizer piping were jacketed in LN_2 lines maintained at minus 310°F.[155]

The JPL Edwards Test Station contains numerous other

[155]For comparison, at atmospheric pressure the following gaseous substances liquefy at the following temperatures: He, -452°F; LH_2, -434°F; LF_2, -370°F; LO_2, -361°F; LN_2, -346°F; B_2H_6, -266°F; ClF_3, -117°F; N_2O_4, -13°F; N_2H_4, +34°F.

buildings which support the testing and the general operation of the test station. Buildings 4225/E-26, Blower House No. 2; 4226/E-27 Helium Compressor Facility; 4227/E-28, Booster Pumping Station; 4228/E-29, Water Tank, which has been demolished; and 4229/E-30, Generator Building were built in 1959 in conjunction with Test Stand "D" to enhance the operations of the overall test station.

Test Stand "E" and the Solid-Propellant Processing Line

The JPL Edwards Test Station grew at an exponential rate in the early 1960s. The growth was centered on the addition of JPL's solid-propellant rocket motor manufacturing operation, which was moved from Pasadena to the JPL Edwards Test Station in the early 1960s. The solid-propellant manufacturing and testing facilities were primarily built by Greynald Construction of Sherman Oaks, California and the Ruane Corporation of San Gabriel, California in 1962 and 1963. The addition of the solid-propellant processing operation brought an influx of JPL employees to the Edwards Test Station in the early 1960s; 97 employees worked at the JPL Edwards Test Station at its zenith in 1967. The ETS solid-propellant manufacturing capability was NASA's only in-house solid propulsion processing and testing facility.[156]

Between 1961 and 1963, a new security fence was erected, approximately 575 acres was added to the JPL Edwards Test Station complex, the solid-propellant processing line and Test Stand E were constructed, the storage area and new docks were constructed, a new administration building was built in the complex's southwest corner, and an aircraft hardstand and taxiway which linked the JPL Edwards Test Station with the North Base runway was added. The capability to park aircraft at the JPL Edwards Test Station facilitated quicker access to the JPL laboratory in Pasadena. This was by far the largest single expansion program ever undertaken at JPL Edwards.

The JPL Edwards Test Station became a large, extensive complex when the solid-propellant processing line was added. The size is a reflection of not only the need for additional buildings, but also safety concerns relating to the hazardous nature of rocket engine and motor testing. The cultural landscape reflects an overwhelming preoccupation with intra-line quantity-distance limits and personnel safety at the JPL Edwards Test Station; it is a landscape filled with constant visual,

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[156] Gibbons and Tibbitts, 2.

auditory, and architectural reminders of the danger and hazards of testing rocket engines and motors. Warning lights, the intercom system, air horns, emergency shower and eyewash stations, blast barricades, fire and chemical hazard symbol signboards, and test-in-progress safety signs abound. Unlike the liquid-propellant test stands, the layout of the solid-propellant line doesn't seem influenced by prevailing winds, except for the location of Test Stand "E."

Blast barricades were placed in conjunction with buildings that had a greater likelihood of exploding. The blast barricades were not designed to stop or contain a blast, but to check flying shrapnel. Blast barricades are located on both the north and south facades of Building 4233/E-34, the solid-propellant mixer building, since it was located too close to the administrative building. If the building exploded, the personnel working in the administrative building were potentially threatened. These high metal barricades are filled with native soil. Two other types of blast barriers were built at the JPL Facility: the poured concrete barricade such as at Test Stand "B" and "C" and the plank barricades located at Test Stand "A" and Building 4234/E-35, Building 4242/E-43, and Building 4272/E-73. Blast barricades are also present at Test Stand "A," Test Stand "B," Test Stand "C," Test Stand "E," Building 4234/E-35, Building 4242/E-43, and Building 4272/E-73.

The architecture and spatial organization of the solid-propellant processing line also reflect safety concerns. The buildings are constructed from non-combustible reinforced concrete block and are windowless. Large steel doors are the primary entrances into the workspaces. The solid-propellant buildings have simple floor plans, most are two-roomed structures. The first room is the workspace; the back room is the machine room, which contains the equipment operating the building's systems. This floor plan offered not only the standardization of functions, but also architectural simplicity for firefighters and emergency personnel. Frangible walls that are easily broken are present at many buildings along the solid-propellant processing line. Buildings 4233/E-34, Mixer; 4236/E-37, Mixer and Casting Building; 4237/E-38, Oxidizer Dryer Building and 4243/E-44, Remote Preparation all have frangible walls. Emergency slides, a common industrial safety precaution, are present on several buildings to provide egress from roofs and second floors. The Mixer, Building 4233/E-34, has a rear emergency slide on the west facade.

The solid propellant processing line is extensive--approximately 40 buildings are spread between two major areas.

The storage area dominates the east side of the complex; the manufacturing and testing area composes the west side of the complex. The volatile nature of the complex has resulted in a spacious industrial land-use pattern. Unlike the structures in the liquid-propellant testing area which are tightly clustered together relatively speaking, the solid-propellant buildings are located approximately 100 to 300 feet apart. A spread out complex would potentially help contain an explosion or fire to a single structure. One exception to this pattern is the preparation complex which was for preparing solid-propellant motors. However, blast barriers and frangible walls protect the preparation complex buildings. The solid-propellant processing line structures are clustered by function: the cure buildings are adjacent to each other and the conditioning structures are contiguous.

Along the remotely operated solid-propellant processing line, fuels and oxidizers were ground, mixed, and cast as solid-propellant rocket motors. The motors were then cured, conditioned, and test fired. NASA Standard Igniters (NSIs), necessary to ignite solid-propellant motors in space were also prepared at the JPL Edwards Test Station. The propellant-processing facilities were dedicated for propellant ingredient weighing, and oxidizer drying and grinding. Five remotely controlled Baker-Perkins mixers provided propellant mixing in quantities ranging from 1 pint to 150 gallons. Four walk-in ovens cured the solid propellant, walk-in temperature chambers conditioned the solid propellant, and hammer mills ground the oxidizers. A Liner Laboratory provided experimentation space and housed the solid propellant office. A control building managed the processing line and contained facilities to weigh the solid propellant. A 5′-0" x 8′-0" autoclave allowed the curing of solid materials up to 400° Fahrenheit. The solid-propellant processing line contained the necessary solid propellant measurement devices, including an X-ray Facility for inspecting solid propellant motors for cracks and voids.[157] The composition of solid propellant motors is "a bit of a black art" according to JPL personnel.

The solid propellant processing line includes a test stand to test solid propellant rocket motors. The Ruane Corporation constructed Building 4259/E-60, Test Stand "E," in 1962. It is a 15′-0" x 70′-0" steel-reinforced poured concrete structure with a four-bay plan (see HAER photos CA-163-I-1, -2 for drawings) located at UTM coordinates 11.420900.3872340. Test Stand "E"

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[157] Gibbons and Tibbitts, 2.

consists of two individual atmospheric solid-propellant rocket motor firing cells and an X-ray inspection cell (see Fig. 20 for a simple plan). The two rocket motor cells are located on the north half of the test stand, and the X-ray inspection cell is on the south facade. The north bay is open on the east facade; it contains a large metal work bench and a 2-ton steel I-beam hoist. A remote camera is trained on the work bench. A corrugated metal sheathing covers the north bay. The adjacent south bay has tall concrete walls and an upper divider for separating equipment and tests. It has an open roof, and is open on the east facade. The center bay was used for vertical and horizontal rocket motor firings. An octagonal tiedown is on the ground. Openings through the west walls convey instrumentation and utility cables into the tunnel system. These test cells normally handled motors that produced between 1,000 and 10,000 pounds thrust direct, and 5,000 pounds thrust reverse. Maximum thrust capability was 50,000 pounds.[158]

The center bay is an integrated workshop and office space; it is enclosed with a shed roof. An off-center door accesses a workspace that connects Test Stand "E" to the tunnel system on the west facade of the test stand. The tunnel corridor that accesses the tunnel system extends past the west facade. Two doors flank the tunnel on its north and south facades. The adjacent bay to the south, the former X-ray test cell, is now a storage space. Two 1-ton hoists run perpendicular to each other through the bay. One hoist extends past the east facade. A large storage tank is located on the south facade of the test stand; the nozzle extends through the wall into the test cell. A pair of double doors are on the east facade of the south bay, and a door is on the south facade of Test Stand "E." A one-story, 10'-0" x 10'-0" concrete block addition is attached to the west facade of the south bay. It housed a generator and monitor; a door on the south facade of the addition accessed the equipment. Two fully enclosed wooden plank blast barriers (native soil and cribbing) are located on the north and south facades of Test Stand "E." The north blast barrier has been extended and encased in a metal sheathing.

Test Stand "E" was first used to support NASA's commercial satellite and spaceflight program. Solid-propellant kick motors, used to place Application Technology Satellites (ATS) in geosynchronous orbit around the earth, were tested at Test Stand

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158 Koebig and Koebig.

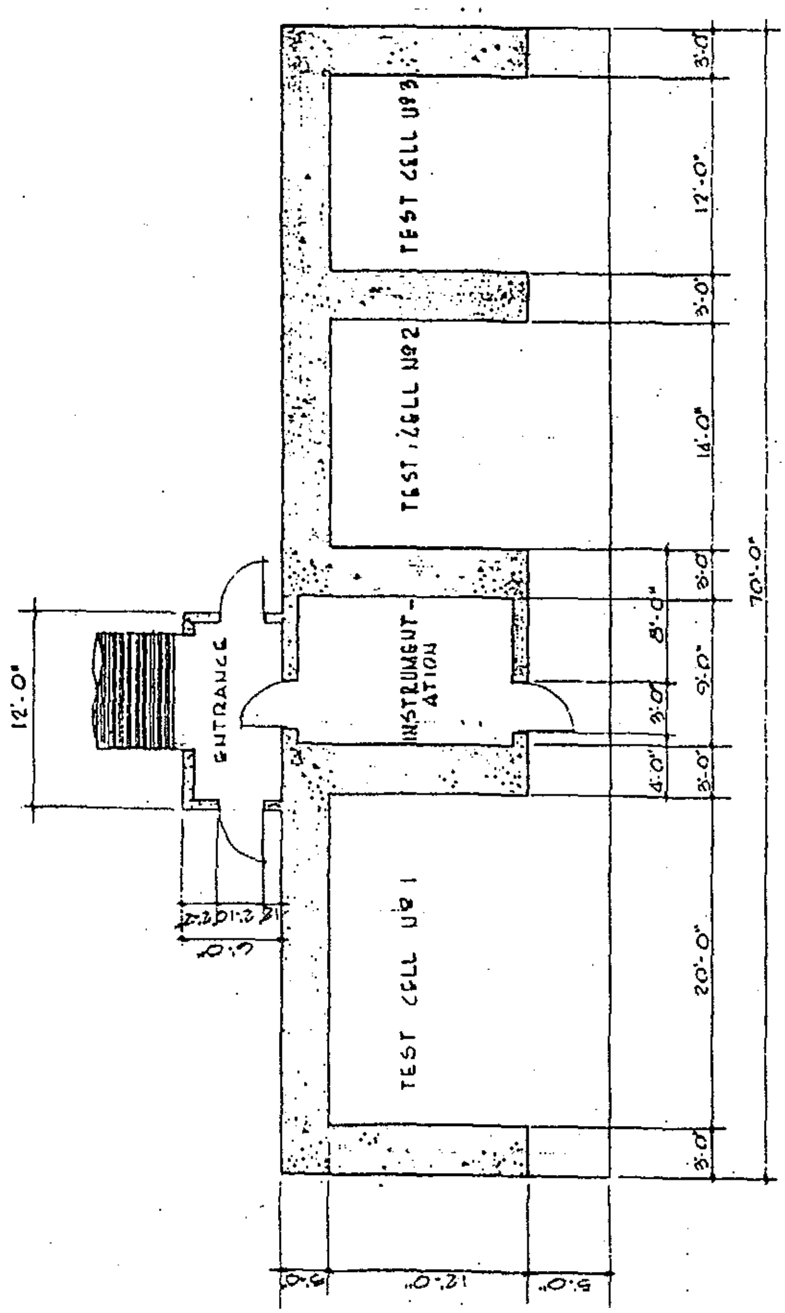

Fig. 20
Basic plan for Test Stand "E".

"E" in the 1960s.[159] A 10,500-pound solid-propellant motor and solid-propellant nozzles under development for the Space Shuttle program were tested on Test Stand "E" in the late 1970s.[160] The two test cells were modified to accommodate testing of 48-inch motors for the Space Shuttle program. In later years, the Advanced Solid Rocket Motor (ASRM) was tested at Test Stand "E." The last test firing at Test Stand "E" was conducted in April 1994.

The storage area on the east side of the complex is JPL Edwards Test Station's other major area with a solid propellant component. The storage sheds are physically separated from each other, a standard safety precaution for the storage of hazardous material. Safety concerns are manifest in the cultural landscape by the extensive storage complex. The isolated sheds are located approximately 150 feet apart from each other on the east side of the complex, away from all permanently occupied buildings. The native vegetation was scraped away from each of the building locations to help decrease the spread of fire, if an explosion did occur.

Ten one-story, open, corrugated metal storage sheds contained solid fuels, solid and liquid oxidizers, and flammable waste. The open storage sheds are partially enclosed on two or three sides. The sheds were primarily two sizes--a small 8'-7" x 10'-10" shed and a larger 16'-4" x 40'-6" shed. Three closed one-story, corrugated metal storage sheds are present as well; however, Buildings 4250/E-51 and 4251/E-52 were originally built as identically-sized 12'-7" x 40'-6" docks for solid fuel and oxidizer. They were later converted into storage areas; the second shed at Building 4250/E-51 was built in 1983. The roll-up doors were built in 1983 as well. The sheds each rest on a poured-in-place concrete foundation, and have steel I-beam frames bolted to concrete foundations. A plumbed emergency shower and eyewash station is present at each building. Concrete hazardous waste retention basins for collecting hazardous materials were constructed at each of these buildings in 1991. In addition to supporting the solid propellant research, the storage area also supported the liquid propulsion research.

Research work on solid and liquid rockets began to decline in the 1970s and 1980s as funding cutbacks affected American

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159 Gibbons and Tibbitts, 2.

160 JPL, 1981; National Aeronautics and Space Administration and Jet Propulsion Laboratory, 1987:2.

space programs. However, JPL Edwards Facility staff has been involved in many JPL programs such as *Galileo* and *Magellan* interplanetary spacecraft flight projects, which included flight support at Cape Kennedy, Florida.

Galileo, a Jupiter orbiter and probe, was envisioned in the late 1970s as a follow-up project to Voyager, called JOP (Jupiter Orbiter Probe).[161] *Galileo* suffered from delays throughout the 1980s as it fell victim to Space Shuttle delays, concerns over budgets, and space-borne launch systems.[162] *Galileo* was finally launched from the Space Shuttle *Atlantis* on 18 October 1989, using the IUS (Inertial Upper Stage) booster. It is scheduled to encounter Jupiter in December 1995. It is flying a complex trajectory called VEEGA (Venus-Earth-Earth-Gravity-Assist). *Galileo* performed flybys of Venus and Earth in 1990, before it commenced the direct leg of its trajectory to Jupiter. When *Galileo* reaches Jupiter in December 1995, it will release an atmospheric probe into the Jovian atmosphere, which "will measure the atmosphere's composition and perform other scientific measurements as it descends through Jupiter's thick cloud layers."[163] The orbiter will study four of Jupiter's moons, concentrating on Io, monitor Jupiter's atmosphere and magnetosphere and study the radiation belts surrounding the planet. *Galileo* observed the comet Shoemaker-Levy 9, which collided with Jupiter in July 1994.[164]

Magellan, a Venutian synthetic aperture radar mapping mission, was also originally conceived in the mid 1970s.[165] Synthetic aperture radar is an airborne electronic technique using a timed pulse signal, which allows the antenna to perform as if it were much bigger than it is. Synthetic aperture radar produces an enhanced, detailed radar image, excellent for cartographic purposes. It was delayed throughout the early 1980s because of Space Shuttle and budgetary problems. *Magellan* was finally launched from the Space Shuttle *Atlantis* in May 1989. *Magellan* reached orbit in 1990 and mapped 99 percent of Venus's surface, including volcanoes, lava plains, highland plateaus and

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161 Murray, 191.

162 Murray.

163 Neal *et al*, 180.

164 Neal *et al*, 180-81.

165 Murray, 244.

impact craters.[166]

Solid-propellant testing has occurred within the last fifteen years, but not in support of specific projects and programs, with the exception of the solid-propellant testing and manufacturing undertaken for Phillips Laboratory, Edwards AFB, California. JPL Edwards Facility has attracted research and development projects on non-propulsion oriented technologies in order to supplement its income, including a Remotely Controlled Tank Target Vehicle for the Army, and Simulation of Area Weapons Effects (SAWE) system for training exercises. The runways at Edwards AFB hosted evaluation tests for Electric Powered Vehicles and Hybrid Vehicles for the Department of Energy, and in the 1980s the DOE's Solar Thermal Program established a Parabolic Dish Test Site at the Edwards Facility to develop ways of generating electricity from solar energy.[167]

The JPL Edwards Test Station is a unique rocket engine testing facility. Not only is it one of the oldest such facilities in the country, but its cultural landscape exemplifies important trends in the history of the Space Age. The Nation's earliest successful guided missiles were tested at the JPL Edwards Test Station. Each of the deep space probes and landers JPL launched before 1987 had its propulsion subsystems qualified at the JPL Edwards Test Station. A unique landscape with associated architecture and engineering evolved to meet the demands of the dangerous and exotic solid and liquid propellant rocket engines used in these spacecraft and rockets. The JPL has led the United States in missile and deep space technology since WWII, and was the Nation's prime builder and developer of missiles and unmanned spacecraft into the 1970s. The JPL Edwards Facility's decline mirrors that of the deep space program as it slowed down and was eclipsed by the reusable Space Shuttle in the early 1980s. However, the JPL Edwards Facility remains as a historic resource whose industrial cultural landscape displays the extraordinary lengths to which people went in order to achieve spaceflight. Because of the significance of the installation to the history of space exploration, the JPL Edwards Facility potentially meets eligibility criteria for listing on the National Register of Historic Places as a National Register Historic District. On 1 October 1995 the Edwards Facility will be transferred to the Air Force Flight Test Center at Edwards AFB, and closure plans call for the demolition of 13 structures, including Test Stands "A," "B," "C," and "D." The Air Force's 18th Space Surveillance Squadron, which monitors floating debris in near-earth orbit, is scheduled to occupy former JPL

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[166] Neal *et al*, 165.

[167] Gibbons and Tibbitts, 3.

administrative buildings, and the solid propellant line will be transformed into storage space for Base Civil Engineering.

JPL Glossary

Ablation-Type Nose Cone: A nose cone designed to reduce heat transfer to the internal structure; it wears away during descent and transfers the heat.

Ballistic Missile: A missile which does not rely upon aerodynamic surfaces to produce lift and consequently follows a ballistic trajectory when thrust is terminated.

Excitable: The ability of an atom or molecule to be raised to a higher energy level.

Fairing: An auxiliary member or structure whose primary function is to reduce drag where it is fitted to the rocket.

Film-cooled: The cooling of a body or surface, such as the inner surface of a rocket combustion chamber, by maintaining a thin fluid layer over the area.

Flyby: An interplanetary mission in which the spacecraft passes close to a planet, but does not impact it or goes into orbit around it.

Frangible: Designed to be easily broken or fractured in a predetermined area.

Fuel: A substance used to produce heat by chemical reaction.

Guided Missile: Any missile capable of guidance or direction after having been launched.

Hydrobomb: A warhead or bomb detonated underwater where the destructive force is a pressure wave greater than the resulting explosion.

Hypergolic: A family of rocket propellants that ignite spontaneously when mixed together.

Launch Window: The postulated opening in time or space through which a spacecraft must be launched in order to rendezvous at the desired time or place.

Liquid Propellant: A rocket propellant in liquid form.

Monopropellant: A rocket propellant consisting of a single substance, especially a liquid, capable of producing thrust without the addition of a second substance.

Oxidizer: A substance, not necessarily containing oxygen, that supports the combustion of a fuel or propellant.

Phase-lock loop tracking system: A tracking or homing system employed on a rocket or missile that acquires its target by comparing the difference between the two signals.

Ramjet: A engine type with no internal mechanical components consisting of a specially shaped tube open at both ends.

Regenerative-cooled: The cooling of a rocket engine combustion chamber and/or nozzle by circulation the fuel or oxidizer, or both, around the parts to be cooled prior to combustion in the engine.

Solid Propellant: A rocket propellant in solid form; usually containing both the fuel and oxidizer combined or mixed, and formed into a monolithic grain.

Sounding Rocket: A rocket that carries scientific equipment for making observations of or from the upper atmosphere.

Specific Impulse: Equivalent to the effective exhaust velocity divided by the gravitational acceleration.

Star-shaped solid propellant charge: A hollow rocket propellant charge; with the cross section of the hole having a multipointed shape.

Thrust: The pushing or pulling force developed by a rocket engine.

Jet Vanes: A fixed or movable surface used in the jetstream of a rocket for stability control, where external aerodynamic controls are ineffective.

Wasserfall: A World War II German liquid propellant surface-to-air guided missile that used a cascading water cooling system.

Water-cooled: Cooling the engine by water.

Acronym List

AAF Army Air Force

ABMA Army Ballistic Missile Agency

ACE Army Corps of Engineers

AFB Air Force Base

AFFTC/HO Air Force Flight Test Center/History Office

AFFTC/EM Air Force Flight Test Center/Environmental Management

ASRM Advanced Solid Rocket Motor

BHPO Base Historic Preservation Office

BTU British Thermal Unit

Caltech California Institute of Technology

CSC Computer Sciences Corporation

DSN Deep Space Network

ETS Edwards Test Station

GALCIT Guggenheim Aeronautical Laboratory/California Institute of Technology

GCMS Gas Chromatograph/Mass Spectrometer

GE General Electric

GPM Gallons per minute

HABS Historic American Buildings Survey

HAER Historic American Engineering Record

IUS Inertial Upper Stage

JATO Jet-Assisted-Takeoff

JOP Jupiter Orbiter Probe

JPL Jet Propulsion Laboratory

MJS Mariner/Jupiter/Saturn

MMH	Mono Methyl Hydrazine
NACA	National Advisory Committee on Aeronautics
NASA	National Aeronautics and Space Administration
NHL	National Historic Landmark
NRHP	National Register of Historic Places
NRL	Naval Research Laboratory
NSI	NASA Standard Igniter
ORDCIT	Ordnance Department/California Institute of Technology
ONR	Office of Naval Research
PSI	Pounds Per Square Inch
RCRA	Resource Conservation and Recovery Act
RFNA	Red Fuming Nitric Acid
RTV	Reentry Test Vehicle
SAWE	Simulation of Area Weapons Effects
SHPO	State Historic Preservation Office
UDMH	Unsymmetrical Dimethyl Hydrazine
USGS	United States Geological Survey
WAC	Without Altitude Control or "Women's Army Corp"
WFNA	White Fuming Nitric Acid
WWII	World War II
VEEGA	Venus-Earth-Earth-Gravity-Assist
VfR	Verein für Raumschiffahrt ("Society for Space Travel")

Chemical Names and Formulas

Aniline: $C_6H_5NH_2$ (also called *aminobenzene* or *phenylamine*)

Boron oxyfluoride: BOF

Boron trichloride: BCl_3

Boron trifluoride: BF_3

Calcium fluoride: CaF_2

Calcium hydroxide: $Ca(OH)_2$

Calcium hypochlorite: $Ca(ClO)_2$ (commercially known as Perchloron)

Calcium tetraborate: CaB_4O_7

Carbon dioxide: CO_2

Chlorine trifluoride: ClF_3

Chlorine pentafluoride: ClF_5

Decaborane: $B_{10}H_{14}$

Diborane: B_2H_6 (also known as boron hydride)

Dichlorodifluoromethane: CCl_2F_2 (commercially known as Freon)

Dihydrotetraborane: B_4H_{10}

Ethyl aniline: $C_2H_5 \cdot C_6H_4NH_2$ (several isomers exist)

Fluorine: F_2

FLOX: cryogenic mixture of liquid oxygen (LO_2 or LOX) and liquid fluorine (LF_2)

Gaseous hydrogen: GH_2

Gaseous nitrogen: GN_2

Helium: He

Hexaborane: B_6H_{10}

Hydrazine: N_2H_4

Hydrofluoric acid: HF

Hydrogen: H_2

Hydrogen peroxide: H_2O_2

Lime: CaO

Liquid fluorine: LF_2

Liquid nitrogen: LN_2

LOX: liquid oxygen: LO_2

Lithium hydride: LiH

Mono methyl hydrazine, or MMH: $CH_3HN \cdot NH_2$

Nitrogen: N_2

Nitrogen dioxide: NO_2

Nitrogen tetroxide: N_2O_4

Oxygen difluoride: OF_2

Pentaborane: B_5H_9

Sodium borate: $Na_2B_4O_7$

Sodium fluoride: NaF

Sodium hydroxide: NaOH

Unsymmetrical dimethyl hydrazine, or UDMH: $(CH_3)_2N \cdot NH_2$

Water: H_2O

PROJECT INFORMATION

This HAER report had its genesis in a Phase II cultural resource evaluation of the Jet Propulsion Laboratory Edwards Facility conducted by Scott M. Hudlow, Architectural Historian, Environmental Engineering Department, Applied Technology Division, Computer Sciences Corporation, Edwards Air Force Base, Edwards, California. The Phase II study determined that the Edwards Facility was eligible as a National Register of Historic Places historic district, and that the JPL/Air Force Flight Test Center closure plans resulted in adverse effects which merited mitigatory HABS/HAER documentation under Sections 106 and 110 of the National Historic Preservation Act. The historical background and sources from Mr. Hudlow's work were adapted by Richard K. Anderson, Jr. to meet the HAER report format and HABS/HAER standards as required by the Phase III cultural resource documentation project conducted by Mr. Hudlow. Mr. Anderson also included in the report numerous technical and historical observations derived from reviews of historic engineering drawings, JPL photographic records, site visits to test stands, and telephone and taped interviews with JPL test engineers. Photocopied engineering drawings from JPL Edwards engineering office, and copies of test stand schematics used in preparing the HAER report and drawings have been filed with the HAER project field records, along with several dozen 35mm field photographs taken by Mr. Hudlow in 1994-1995. Neither time nor funding was available to study the impact of individual engineers and personalities on either the design and evolution of the JPL Edwards Facility or its individual test stands. Nor could these individuals' contributions to the design and success of spacecraft series be evaluated. The financial aspects of JPL Edwards operations, such as the costs and schedules of any or all specific series of tests (equipment, propellants, etc.) were outside the scope of this report. Neither time or opportunity to review the design and results of individual tests for what they might reveal about the evolution of the test stands was available. The history of specific rocket engine designs tested at JPL Edwards was beyond the scope of this report. All of these topics deserve further research given the uniqueness of the site and its historic mission.

In addition to the HAER report, Mr. Anderson prepared four HAER measured drawings, and collaborated with Mr. Hudlow in selecting sites for HAER photographic documentation as well as photocopies of historical photographs and drawings for inclusion in the HAER project record. Contemporary (1994-95) large format photography was conducted by Brian Grogan, Yosemite Photographics, Inc., Yosemite, California. Historical JPL negatives were photocopied by Bob Schlosser of the Huntington Library, San Marino, California, with the invaluable help of David Deats at the JPL Photographic Laboratory in Pasadena, California. Some of the HAER record photographs are photocopies of 35mm field photography made by Mr. Hudlow and are included with his permission. The HAER report, measured drawings and large format photography were prepared under Computer Sciences Corporation purchase order no. CS5-00722, 14 December 1994, Richard K. Anderson, Jr., vendor.

Mssrs. Hudlow and Anderson appreciate the numerous hours of assistance given by JPL employees William C. Tibbitts (JPL Edwards Facility Manager), John Richard ("Dick") Bonner (JPL Facility Test Engineer), David Quarles (JPL Facility Test Engineer), John Bluth (JPL Archivist, Pasadena) and others in pointing out files, investigating facilities, answering questions and reviewing the HAER documentation at various stages of its preparation.

Primary and Secondary Research

Primary and secondary research for the Phase II architectural evaluation was conducted between July and November 1994. Primary records were reviewed at the National Archives in Laguna Niguel, California. Historic construction drawings and site plans were located at this National Archives facility.

The Air Force Flight Test Center History Office (AFFTC/HO) had little documentation pertaining to the JPL Edwards Facility. Because JPL is a non-Air Force tenant organization, its historic records have not been systematically retained by the AFFTC/HO. The AFFTC/HO did, however, contain some useful written documents regarding JPL, including historic Army reports. The JPL has its own archive in Pasadena, California, where the JPL Edwards Facility collections will be deposited after closure. Primary records in the custody of the JPL Edwards Facility were consulted. The JPL Edwards Facility real estate files recorded information concerning the construction of each of the standing buildings, and the JPL Edwards Facility "as-built" drawings document the standing structures and their cultural landscape. Selected files were consulted for test stand process schematics and relevant operator's manuals. The base library proved useful for locating secondary sources on JPL and the space program.

Off-base libraries and repositories were contacted and/or visited to complete the project. Beale Memorial Library (the main branch of the Kern County Library) in Bakersfield, California, was contacted and visited, but little relevant information was obtained. The Walter W. Stiern Library at California State University, Bakersfield, was also consulted. Secondary sources on JPL and the space program were located at Beale and Stiern libraries. Finally, the JPL archive in Pasadena, California was consulted. The JPL archive contains historic photographs, articles, historic reports, and JPL's newspaper. The JPL archive housed the most quintessential historic information germane to the JPL Edwards Facility.

ILLUSTRATION SOURCES

Fig. 1 Compiled from two engineering drawings: bottom half based on California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, "Edwards Test Station Plumbing Distribution," drawing no. EPD/12-1, 4 March 1972; top half based on California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, "Exhaust Scrubber Facility Location & Vicinity Map", drawing no. E18/15, no date (ca. 1969).

Fig. 2 Test Stand "A" process schematic from the "A" Stand files of David Quarles and John Richard Bonner, JPL test engineers, JPL Edwards Facility, Edwards AFB, California.

Fig. 3 Tunnel Section from Koebig & Koebig, Inc., Engineering, Architecture, Planning, December 1974. *1974-1979-1984 Master Plan for Edwards Test Station, National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.* Report on file, JPL Edwards Facility, Edwards AFB, California.

Figs. 4-6 From schematics in the files of David Quarles and John Richard Bonner, JPL test engineers, JPL Edwards Facility, Edwards AFB, California.

Fig. 7 From cover sheet of original "D" Stand drawings, titled "Request 59-4 for Approval for Test Stand E-24 and Set Up Shop E-23 at JPL-Edwards Test Station, Muroc, Calif.", drawing no. E-24/1-0, 29 January 1959.

Figs. 8-12 From schematics in the files of David Quarles and John Richard Bonner, JPL test engineers, JPL Edwards Facility, Edwards AFB, California.

Fig. 13 From JPL negative no. 384-3730, 26 July 1963. Draftsman undetermined.

Figs. 14-17 Schematics from the files of David Quarles and John Richard Bonner, JPL test engineers, JPL Edwards Facility, Edwards AFB, California.

Fig. 18 From typescript operator's manual by Frank C. Brown & Company, Inc. "Toxic Exhaust Scrubber Facility."

Revised December 1969, p. 6. Found in "C" Stand files of David Quarles and John Richard Bonner, JPL test engineers, JPL Edwards Facility, Edwards AFB, California.

Fig. 19 Schematic from the files of David Quarles and John Richard Bonner, JPL test engineers, JPL Edwards Facility, Edwards AFB, California.

Fig. 20 Plan of Test Stand "E" from California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, "Test Stand Building E-60," drawing no. E-60/00, 10 August 1962.

NOTE: Larger copies of the line illustrations are contained in project field notes transmitted with project history, photographs and measured drawings. Copies of other schematics and engineering drawings of interest were retained in the field notes as well.

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"Real Property Record - Buildings," a series of cards on each structure at JPL Edwards Facility, recording construction, alterations and costs. Records on file at JPL, JPL Edwards Facility, Edwards AFB, California.

B. Maps and Drawings

California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL, JPL Edwards Facility, Edwards AFB, California.

Schematics and drawings from test stand files of David Quarles and John Richard Bonner, JPL test engineers. Schematics and drawings on file at JPL, JPL Edwards Facility, Edwards AFB, California.

C. Historical Photographs

A large collection estimated at 2000 images was reviewed at JPL Edwards Facility in 1994-1995. Original negatives are retained by JPL at its Pasadena, California headquarters as series 11, 384, and 344. Of these images, ones used for this report or photocopied for the HAER record are cited by negative number.

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ADDENDUM TO
Jet Propulsion Laboratory Edwards Facility
(JPL Edwards Test Station)
Edwards Air Force Base
Boron Vicinity
Kern County
California

PHOTOGRAPHS

WRITTEN HISTORICAL AND DESCRIPTIVE DATA

Historic American Engineering Record
National Park Service
Department of the Interior
San Francisco, California

HISTORIC AMERICAN ENGINEERING RECORD

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Photographs CA-163-1 to Ca-163-7 were transmitted to Library of Congress in 1995.

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Credit PSR: Philipp S. Rittermann, Photography & Preservation Associates, Inc., September, 1995

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CA-163-8 Credit WCT. Original 4" x 5" black and white negative housed in the JPL Archives, Pasadena, California. This aerial photograph displays solid propellant line structures E-34 through E-40 (JPL negative no. 384-6572A, 24 May 1967).

CA-163-9 Credit PSR. This overview displays the concentration of JPL solid propellant production buildings as seen when looking directly north (6º) from the roof of the Administration Building (4231/E-32). The structures closest to the camera contain the equipment for weighing, grinding, mixing, and casting solid propellant grain for motors. Structures in the distance generally house curing or inspection activities.

CA-163-10 Credit PSR. This group view shows propellant preparation buildings 4241/E-42, 4242/E-43, and 4243/E-44 (left to right) as seen when looking northwest (314°). Note the warning lights at the extreme left of the view, and the use of lightning rods on structures. Building 4241/E-42 housed solid rocket motors after they were cast and awaiting curing. Building 4241/E-42 was the Preparation Control center which housed remote controls for operations in the other two buildings. Buildings 4243/E-44 housed a remotely controlled mandrel puller for pulling mandrels (casting cores) from cured grain, and a vertical lathe for trimming grain to shape and size.

HISTORIC AMERICAN ENGINEERING RECORD

JET PROPULSION LABORATORY EDWARDS FACILITY
(JPL Edwards Test Station)

This report is an addendum to a 119 page report previously transmitted to the Library of Congress in 1995.

Location:	Edwards Air Force Base Boron Vicinity Kern County California UTM coordinates of property line: 11.419140.3872000, 11.419690.3872840, and 11.419690.3873160, USGS 7.5 min Edwards quadrangle, 1973 11.420320.3873760 and 11.421280.3873760, USGS 7.5 min North Edwards quadrangle, 1973 1.421280.3872470 and 11.419970.3872010, USGS 7.5 min Rogers Lake North quadrangle, 1973
Date of Construction:	1962-1963; Modifications to facilities occurred on a frequent basis in the 1980s.
Fabricators:	Greynald Construction of Sherman Oaks, California and the Ruane Corporation of San Gabriel, California.
Present Owner:	United States Air Force
Present Use:	Test facility
Significance:	Operated by the California Institute of Technology, the Jet Propulsion Laboratory Edwards Facility was the United States' first university-sponsored research and testing facility for the development of liquid-fueled rocket engines and components. It became an important national test facility. Solid-propellant rocket motors were built and tested at the JPL Edwards Test Station, including Space Shuttle nozzles and motors, *Syncom 1, 2,* and *3* motors, Application Technology Satellites solid rocket motors, and the solid rocket motors for the *Surveyor* and *Voyager* lunar and interplanetary probes.

Historians: Primary: Scott M. Hudlow, Architectural Historian, Computer Sciences Corporation, Edwards Air Force Base, California
Secondary: Richard K. Anderson, Jr. Columbia, South Carolina. July 1995-December 1995.

TABLE OF CONTENTS

Historical Background and Context

The Jet Propulsion Laboratory (JPL) dates from 1936. It originated as part of the applied mechanics program at the Guggenheim Aeronautical Laboratory/California Institute of Technology (GALCIT). Six student scientists, Hsue Shen Tsien, Apollo M. O. Smith, John W. Parsons, Edward S. Forman, Weld Arnold, and Frank W. Malina, led by Hungarian émigré Theodore von Kármán, conducted the first static tests of rocket engines in 1936 in the Arroyo Seco, a dry riverbed, located at the western edge of the San Gabriel Mountains in Pasadena, California. The Arroyo Seco was chosen for its relative isolation from urban development, lack of foliage, and proximity to the California Institute of Technology (Caltech) campus in Pasadena.[1] GALCIT was an early, amateurish rocket project that conducted both liquid-propellant and solid-propellant research.[2] Caltech has since been recognized as the first university in the United States to sponsor formal rocket research.

GALCIT and Solid Propulsion

The GALCIT group went through rough years in 1936 and 1937 as the crisis in Europe deepened. However, in the spring of 1938, the U.S. military's nascent desire to harness the potential power of rocketry engendered a financial commitment from the National Academy of Sciences Committee on Air Corps Research to fund the GALCIT rocket group.

John W. Parsons, an expert in explosive chemicals, particularly harbored an interest in solid propellants.[3]

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[1]. Daniel, Mann, Johnson, and Mendenhall. "JPL Master Facilities Plan 1977". Report on file at JPL, JPL Edwards Facility, Edwards AFB, California, unpaginated; Koppes, Clayton R. *JPL and the American Space Program: A History of the Jet Propulsion Laboratory*. New Haven, Connecticut: Yale University Press, 1982.

[2]. Koppes, 1-8.

[3]. Solid propellants are a combination of fuel and oxidizer, brought together and mixed into a single solid mass called the "grain." The fuel is usually prepared in a liquid state, and the oxidizer is prepared in a solid state, usually as a powder, and later mixed with the fuel. When the "grain" is conditioned; it solidifies to form the propellant. The two constituents together provide better burn characteristics than either demonstrated alone. An alternative solid propellant is a double-base type solid propellant. In this combination, each of the two primary

Parsons "...possessed an encyclopedic command of explosives and similar chemicals," and had worked occasionally for powder companies before his association with GALCIT.[4] Awash with the National Academy of Sciences money, GALCIT and Parsons experimented with diverse powder combinations trying to create a safe solid-propellant charge.[5] The U.S. Army provided the immediate impetus for solid-propellant research due to its preference for solid propellants because of their ease of handling and its interest in rocket-assisted takeoff for propeller-driven aircraft. Yet, solids research was especially difficult for GALCIT scientists. Clayton Koppes, historian, relates that:

> To be effective in helping boost propeller-driven planes at takeoff, rockets would have to burn for perhaps 10 to 20 seconds. But no solid-propellant engine then known burned for more than about 3 seconds. It couldn't be done, most of the experts advised. The conventional wisdom held that once the propellant was ignited, pressure would build rapidly in the chamber and cause the engine to explode. Repeated explosions with almost every version Parsons tried seemed to prove the experts right. He tried innumerable combinations of black powder in several configurations, most designed to burn slowly from one end, like a cigarette. The experimenters clung to the hope that the difficulties were mechanical, not fundamental. They surmised that somehow the walls of the powder charge were ignited or that the charge cracked when the pressure in the chamber rose. But by spring 1940 the explosions and expert advice had driven the group to the point of giving up on solids.[6]

Although experts believed that solid propellants were not practicable, the GALCIT group inched forward. First, they demonstrated that long-duration, end-burning, solid-propellant rocket motors were theoretically possible. Second, in the summer of 1941, GALCIT developed a small two-pound amidic, end-burning, black powder solid-propellant charge, later designated GALCIT 27. It burned modestly for 12 seconds and produced 28 pounds of

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constituents could, theoretically, burn on its own accord in a vacuum. The double-base type solid propellant contained a mixture which has the properties of both fuel and oxidizer.

4. Koppes, 3.

5. Koppes, 10.

6. Koppes, 10.

thrust. The solid-propellant charge was compressed into a cylinder 10 inches long and 1.75 inches in diameter with a blotting-paper liner in 22 increments at a pressure of 18 tons.[7] GALCIT 27 was the basis for the first solid-propellant jet-assisted takeoff (JATO) rocket.

The GALCIT group first tested the solid-propellant JATO rocket at March Field in Riverside, California in August 1941. The JATO rockets were tested at Muroc Army Air Base, now Edwards Air Force Base (AFB) beginning in 1942. First, static testing was conducted, second the rockets were ignited after the plane was in flight, and last, the JATO rockets were used to assist takeoff. The rockets were tested on a propeller-driven Ercoupe, a lightweight, low-wing monoplane. Three bottle-shaped solid-propellant motors were inserted under each wing. Lt. Homer Boushey, on 12 August 1941, soared into the air using rocket power for the first time in American history. Koppes states that "The JATOs cut the distance required for takeoff nearly in half, from 580 feet to 300 feet; the time required to become airborne was reduced almost as much, from 13.1 seconds to 7.5 seconds, or 42.8 percent. The plane's structure suffered no ill effects; in fact, Boushey reported, "...it was easier to handle the plane with the rocket thrust."[8]

Parsons and the rest of the GALCIT group soon discerned a major problem- JATO rockets were not stable. The GALCIT 27 JATO rockets deteriorated quickly; long-term storage of JATO rockets in combat conditions was unfeasible. The GALCIT group searched for a solution: they modified the JATO design, tested different types of blotting paper, and investigated diverse chemicals as propellants. After the United States entered World War II (WWII) in December 1941, the U.S. Navy desired a JATO rocket that would provide 200 pounds of thrust for 8 seconds. The U.S. Navy contracted with GALCIT to provide this product.[9] Parsons and the GALCIT researchers were desperate for a solution to the long-term stability problem.

Parsons decided to eschew the black powder/saltpeter solid propellant combination altogether. He instead tried paving asphalt as a fuel and potassium perchlorate as an oxidizer. This solid-propellant combination, designated GALCIT 53, was immediately successful. By 1943, refinements led to GALCIT 61-C,

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7. Koppes, 11.

8. Koppes, 11-12.

9. Koppes, 12.

which when burned at a chamber pressure of 2,000 pounds psi (per square inch), had an Isp (specific impulse) of 186, an exhaust velocity approximating 5,900 feet per second, and could be stored indefinitely within wide temperature extremes (between -9°F and +120°F). After this fundamental breakthrough in solid-propellant research, the U.S. Navy was able to use JATO rockets extensively during the last two years of WWII for carrier-based operations in the Pacific theatre.[10]

The GALCIT rocket project made significant and important theoretical and practical advancements in solid-propellant rocket technology. GALCIT was the first group to demonstrate the feasibility of constant pressure, long-duration solid-propellant rockets using the GALCIT 53 asphalt-based propellants.

Aerojet Engineering Corporation, a JPL spin-off company, was created to further develop and market JATO motors during WWII. Theodore von Kármán, Andrew Haley (Kármán's attorney), Parsons, Malina, Forman, and Martin Summerfield, a JPL liquid propellant researcher, provided the capital and assigned all patents to Aerojet. GALCIT and Aerojet had an interlocking relationship as employees moved between the two organizations. Parsons left GALCIT to work for Aerojet permanently; however, Kármán and Malina instead worked as Aerojet consultants. Aerojet also had many of its applications tested at the GALCIT test station in the Arroyo Seco.[11]

GALCIT began formally calling itself the Jet Propulsion Laboratory in 1944.[12] The name JPL was chosen carefully and consciously. David Baker, a science writer, states:

> ...that while most of the work embraced by these assignments was centered on rocket propulsion, the word 'jet' was applied in each and every case when an organization was set up to conduct theoretical and practical tests. The popular interpretation of the word 'rocket' had too flippant a connotation to engender the degree of respectability demanded by the work![13]

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10. Koppes, 12-13.

11. Daniel, Mann, Johnson, and Mendenhall; Koppes, 16-17.

12. Koppes, 20.

13. Baker, David. *The Rocket: The History and Development of Rocket & Missile Technology.* New York, New York: Crown Publishers, Inc., 1991:72.

GALCIT's new name, JPL, enabled an additional $3 million in funding, and the staff tripled to more than 250 people.[14]

Post-War Contributions to Solid-Propellant Technology

Solid-propulsion research at JPL continued after WWII. Sergeant, Loki, Thunderbird, and the RTV (Reentry Test Vehicle) were important late 1940s and 1950s military and space science solid-propulsion projects. The GALCIT/JPL solid-propellant achievements are a distinct American and JPL contribution to the history of rocketry that led directly to the development of significant large Cold War solid-propellant missiles such as Polaris, Poseidon, and Minuteman at various other laboratories.[15]

The tremendous technological advances generated both positive and negative results. JPL was able to advance rocketry and lay the foundation for the unmanned space program; however, JPL began to have problems with its Arroyo Seco location that jeopardized the testing operation.

By the mid 1940s, population growth in the surrounding communities of Pasadena, Altadena, La Cañada, and Flintridge began to limit the facility's ability to conduct large-scale rocket engine tests.[16] At WWII's conclusion, the area was heavily settled with upper middle-class residents, some of whom overlooked the Arroyo Seco. The area's residents "...objected to the noise of static tests, and to the laboratory's unsightliness."[17] For example, the Corporal E liquid rocket engine produced 120 decibels of noise at an altitude of 200 feet.[18] JPL scientists and engineers were forced to find an isolated location where it was possible to conduct noisy and hazardous tests.

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14. Daniel, Mann, Johnson, and Mendenhall.

15. Koppes, 17.

16. Gibbons, John and William C. Tibbitts. "JPL Edwards Facility Historic Overview". Typescript on file at AFFTC/EM, Edwards AFB, California, 1991:1.

17. Koppes, 48.

18. Bluth, John (Archivist, Jet Propulsion Laboratory, Pasadena, California). Telephone conversations with Scott M. Hudlow, January 1995.

JPL had tested JATO rockets at Muroc and was familiar with the Base. Consequently, the Muroc Flight Test Base was perceived as a perfect location when JPL conducted a search in 1944 for a nearby, yet isolated, site for its rocket engine testing facility. The new JPL facility was initially designated the ORDCIT (Ordnance Department, California Institute of Technology) Test Station; it was renamed the JPL Edwards Test Station in 1951. Although the liquid-propellant engine testing was moved to the high desert, the solid-propellant motor testing remained in Pasadena until 1962, when it was moved to the JPL Edwards Test Station.

The ORDCIT Project, which dated to WWII, was designed to develop a series of rockets and associated launching hardware. The ORDCIT Project focused on liquid propulsion technology; however, JPL was interested in continuing to improve solid propellants after it had discovered the asphalt-based solids. This was the beginning of the Private, Corporal, and Sergeant rockets JPL developed for the Army. Private and Corporal were liquid rockets;[19] Sergeant was a solid-propellant rocket, and the nation's first solid-propellant ballistic missile.

In the mid 1940s, the prevailing scholarly opinion was that solid propellants could not equal the potential of liquid propellants for large rockets. G. Edward Penray, a founder of the American Rocket Society, stated in 1944 that solids would "...never give the power and sustained performance needed for high-altitude sounding rockets...or long-range military or trajectory rockets."[20] Solid propellants had power and sustainability problems that were difficult to overcome. Solid propellants also needed to burn slowly, consistently, evenly, at a relatively low initial temperature, use an internal-burning grain, and be operational within wide ambient and controlled temperature ranges. These characteristics are inconsistent with the asphalt-based solid JATO motors, so JPL engineers and scientists began searching for a solution. They wanted to design a larger solid-propellant rocket.

In late 1945, a JPL engineer established that a rubberlike polysulfide developed by the Thiokol Corporation possessed many of the best characteristics of the asphalt-based solid propellants the JPL was using in its JATO without their weaknesses. However, the rubberlike polysulfide developed a

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[19]. Please consult the original HAER report for a lengthy discussion of the Corporal and Private programs.

[20]. Koppes, 36.

burning-rate problem and formed a cone inside the propellant charge that changed the rate at which the propellant burned.

As JPL attempted to solve this practical problem, Army Ordnance contracted with JPL to develop a small six-inch solid booster rocket known as Thunderbird. The Thunderbird was used as a test vehicle to solve the burning-rate problem, and to ascertain whether the polysulfide could withstand the exaggerated acceleration pressures associated with launching. An internal-burning propellant charge with a star-shaped central hole through the propellant grain was developed by English researchers and scientists at the Allegheny Ballistics Laboratory in West Virginia. JPL appropriated the internal-burning star to ascertain whether it could solve the burning-rate problem by providing constant thrust.[21] Clayton Koppes relates that:

> ...JPL researchers learned of the star almost by accident, through an appendix to another report being circulated among military laboratories. For the Thunderbird motor the engineers applied a thin liner to the wall of the combustion chamber, then mounted a ten-point-star-mold core in the center of the chamber. They poured the polysulfide propellant in the chamber and, when the propellant began to harden, removed the star. The design was simplicity itself. When the Thunderbird motor was ignited, the charge burned slowly from the inside, and the star gradually formed a cylinder. The burning-rate problem was solved, and the polysulfide proved it could withstand the acceleration.[22]

The successful Thunderbird tests in early 1948 led to ambitious tests on larger solid-propellant motors. Theoretical models demonstrated that solid-propellant motors the size of the WAC (Without Altitude Control) Corporal 12-inch liquid propellant engine could reach an altitude of 810,000 feet. However, static tests performed on a 15-inch motor caused explosions due to thin steel liner cases. The unexplained explosions (at the time) lessened enthusiasm for solid-propellant research at the same time JPL was gearing toward the militarization phase of the liquid propellant Corporal rocket program.[23]

JPL continued to conduct minor solid-propellant research in

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[21]. Williamson, Mark. *Dictionary of Space Technology*. Adam Hilger: New York, New York, 1990:263; Koppes, 36-37.

[22]. Koppes, 37.

[23]. Koppes, 37.

the early 1950s in Pasadena. Loki, an antiaircraft missile derived from the German's WWII Taifun missile, was the first JPL solid-propellant program to benefit from these new discoveries. Taifun was a small pencil-thin unguided antiaircraft rocket with a diameter of 4 inches and a height of 6 feet.[24] Army Ordnance considered Loki a backup to the Hercules Powder Company's Nike[25] antiaircraft missile in case Nike failed.

Loki was an impractical weapon, but an interesting research project. The small rocket measured approximately 6 feet long and 3 inches in diameter and had a package of high explosives strapped on the end. The unguided Loki was launched in supersonic barrages, upward of Mach 6.5 to Mach 7. Nike, however, worked. The Army canceled Loki, to the consternation of JPL engineers. JPL had Loki's solid propellants burning faster than any previous solid-propellant motors ever designed, and had made important advances in aerodynamics and stability, which JPL engineers relinquished when Army Ordnance canceled the project. One JPL engineer suggested Loki would make an excellent pyrotechnic launching device; it was later utilized as a high-altitude sounding rocket.[26]

After Loki, JPL began actively working on the Sergeant missile, which was Corporal's successor. Sergeant was a solid-propellant battlefield ballistic missile, and the U.S. Army's first large solid-propellant missile. It was tested at Pasadena in the late 1940s and into the 1950s. The Sergeant missile emerged as a single-stage, solid-propellant rocket with a 34-foot length and a 30-inch diameter. The forward section was a straight-sided elongated cone that converged to a point; four stabilizing aerodynamic fins were clustered around the base. The Thiokol XM-100 solid-propellant rocket motor produced 20.4 tons of thrust; launch weight was approximately 4.58 tons.[27] Sergeant was the first large ballistic missile to benefit from advancements in solid-propellant technology.

Sergeant went into service in 1963. It was a mobile system that was transported by air in four sections. Sergeant was the

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[24]. Neufeld, Michael J. *The Rocket and the Reich: Peenemünde and the Coming of the Ballistic Missile Era*. New York, New York: The Free Press, 1995:254.

[25]. Baker, 240.

[26]. Koppes, 62-3.

[27]. Baker, 248.

army's main short-range (between 60 and 190 miles) battlefield missile. The long-distance Pershing rocket, which had an approximate range of 1100 miles, complemented the Sergeant missile. The Sergeant missile was capable of hitting both advancing and rear echelon units. As recently as 1977, West German and U.S. Army units operated the Sergeant missile.[28]

JPL, as an organization, had harbored desires to attempt space flight since the 1930s. As the 1950s progressed JPL was increasingly uncomfortable conducting classified military research for military applications, although it was successful in developing the Corporal and Sergeant missiles. JPL began looking to the stars, and to conducting the space scientific research at the core of the original GALCIT dream. The need for secrecy struck many JPL personnel as distinctly at odds with the goals of higher education exemplified at Caltech and with their desire to conduct space scientific research.[29] JPL ceased military applications after the Sergeant missile's successful development and militarization in 1960, ending its association with Army Ordnance.[30]

JPL spent the 1950s transforming the Corporal E and Sergeant missiles into effective weapons systems for the U.S. Army. However, during the same period they began shifting from guided missile research to instrumented deep space exploration. In 1954, JPL's first foray into space exploration began modestly. JPL embarked on the development of Orbiter, an artificial earth satellite, in collaboration with the Army Ballistic Missile Agency (ABMA) and the Office of Naval Research (ONR). This project marks the beginning of JPL's phased program of instrumented deep space exploration.[31] The Orbiter project was planned to help celebrate the upcoming 1957 International Geophysical Year (IGY). This project was competing for the right to build the first American satellite. The Orbiter satellite proposal was composed of an Army Redstone solid-propellant rocket as a first stage, and downsized Sergeant motors for the second and third stages necessary to place the satellite in orbit around

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28. Baker, 248.

29. Koppes, 30-61.

30. In the late 1980s, JPL began conducting classified military research again for the first time since the 1950s. However, military applications comprise less than 5 percent of JPL's overall work.

31. Daniel, Mann, Johnson, and Mendenhall; Koppes, 79-87.

the Earth.

The impressive ABMA/ONR/JPL Orbiter proposal was joined by two additional proposals. The Orbiter proposal's competition came from the Naval Research Laboratory's (NRL) Vanguard proposal, and an Air Force proposal, which entailed the use of an Atlas rocket coupled with an Aerobee-HI second stage to achieve earth orbit. President Dwight D. Eisenhower wanted the project to have a non-military focus and desired America's first artificial satellite to be utilized in peaceful and scientific studies.[32]

Faced with three plans, the Department of Defense organized a special advisory group to review the various proposed satellite programs and make recommendations. Although the advisory group favored both the use of the Air Force's Atlas missile and the ABMA/ONR/JPL proposal, it was concerned about adapting military missiles for satellite deployment. The advisory group advocated developing a nonmilitary launch vehicle. The NRL granted Vanguard superior electronic technology to transmit scientific data from space to Earth-- the advisory group decided Vanguard had the best chance of placing the most useful satellite into orbit within the IGY This decision led to a controversy over which was the best proposal, Orbiter or Vanguard. The Soviet Union's successful launching of Sputnik on 4 October 1957 made the Orbiter-Vanguard debate a moot point. Instead, Sputnik bred a controversy over whether choosing Vanguard was a good decision.[33]

JPL, meanwhile, found an outlet for its Orbiter project. The ABMA in the mid 1950s was engaged in an interservice rivalry with the Air Force; it was attempting to develop the Jupiter medium-range ballistic missile before the Air Force finished its Thor medium-range ballistic missile. The Orbiter studies helped the ABMA create the RTV; it was designed to test the Jupiter missile's ablation-type nose cone, which was used to counteract the intense heat produced by reentry. The RTV was similar to the Orbiter proposal; the missile needed only a fourth-stage rocket and a payload to launch an artificial satellite. JPL's Microlock electronics technology was also adapted to the RTV program. The Microlock electronic technology is a phase-locked loop tracking system, which later became the foundation of the Deep Space

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32. McDougall, Walter. ...*The Heavens and the Earth: A Political History of the Space Age*. New York, New York: Basic Books, 1985:119-123.

33. Koppes, 78-84.

Network that tracks deep space vehicles. The Microlock system could send data back to ground control on the missile's heating effects during flight, and its tracking mechanism made possible the nose cone's recovery at the end of the flight.

The RTV also incorporated JPL's solid-propellant technology in the last stages of the launch vehicle. The first stage was a modified Redstone missile, designated Jupiter C. The second stage incorporated eleven small solid-propellant Sergeant motors mounted annularly inside a tub; the three motors of the third stage fit inside the second stage, and the fourth-stage motor and payload rested in the center. When each stage fired, the shear pins attaching it to the previous assembly were broken allowing the previous stage to descend to Earth.

For greater accuracy, the upper stages were enclosed in a spinning tub powered by two battery-driven electric motors. The tub began spinning at 550 rpm (revolutions per minute) before takeoff; the speed gradually increased to about 750 rpm around 70 seconds into the flight. This procedure eliminated the resonance between the missile's spin and bending frequencies which increased as the first-stage propellants were depleted. The spinning tub imposed severe vibration and centrifugal force on the second stage. Throughout the design of the upper stages, highly accurate positioning and balance was necessary to curb the vibration and deflection concerns.

The Army fired the first RTV at Cape Canaveral, Florida on 20 September 1956; it attained an altitude of 682 miles and had a range of 3,350 miles, both new records for American missiles. The test objectives were met: the motor demonstrated the desired power, the aerodynamic design worked satisfactorily, and the Microlock system performed close to theory. The ABMA was not allowed to launch a satellite, so the fourth stage was filled with sandbags. If the RTV had contained a small Sergeant motor for use as an apogee kick motor in a true last stage, it would have become the world's first orbiting artificial satellite over a year before Sputnik.[34]

After the Soviets launched Sputnik, the diverse American groups scrambled to respond to the immediate loss of prestige. The American public perceived that the U.S. was falling behind the Soviet Union.[35] Three weeks after Sputnik, Orbiter was given a renewed opportunity, but not before the Vanguard team had

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[34]. Koppes, 80.

[35]. McDougall, 132.

its try. Orbiter's name was changed to *Explorer 1*; it continued as a backup to Vanguard. Before Vanguard got its chance, the Soviets, on 3 November 1957, placed *Sputnik 2* in orbit, which included Laika, the space dog.

Project Vanguard was plagued with technical problems. The Vanguard launch vehicle, which had not been perfected prior to this undertaking, frequently exploded. Vanguard was launched from Cape Canaveral, Florida on 6 December 1957. Vanguard never left the pad; instead, it sat and burned uncontrollably on national television.

Meanwhile on 8 November 1957, JPL had been authorized to proceed with Explorer launch preparations. The Explorer satellite was launched from Cape Canaveral, Florida on 29 January 1958, boosted by the ABMA's Redstone medium-range rocket. The successful *Explorer 1* was America's first artificial satellite. While *Explorer 2* did not achieve orbit because of a structural failure, *Explorer 3* was the second American satellite in orbit on 26 March 1958. *Explorer 3* discovered the Van Allen radiation belts which circle the Earth. JPL was now firmly established as the nation's leading space organization, as well as, a leading missile development agency.

In December 1958, the National Aeronautics and Space Administration (NASA) was created. It was formed from the National Advisory Committee for Aeronautics; President Eisenhower gave NASA the right to absorb any space-related agency it wanted, such as the NRL, which had developed the failed Vanguard rocket and satellite, the ABMA, which became Marshall Space Flight Center in Huntsville, Alabama, and JPL, including the test station at Edwards AFB.[36] JPL was reluctant initially to join the new space agency. JPL felt it had the opportunity to become the lead contractor for the new space agency, a role which NASA did not endorse.

By 1959, NASA's primary goal was to land a manned spacecraft on the Moon. NASA was specifically pushing Project Mercury, the first manned space program. However, JPL decision makers decided to develop unmanned robotic spacecraft rather than manned spacecraft, since JPL would have the primary role in the unmanned program, rather than join the other NASA installations involved

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36. Butowsky, Harry A. *Man-in-Space National Historic Landmark Study*. Washington, D.C.: National Park Service, Department of Interior, 1984:19.

in the manned spacecraft program.[37] The Edwards Test Station (ETS) played an important role in JPL's unmanned space exploration program, which included not only deep space vehicles, but also earth orbiting satellites.

Solid Propellant Testing at the JPL Edwards Test Station

Solid propellant testing remained in Pasadena until 1962, when the operation was moved to the JPL Edwards Test Station. The JPL Edwards test station had been in operation since 1945 testing liquid-propellant engines on its four test stands. The ETS solid-propellant processing line was NASA's sole in-house solid-propellant facility. The solid-propellant processing line was removed to Edwards for many of the same reasons the liquid propellant testing was transferred to the desert in 1945. The local population continued to grow and JPL grew as it created a modern science laboratory complex in the Arroyo Seco as a result of the unmanned space program. Solid-propellant testing was a dangerous and hazardous operation. It needed space, which was no longer available in the Arroyo Seco, to conduct tests in a safe manner.

Another major factor in moving the solid-propellant testing to the JPL Edwards Test Station was to buttress the station's mission. Gilbert Bell, the ETS engineer-in-charge, attempted in the late 1950s to move the station and dramatically change its testing profile to accommodate test stands for motors and engines upward of 1,000,000 pounds of thrust. This proposal would have entailed moving the station to a different location to provide the necessary space for colossal new test stands. JPL considered locations at Fort Irwin, Camp Cooke (now Vandenberg AFB), Camp Pendelton, and Edwards AFB, east of Phillips Laboratory. Several of these locations were approved; the test station was gearing to move to Camp Cooke in 1959, when the plans were canceled for unknown reasons. The JPL test station stayed at its present location. Gilbert Bell, the architect of these expansion plans, died three years later in a fatal train and car collision, which squelched the call for new significant growth at ETS. The transfer of the solid-propellant line appears not only to have answered the spatial needs of the lab in Pasadena, but also seems to have satisfied the ETS's desire to grow.[38] The advent of NASA and JPL's acquiescence to NASA probably were factors in the

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37. Newell, Homer E. *Beyond the Atmosphere: Early Years of Space Science*. Washington, D.C.: National Aeronautics and Space Administration, 1980:103; Koppes, 94-100.

38. Bluth, personal communication.

decision to retard the JPL Edwards Test Station's growth.

Although the JPL Edwards Test Station did not expand in the manner the JPL Edwards Test Station wanted, it did increase enormously in 1962 when the solid-propellant line was built at ETS. A Chemical Propulsion Information Agency survey of solid-propellant facilities, including the facilities which conducted small arms and hand-held weapons research, noted in 1963 that 22 different organizations conducted solid propellant research at 35 operational locations across the country, particularly California and Maryland. Many of these facilities were quite small, and limited in scope, testing only extremely small motors.[39] The JPL Edwards Test Station solid-propellant line was a medium-sized processing line that specialized in satellite motors and solid rocket motors for JPL deep space probes. Two major JPL satellite projects were Syncom (Synchronous Communications Satellite)[40] and ATS (Application Technology Satellite) satellites. Surveyor and Voyager solid rocket motors were also developed at the JPL Edwards Test Station.[41]

Syncom was an important joint NASA and Department of Defense communications satellite program developed in the early 1960s. The Hughes Aircraft Company built the Syncom satellites and JPL designed the solid rocket apogee motors that placed the Syncom satellites in orbit; a typical Syncom motor was 12" in diameter and contained 60 pounds of solid propellant.[42] JPL also developed the internal insulation and the nozzles for the Syncom apogee motors.[43]

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39. Chemical Propulsion Information Agency. *Solid Propellant Rocket Static Test Facilities*. CPIA Publication No. 26, August 1963. E-32, Room 38, File 3, Drawer 1, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

40. Sharpe, Mitchell R. *Satellites and Probes: The Development of Unmanned Spaceflight*. Doubleday and Company, Inc.: Garden City, New Jersey, 1970:125.

41. Compton, L. E. and J. H. Kelley. *Risk Reduction in Solid Rocket Motor Propellant: A Proposed Program Presented for NASA Code Q*. 1991:47. E-32, Room 38, File 3, Drawer 1, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

42. Interview with Robert L. Ray by Richard K. Anderson, Jr. and Scott M. Hudlow, 16 August 1995.

43. Compton and Kelley, 47.

Syncom 1 was designed for geosynchronous orbit, 22,300 miles above the Earth's equator; it was launched from Cape Canaveral, Florida on 14 February 1963. It achieved the correct orbit, but *Syncom 1*'s electronics failed within five and a half hours after launch.[44] *Syncom 1* had a three-minute test tape to test communications failures, which ended playing "The Star Spangled Banner."[45]

Syncom 2 was launched on 26 July 1963 from Cape Canaveral, Florida after *Syncom 1* failed. NASA fixed the initial electronics problems; the satellite was a success. *Syncom 2* was the world's first geosynchronous communications satellite;[46] it was initially fixed over the mouth of the Amazon River, to provide continuous communications between the United States and Europe. It was a simple spacecraft; however, *Syncom 2* was larger and heavier than originally anticipated. JPL was able to modify the apogee motor to provide more thrust to carry the additional mass. *Syncom 2* was a relay satellite for different types of electronic signals, excluding television. It led an eventful existence working for NASA. *Syncom 2* was pushed into a position over Africa, then propelled back to Brazil, and later moved to the Indian Ocean. The satellite could be located anywhere NASA needed it, with the limitation it had to be in an equatorial position.[47] *Syncom 2* was later transferred to the Army.

Syncom 3 was a technically improved version of its two predecessors. It was launched from Cape Canaveral, Florida on 19 August 1964, days before the satellite relayed the 1964 Olympic Games from Tokyo, Japan to the United States. The satellite was stationed at the intersection of the equator with the international dateline, about 1,250 miles north of the Fiji Islands, in the middle of the Pacific Ocean at an altitude of 22,300 miles. This was a central location between the west coast of the United States and Japan.[48]

Syncom 2 and *3* were incredibly successful; their impressive performance behooved Comsat (Communications Satellite Corporation) to model its first satellites on Syncom.[49] *Syncom*

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44. Sharpe, 125.
45. Bestler, Alfred. *The Life and Death of a Satellite: A Biography of the Men and Machines at War with Space*. Boston, Massachusetts: Little, Brown and Company, 1966:189.
46. Paul, Günter. *The Satellite Spin-Off: The Achievements of Space Flight*. Washington, D.C.: Robert B. Luce, 1975:48.
47. Paul, 49.
48. Paul, 50; Bestler, 189.
49. Sharpe, 125.

2 and *3* were later transferred to the Army, after NASA was finished with the satellites. NASA left the field of communication satellites to civilian agencies until the late 1980s, when it launched a new Syncom satellite from the space shuttle.

NASA's second major satellite project was the ATS satellite project. ATS was a "...new satellite program specifically concerned with general problems in applied satellite technology."[50] ATS was an outgrowth of Syncom and was NASA's basic research satellite, particularly in regards to satellite meteorology, communication, navigation, and spacecraft control technology that was an outgrowth of Syncom. Again, ATSs were built by Hughes and JPL. JPL developed titanium cases, internal motor insulation and nozzles for ATS; a typical motor was 28" in diameter and 28" long and contained 800 pounds of propellant.[51] Five similar spacecraft were launched between August 1966 and August 1969.[52]

The first ATS satellite was launched on 7 December 1966 and stationed over the Pacific Ocean in a medium orbit. *ATS 1* demonstrated NASA's research goals; it conducted communications, navigation, and meteorological research. However, ATS's main task was to transmit telephone and television broadcasts between the continents bordering the Pacific Ocean. ATS also had spinscan cameras that could photograph the region every twenty minutes.[53] ATS also on occasion relayed radio transmission between aircraft crews and ground stations; it was a versatile satellite.[54]

The remainder of the ATS satellites had similar missions, except they were intended to have geostationary locations. *ATS 2* and *4* failed to achieve geosynchronous orbit but provided limited data; *ATS 4*'s orbit decayed after two months. *ATS 3* and *4* were spin-stabilized and had 56-inch diameter bodies; the remainder had gravity-gradient stabilization which required larger bodies and thus larger motors. *ATS 5* had a gravity-gradient stabilization system; JPL provided it with a 6,250 pound thrust solid-propellant apogee motor. *ATS 5* conducted a wide variety of experiments. It had the largest and heaviest payload in the

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50. Paul, 60.
51. Robert L. Ray Interview.
52. Wilding-White, T. M. *Jane's Pocket Book of Space Exploration*. New York, New York: Collier Books, 1977:147.
53. Ordway, III, Frederick I. *Pictorial Guide to Planet Earth*. New York, New York: Thomas Y. Crowell Company, 1975:152.
54. Paul, 61.

first ATS series.[55]

ATS 6 was a second generation ATS geostationary satellite launched in May 1974. It had a rectangular Earth Viewing Module as the main spacecraft body, and was equipped with twenty experiments researching direct broadcasting, remote medical diagnosis, high-resolution meteorological radiometry, sensors for analysis of space at synchronous altitude, and general technology experiments. *ATS 6* was moved to a location over India in mid 1975 to provide educational broadcasting for India TV.[56]

From 1959 to 1987, every spacecraft JPL launched had its liquid propulsion subsystems qualified at the JPL Edwards Test Station. This included the *Pioneer* series of interplanetary probes, the *Ranger* lunar series in the early 1960s, the *Surveyor* lunar landers in the mid 1960s, the *Mariner* series of interplanetary landers and probes in the 1960s and early 1970s, the *Viking* Mars orbiters and landers in the mid 1970s, and the *Voyager* series which conducted flybys of Jupiter in the late 1970s.[57] The liquid propellant propulsion testing for these spacecraft was conducted at Test Stand D, built in 1959.

The *Surveyor* lunar landers and the *Voyager* series also had their solid rocket motors manufactured and qualified at the JPL Edwards Test Station. The titanium case technology for the Surveyor and Voyager solid rocket motors, and the internal insulation and nozzle technology for the Surveyor solid rocket motor were developed at the JPL Edwards Test Station.[58] The solid motors were apogee kick motors to help the Surveyors reach the moon, and to help the Voyagers establish orbit around the earth before they headed to Jupiter.

The *Ranger* series led from hard lunar landers to the *Surveyor* series of controlled soft lunar landers. The *Surveyor* series transpired in the mid 1960s in direct support of NASA's manned Apollo program. *Surveyor 1* made the first soft landing on the moon on 2 June 1966 and demonstrated that the lunar surface could support a spacecraft and that man could walk safely on the moon. *Surveyor 6* lifted off from the moon and moved to a new location, demonstrating the first engine restart on an

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55. Wilding-White, 147.
56. Wilding-White, 149.
57. Gibbons and Tibbitts, 1.
58. Compton and Kelley, 47.

extraterrestrial body.[59]

The late 1960s brought the initial planning for Voyager, which was conceived as proceeding on a "Grand Tour" of the solar system.[60] The Grand Tour was canceled in 1972 due to budgetary concerns, since it was planned as an expensive flyby project through the entire solar system. JPL responded by formulating a new, economical project called Mariner/Jupiter/Saturn, which was approved and transformed into Voyager. The Voyagers were scheduled to encounter Jupiter and Saturn, and possibly Uranus. The Voyagers had enhanced computers which drove the attitude control system.[61]

The identical *Voyager 1* and *Voyager 2* were launched in 1977. *Voyager 2* was launched on 20 August 1977, sixteen days before *Voyager 1*, which was launched on 8 September 1977. *Voyager 1* was the first Voyager probe to encounter Jupiter, hence the name. *Voyager 1* was on an easier, faster trajectory to Jupiter, while *Voyager 2* was a longer trajectory which could be retargeted later to reach Uranus. *Voyager 1* encountered Jupiter in March 1979 four months before *Voyager 2*, and then flew by Saturn, 20 months later in November 1980. The *Voyager 2* launch was smooth; however, the spacecraft experienced several bouts of robotic "vertigo." The disoriented spacecraft alarmed JPL controllers, who subsequently discerned a slight mis-setting of computer parameters.[62] The spaceflight was uneventful once the initial problems were corrected.

Voyager 1 discovered a thin ring around Jupiter. It studied the planet's magnetic field and the Great Red Spot, a permanent storm which moves in a counter-clockwise rotation. *Voyager 1* utilized Jupiter's gravity to fly on to Saturn. Studies of Saturn's rings revealed that the rings are composed of "...thousands of ringlets made up of countless ice and dust particles."[63] Several Saturnian moons were discovered, bringing the known total to 20. *Voyager 1* also studied Titan, a Saturnian moon, which was found to have a thick, smoglike atmosphere, before heading out into the solar system.

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[59]. Neal, Valerie, Cathleen S. Lewis, and Frank H. Winter. *Spaceflight: A Smithsonian Guide.* Macmillan: New York, New York, 1995:135.
[60]. Koppes, 186.
[61]. Murray, Bruce. *Journey into Space: The First Thirty Years of Space Exploration.* New York, New York: W.W. Norton, 1989:140-1.
[62]. Murray, 145-46.
[63]. Neal *et al*, 178.

After *Voyager 2* encountered Saturn in August 1981, it continued on to Uranus and Neptune. In January 1986, *Voyager 2* made its closest flyby of Uranus. *Voyager 2* studied Uranus's ring system, photographed its surface and moons. *Voyager 2* revealed ten additional undiscovered Uranian moons, bringing the known total to 15. *Voyager 2* proceeded to Neptune, which it encountered in late 1989. It studied Neptune's ring system and its largest moon Triton, and discovered six new Neptunian moons.[64] *Voyager 2* continues to transmit data in the 1990s as it speeds toward the edge of the solar system.

The 1970s brought a major shift at the JPL Edwards Test Station away from the solid rocket apogee kick motors toward new research and development projects including many for the proposed Shuttle Transportation System (STS). JPL also began experimenting with exotic high energy solid fuels and developing new solid-propellant research techniques.

The STS or the "space shuttle" as it became commonly known was proposed as a reusable space plane that could land on a conventional landing strip. The space shuttle was to be boosted into earth orbit by large jettisonable solid rocket boosters (SRB). JPL conducted numerous tests for these new large motors, and developed low HCL (*Hydrochloric acid*) solid propellants for the shuttle's SRBs. JPL also developed a low-particulate exhaust propellant for the shuttle's SRB separation motors. The STS research continued into the 1980s. JPL evaluated candidate nozzle materials for STS solid rocket motors using 48-inch motor firings. JPL continued the insulation research it conducted in the 1960s and developed asbestos-free insulation systems for the space shuttle. The early shuttle missions experienced several early orbit anomalies; JPL Edwards Test Station personnel were asked to solve these problems. The JPL engineers were able to develop a propellant erosive burning evaluation methodology and to establish a threshold scaling law for erosive burning rate augmentation problems, which solved the orbit problems.[65]

The JPL Edwards Test Station had a long established reputation for conducting exotic fuels research for liquid propellants. Test Stand B was built in 1953, ostensibly for this purpose. The fluorine scrubber attached to Test Stand C was the country's first scrubber to clean this dangerous chemical from engine exhaust, before it was released into the atmosphere. The exotic fuels research later extended to the solid propellants in the 1980s. JPL researched beryllium, beryllium hydride, aluminum

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64. Neal *et al*, 178-79.
65. Compton and Kelley, 48.

hydride, and boron compounds as potential fuels and high energy oxidizers. The high energy research extended into the development and demonstration of a 12" diameter motor utilizing a beryllium hydride propellant. This system produced a measured vacuum Isp of 342 seconds, the highest for a solid propellant. JPL also researched and proposed to NASA a high performance hybrid (liquid and solid) propulsion system.[66]

Research methods and problems were developed and solved during this period, which had general application for the entire field of solid-propulsion technology. A microwave doppler velocimeter technique for combustion research was perfected. JPL also developed low burn rate propellants and sterilizable propellants for planetary applications, a problem dating to the early 1960s and the Ranger mishaps which plagued JPL. JPL cooperated with the Marshall Space Flight Center late in the 1980s to develop the next generation test motor-- the ASRM (Advanced Solid Rocket Motor). This project included live motor firings, subscale motor firings, and chemical and physical properties testing. JPL tested igniter compounds, clean propellant, and conducted propellant liner evaluations, motor insulation materials review, and inert propellant formulation for the ASRM into the early 1990s.[67]

Although JPL was conducting valuable and important solid-propellant research, the work slowed perceptibly in the early 1980s. Solid-propellant testing has continued in the last fifteen years; the last motor firing was April 1994. The primary work has been the solid-propellant testing and manufacturing undertaken for the Air Force's Phillips Laboratory, Edwards AFB, California.

Site Characteristics

The climate at Edwards AFB is a mid-latitude desert type with hot, dry summers and cool, slightly moist winters. Average precipitation is less than 12.7 centimeters (5 inches) per year, with most occurring as rainfall during the winter months. Temperatures range between 38 and 43 degrees Celsius (100 and 110 degrees Fahrenheit) in summer and drop to well below freezing in the winter. The climatological regimen dictates a reliance on subsurface water for contemporary permanent human habitation. Prevailing winds are from the west south west and southwest; calm presides only 15 percent of the time (see the wind rose on Sheet 1 of 4 in the HAER drawing set completed prior to this addendum).

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[66]. Compton and Kelley, 48.
[67]. Compton and Kelley, 48.

The Base occupies portions of the alluvial floors of several intermontane valleys in the western Mojave Desert. The JPL Edwards Facility is located between 1.5 and 10.7 meters (5 and 35 feet) below the fossil shoreline of Pleistocene Thompson Lake[68] at an average altitude of 701 meters (2300 feet) above sea level.

Edwards AFB is located within the geologic structure known as the Mojave Block, and is bounded by the Garlock and San Andreas Fault zones. The faulting and uplift associated with the Mojave Block has created a region which is geologically complex, with both Tertiary and pre-Tertiary geologic formations as well as later Quaternary alluvial sediments. The JPL Edwards Facility is located in an area of recent Quaternary alluvium composed of alluvial sand and gravel, playa clay, and wave-deposited sandbars.[69]

The JPL Edwards Facility is located within the xerophytic phase saltbush scrub community. The dominant shrubs represented in the project area include allscale (*Atriplex polycarpa*), cheesebush (*Hymenoclea salsola*), golden cholla (*Opuntia echinocarpa*), creosote bush (*Larrea divaricata* var. *tridentata*), boxthorn (*Lycium cooperi*), rice grass (*Oryzopsis hymenoides*), spinescale (*Atriplex spinifera*), and wolfberry (*Lycium andersonii*).[70] Elm trees (*Ulmus spp.*) at the JPL facility were planted to provide shade and relieve some of the visual starkness of the natural landscape.

Cultural Landscape and Architectural Evaluation

In 1995 the JPL Edwards Facility was a complex composed of 83 structures, including 80 industrial structures (7 test stands), one commercial structure, one administrative structure, and one security facility. The complex dates from 1945 and grew throughout the entire Cold War period; building activity ceased in 1992. By which time, the facility had developed an extensive complex dedicated to the testing of liquid and solid propulsion systems for guided missiles, deep space probes, interplanetary landers, and commercial satellites. Building campaigns revolved

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68. Dibblee, Thomas W. "Geology of the Rogers Lake and Kramer Quadrangles, California." USGS *Bulletin 1089-B,* U.S. Department of the Interior, Geological Survey (USDI-USGS), Washington, D.C.: U.S. Government Printing Office, 1960:127.
69. Dibblee, 127.
70. Vasek, Frank C. and Michael G. Barbour. "Mojave Desert Scrub Vegetation," in *Terrestrial Vegetation of California.* Michael G. Barbour and Jack Major, eds. New York, New York: John Wiley and Son, 1977:835-867.

around the diverse spacecraft propulsion systems and their peculiar project requirements. Historical events had a profound influence in shaping the JPL Edwards Facility's missions and thereby its cultural landscape.

A cultural landscape is the communal sum of the natural and built environment, including technology, vernacular architecture, and the social and experiential webs that unite a community, including work communities. Technology, vernacular architecture, and the cultural landscape are reflectors of conscious and unconscious ideas and concepts; they are historical products that reveal intent and define social and cultural relations. A cultural landscape also reflects choices of and adaptations to the natural landscape and its ecological systems. Technology is viewed as "...an expression of our culture, encoded with our dreams, purposes, environment, insights, and limitations."[71] Unlike the highway and utility systems or the parks and buildings composing the familiar landscape of a modern city, the JPL Edwards Facility cultural landscape is spare and organized around requirements focused on either liquid or solid propellant engine and motor testing. The JPL Edwards Facility's built environment reflects the exacting standards and unique construction associated with the rigors of testing advanced technology with safety for both man and nature.

JPL originally moved to the western Mojave Desert in 1945 to escape cramped quarters in Pasadena. The desert was a hostile place few people would visit or settle, so no one would object to the noise or potential hazards of rocket engine tests. Expansion room, security, and public safety could be easily obtained. It probably seemed to JPL and government planners that the desert was a relatively barren place biologically, with little to suffer from technological accidents.

The test station was located at the Muroc Flight Test Base, a separate, autonomous base under the auspices of Materiel Command (later Air Technical Service Command), dedicated to testing experimental aircraft, particularly the Bell XP-59A *Airacomet*, the first American jet aircraft.[72] Construction

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71. Pursell, Jr., Caroll W. "The History of Technology and the Study of Material Culture" in *Material Culture: A Research Guide.* Thomas J. Schlereth, ed. Lawrence, Kansas: University Press of Kansas, 1985:113.

72. Hudlow, Scott M. *Cultural Resource Evaluation of the North Base Complex (The Muroc Flight Test Base and the Rocket Sled Test Track), Edwards AFB, Kern County, California.* Report on file at AFFTC/EM, Edwards AFB, California, 1995: 16.

began in January 1945 on JPL's Muroc test station. JPL quickly built the Corporal Test Stand (Test Stand "A") and additional buildings to support the vital testing at Muroc. The Muroc test station was remotely operated; JPL personnel from Pasadena managed the station and drove to it to perform engine testing.

The institutional landscape of the JPL Edwards Test Station evolved episodically between 1945 and 1992. Building sites were chosen as needs were identified. While JPL did not have an initial master plan encompassing all future development, there were some overriding principles that guided the facility's ad hoc land use planning. Construction decisions were made on an individual, building-by-building basis as various missile and space probe programs were implemented by the military services, NASA, and Congress. Decisions to add mew structures to the facility were reactionary and geared toward meeting challenges and solving problems. The Army Corps of Engineers (ACE) built, planned, and laid out the ORDCIT test station in 1945. Other than the advantages of a remote location, the only major environmental factor in planning the original test station was the prevailing easterly wind. The Corporal Test Stand was built to direct engine exhaust downwind. Support structures were built to the west and south of the test stand to escape fumes and exhaust products associated with tests. JPL also planted elm trees to make the desert environment a little more psychologically habitable for human beings, but in recognition of the potential conflict between a more luxuriant natural environment and the hazards of exotic technology, no elms were ever located east of the test stands.

Three major planning principles drove the test station's expansion during the 1940s and 1950s and played a prominent role in the 1950s and 1960s building campaigns. Test Stands "B," "C," and "D" (as well as future stands "E" and "G") all lie along a north-south axis through Test Stand "A" (the original Corporal Test Stand). All their inhabited support structures and monitoring systems (including the Control and Recording Center) lie to the west of this axis to take advantage of prevailing winds, for removal of engine exhaust plumes, vented fumes, or smoke and dust from accidents. The construction of an interstand tunnel system in 1957-58 further established the north-south axis with the physical presence of the easternmost tunnel in the system. The future construction of Test Stand "E" for solid propellant motor firings and Test Stand "G" for vibration tests followed this axis. Secondly, test stands and potentially dangerous support structures were widely separated, reflecting scrupulous observance of intraline quantity-distance safety measures. Structures were separated and the quantities of volatile chemicals in them were limited so that fires or explosions could be securely contained with little danger of spread to other structures. The desert surface was also scraped of natural vegetation in 50-foot wide zones around each building to further inhibit the spread of fires. Finally, fuels and oxidizers were separated at each test stand in the liquid propellant area-- oxidizers to the north and fuels to the south. This north-south relationship carried over into the solid fuel storage area and even into the solid propellant manufacturing area, as can be seen by referring to the facility map (HAER sheet 1 of 4).

The development of the solid propellant manufacturing and testing line in the 1960s continued in the above vein. Fuel and oxidizer storage, flammable waste storage, and the waste disposal burn unit were all widely separated and located to the east of the main north-south axis, guaranteeing that no fumes or debris from them would fall on inhabited support structures to the west. Sites for the manufacturing and assembly of solid propellant motors were spread broadly to the west of the north-south axis. Though hazards of fire and explosion were associated with many structures in this area, the quantities and toxicities were of smaller and lesser concern than the liquid propellants. Unlike the liquid propellants, solid propellants were not hypergolic or cryogenic, so many of the safety hazards and handling problems associated with liquid propellants were obviated. The solid-propellant processing line structures are clustered by function: grinding and mixing buildings are grouped together, the cure buildings are adjacent to each other and the conditioning structures are contiguous.

Along the remotely operated solid-propellant processing line, fuels and oxidizers were ground, mixed, and cast as solid-propellant rocket motors. The motors were then cured, conditioned, and test fired. Facilities contained the necessary solid-propellant measurement and monitoring devices, including an X-ray Facility for inspecting solid-propellant motors for cracks and voids.[73] The propellant processing facilities were dedicated to propellant ingredient weighing and oxidizer drying and grinding. A Liner Laboratory provided experimentation space and housed the solid propellant office. A control building managed the processing line and contained facilities to weigh the solid propellant fuel ingredients in small amounts. Oxidizers were weighed in remote facilities and ground by hammer mills in separate structures. Five remotely controlled Baker-Perkins mixers in various structures provided propellant mixing in quantities ranging from 1 pint to 150 gallons. Four separated

[73]. Gibbons and Tibbitts, 2.

walk-in ovens cured the cast motors. Walk-in temperature chambers conditioned the solid propellants. A 5′ x 8′ Baron autoclave allowed the curing of composite component fabrication materials up to 400°F. An ignition lab prepared igniters which were installed in motors at an assembly building or at the test stand. Storage facilities for wastes and an incinerator were also included.

The JPL′s dynamism underscores the overriding importance ascribed to technological advances during the Cold War, and demonstrates how rapidly technology and corresponding social and cultural changes occur on the landscape. The JPL′s cultural landscape reflects the changing needs of the burgeoning post-World War II missile industry and of a modern deep space research and development facility. The spartan architecture of most structures at JPL belied the importance and the radical nature of the guided missile and space probe testing conducted at the ETS during the second half of the 20th-century.

The ACE initially utilized temporary architecture, construction techniques, and materials drawn from its extensive experience in military housing. The Corporal Test Stand (Test Stand "A") was of necessity built of concrete and steel, but the support structures were all wooden buildings whose character was reminiscent of World War II military quarters. Most of the support structures later built in the liquid propellant test stand area were of wooden construction. The ACE′s design responsibilities ended at ETS when the facility came under NASA′s aegis in 1958. The site plan and structures of the solid-propellant line were designed in 1962 by Austin, Field, and Fry of Pasadena, California, various contractors, and the JPL Plant Engineering office. With the advent of the solid propellant line, more permanent and fireproof steel-reinforced concrete block was adopted as standard building fabric. Despite the retention of architectural and engineering firms, however, the buildings in the solid propellant line make no stylistic overtures that the general public or design professionals might recognize as "architecture." These buildings are stripped of all frills; everything that is incorporated serves some industrial or safety purpose required by process control or regulations at the lowest possible cost. The vernacular gable roofs and wooden sash windows of the ACE era are eschewed.

Almost every solid propellant building is a steel-reinforced concrete block structure that rests on poured-in-place concrete foundations. Those that are not of concrete block are built with steel frames and covered with "Transite" (pressed asbestos) panels, or steel frame with corrugated steel siding and roofing. The ground floors and exterior aprons of all buildings are concrete, while expanded metal grating is the material of choice for stairs and mezzanines. Roofs are commonly of wooden construction covered with plywood, hot-mopped 5-ply roofing paper and gravel. Most of these buildings are windowless, one-story, flat-roofed structures finished with white paint. Concrete block walls are typically 12 inches or 8 inches thick, as mandated by Air Force regulations for structures containing explosives.[74] Only the administration building (E-32/4231) and the weigh and control building (E-35/4234) have windows. (The administration building contained offices removed from the solid processing line, and the weigh and control building had narrow bulletproof windows for observation purposes; windows are excluded from other structures for better internal environmental control.) A majority of the processing buildings have two-room plans with no internal doors. The main room is the workspace; the second room is a machine room which houses specialized environmental control equipment. This floor plan offered not only the standardization of functions, but also architectural simplicity for firefighters and emergency personnel. The primary entrance is a centrally placed heavy strap-hinged steel blast door; the tops of many of these are designed to permit the steel I-beam of a monorail hoist to protrude beyond the doors. Other doors are usually of grounded steel construction. Each building has a lightning rod on each roof corner, and many have grounding systems for personnel and conductive floor finishes to ground static electric charges generated by personnel or machinery. Some structures have frangible "blow-out" or blast walls and doors constructed of lumber and electrostatically conductive plastic sheeting to relieve the pressure of an explosion with little damage to the rest of the structure. Electrical systems are universally enclosed in metal conduit, and the electric lighting fixtures in most buildings are of explosion-proof design. Fire suppression systems are prominent in all processing buildings, and emergency shower and eye-wash stations are standard fixtures at every structure. Emergency slides, a common industrial safety precaution, are present on several buildings to provide egress from roofs and mezzanines. Most buildings have an exterior "chemical pit" with a ground level cover for the temporary storage of wastes or quantities of hazardous materials (see Fig. 21). The impression at each building is one of laboratory neatness and cleanliness combined with the straightforward functionality of an industrial structure. Minor variations in the above general description and appointments will be discussed in conjunction with process descriptions below, since an

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74. Department of the Air Force. *AFR 127-100, Explosive Safety Standards,* 1990:132. Document on File, AFFTC/SEW, Edwards AFB, California.

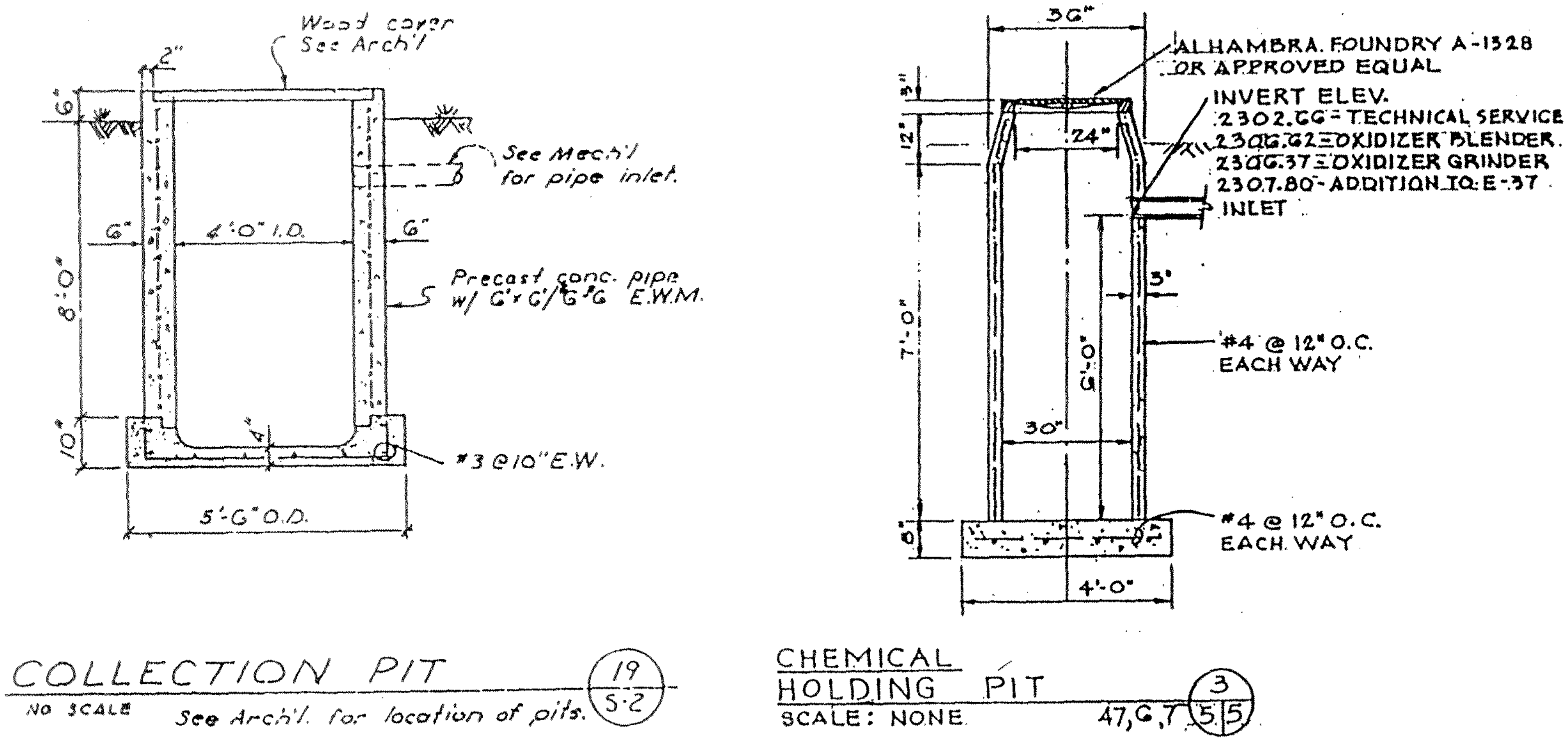

Fig. 21
Examples of JPL Chemical Pits

individual building's design was tightly integrated with its function.

Building Layout and Air Force Safety Regulations

As an added safety precaution (required by regulations) some structures are surrounded by blast barricades designed to deflect gases and shrapnel upward and away from surrounding structures in the event of an explosion. Every building is equipped with a free-standing pole on which rotating safety lights are mounted (see Fig. 22); they indicate the status of interior operations as follows:

Safety lights

Red Light:	Extreme Hazard
Amber Light:	Conditional hazard exists
Green Light:	No hazard exists
No light:	Indicates an amber light condition[75]

Safety regulations mandated that two personnel always be present when conducting any hazardous operation; hence building floor plans had to accommodate at least two operators and their needs to move around various machines.[76]

The operational status of the stand-by generators in Building 4275/E-76 was constantly checked. JPL staff recount that they were vital when the commercial electric power grid failed during grinding or mixing operations.

Building the Solid Propellant Processing Line

The JPL Edwards Test Station quadrupled in land area when the solid-propellant processing line was transferred to ETS from

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[75]. Bailey, Richard L. Operational Methods and Safety Procedures for Section 381, Solid Propellant Engineering at the Edwards Test Station, 25 May 1971. 71-MPT-219-RLB-381. Page 3. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

[76]. Bailey, Richard L. Operational Methods and Safety Procedures for Section 381, Solid Propellant Engineering at the Edwards Test Station, 25 May 1971. 71-MPT-219-RLB-381. Page 6. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

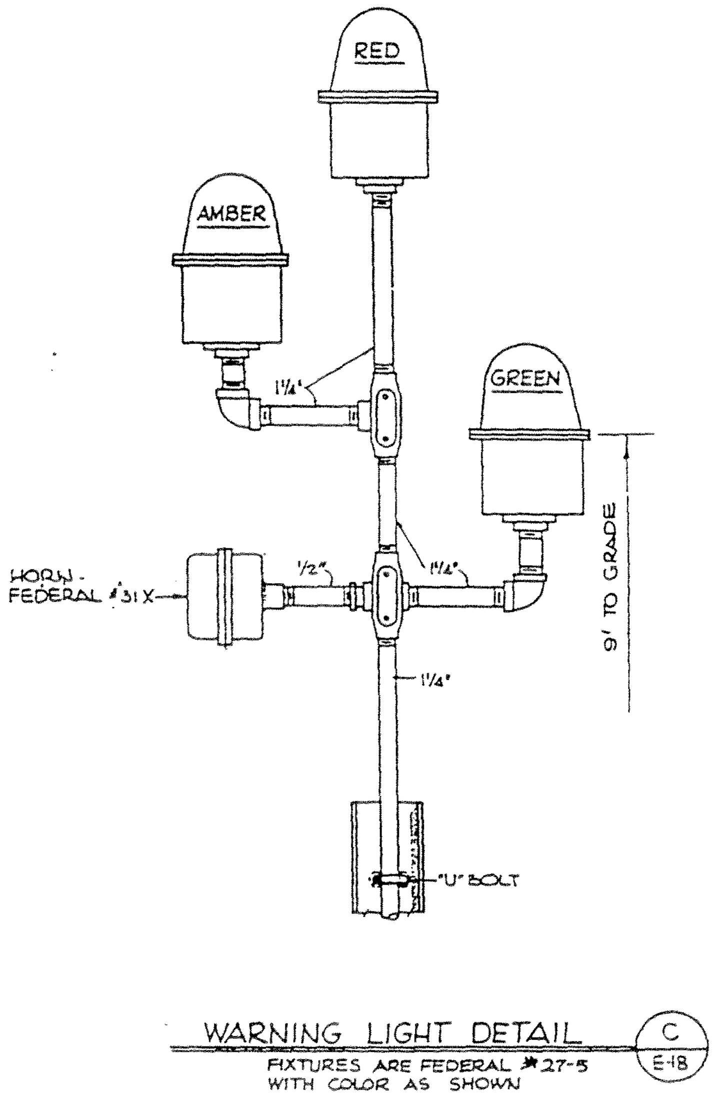

Fig. 22
Standard JPL Warning Light Stand

Pasadena. The JPL Edwards Test Station erected a new security fence, added approximately 575 acres to the ETS complex, constructed the solid-propellant processing line, constructed the storage area and new docks, built an aircraft hardstand, and laid a taxiway which linked the JPL Edwards Test Station with the North Base runway. The addition of the solid-propellant processing operation brought an influx of JPL employees to the Edwards Test Station in the early 1960s; 97 employees worked at the JPL Edwards Test Station at its zenith in 1967.[77]

The original solid propellant processing line, when completed in 1963, consisted of twenty-seven buildings laid out in a semi-circle around the liquid propellant test stand area. Future building campaigns in the solid-propellant area were integrated into this plan. The new site plan and buildings were designed by Austin, Field & Fry of Pasadena, California, a local architecture and engineering firm. JPL was a major Austin, Field & Fry client. Since the JPL Edwards Test Station was located on an Air Force reservation, major site planning criteria were the Air Force regulations concerning explosive safety standards. These regulations governed building construction, intra-building distances and the quantities of propellants allowed in any one structure. Distances and limitations on the weights of various propellant classes at JPL Edwards Test Station were displayed in a 1974 report by Koebig & Koebig on a sheet titled "Intraline Quantity-Distances."[78] This landscape pattern is standard for storing explosive materials. The greater the number of buildings that housed explosives, the larger the complex. This resulted in a geographically extensive complex, due to the need to provide space between buildings so that a potential explosion could be isolated to a single structure.

The solid-propellant processing line was built over twenty-nine years and three construction phases. In 1962 and 1963, Greynald Construction of Sherman Oaks, California and the Ruane Corporation of San Gabriel, California built the solid-propellant motor manufacturing and testing facilities. The solid-propellant processing line and the storage area consists of an administration building, a liner laboratory, mixer buildings, a

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[77]. Gibbons and Tibbitts, 2.

[78]. Koebig & Koebig, Inc., Engineering, Architecture, Planning. *December 1974. 1974-1979-1984 Master Plan for Edwards Test Station, National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.* Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

weigh and control building, oxidizer grinding buildings, conditioning buildings, cure buildings, oxidizer dryer buildings, mixer and casting building, an open burn unit, preparation complex, oxidizer and fuel storage buildings, a test stand, a solids assembly building, an igniter magazine, a tunnel extension with blower house, and a tunnel entrance.

A second building phase in 1964 and 1965 constructed five new solid propellant processing buildings including a weigh and test preparation building, sterilization facility, weigh and storage building, an ignition lab, and a test stand. This construction phase was built by J. D. Dermody Co. & Ralph Walker, Inc. of Lancaster, California and by Santa Fe Engineering of Lancaster, California. Austin, Field & Fry designed these buildings and located them within the existing site plan.

A third construction phase began in 1976 and lasted through 1981. This phase constructed four buildings which had redundant capabilities including oxidizer storage, propellant processing, oxidizer dryer and blender, and a casting and curing building. A separate X-Ray building was also constructed to house a new X-Ray machine, which was purchased from Lockheed Aircraft Corporation. These buildings were constructed by three different firms: Joseph D. Gee Construction Co., Barstow, California; Ashland Construction Co., Lancaster, California, and E. C. Morris and Son of Lancaster, California. These were the last specific buildings constructed for the solid propellant processing line. These buildings were placed on Austin, Field & Fry's site plan. The test station's architecture and cultural landscape continued to reflect its driving principles throughout its history; it eventually became a complicated, planned industrial landscape coexisting with a desert ecology.

Solid Propellant Preparation Parameters

Compared to liquid propellants, JPL propellant engineers regarded the formulation of solid propellants as "a black art" rather than a science. A solid propellant rocket motor contains few parts, but its mechanical simplicity belies the bewildering number of variables applying to the choice of propellant chemicals, processing steps, service conditions, and design of the grain, motor casing, and nozzle. A solid propellant combines fuel and oxidizer in a solid suspension; the chemical components are in intimate contact, but should not react until ignited. Once ignited, a solid propellant motor cannot be shut off or throttled back as can liquid fueled rocket engines.

Fuels and oxidizers are chosen with the following factors in mind: maximum energy yield per unit weight, consistent burn rate, propellant stability (to withstand aging, extreme temperatures and environmental changes), mechanical strength (to maintain shape, support its own weight, adhere to the motor casing during storage and firing), ease of handling (light weight, low toxicity), ease of manufacture (few steps, safety, reproducibility of formulas), lowest cost, and least toxic exhaust byproducts. At one time, sterility and sterilizability were factors for the motors of interplanetary probes and landing vehicles. In addition to these factors, the particle sizes for fuels and oxidizers played a critical role in the reaction rates--generally, the smaller the particle size, the more rapid the reaction. Another problem concerned the mixing of propellant components sufficiently to insure their uniform distribution throughout the propellant mass; uneven distribution affects burning rates and motor performance, and can even cause failures. Finally, the reliability and repeatability of formula batches was critical-- the ninety-third batch of a formula should have the same mechanical and performance characteristics as the first to make motor performance predictable.

Aside from the composition of a propellant per se, the design of the propellant grain was important to the performance of a motor. JPL scientists in conjunction with other researchers found that a hollow, cylindrical grain with a specially shaped hole along the central axis of the grain gave much better performance. The burning rate of a motor is related in part to the amount of surface area in the hole exposed to combustion; all other factors being the same, the larger the area exposed to combustion, the faster the motor burns, and the more energy is released in a given time to propel a rocket. Taken to extremes, if the area is too small relative to the mass of propellant to be burned (for example, a narrow hole in a narrow cylinder of propellant), a motor may burn too slowly to be of practical use; it may not generate enough thrust to lift the motor or its rocket from the earth. On the other hand, if the exposed area is large relative to the mass to be burned, the propellant could burn more quickly than the resultant gases can escape the nozzle, creating an explosion. A happy medium must be sought. The answer is not a modest, simple cylindrical hole in a grain in most cases. The reason is that as such a motor burns, the inner cylinder grows larger, exposing more surface area to combustion. As combustion proceeds, more energy is released per second. In other words, the thrust increases, and the motor's weight decreases. Motor engineers are more concerned with obtaining a steady thrust, or designing a motor so that the maximum thrust is produced at the beginning of flight, when a rocket has the most propellant to consume and its mass is the greatest. JPL's earliest success with asphalt composition propellants derived from the use of a 10-pointed-star shaped hole through the grain. The star-shape presented a larger surface area to combustion than a simple cylinder for a given diameter of hole. As the star shape burned, it ultimately became a cylinder with a surface area similar to the original star-shaped hole. The result was a motor with a much more even burning rate than before. Other configurations of hole were researched, as well as the proportions of area to propellant mass for various propellant formulas.[79] It is also conceivable that some propellants worked better in certain motor designs than others; in this way, propellant formulas could affect motor design, and constraints on a motor design could affect the propellant formula chosen.

Analogous problems applied to the metals and composite materials used to fabricate the motor casings and nozzles. While a solid propellant formula might exhibit desirable characteristics, the motor casings and nozzles had to be correctly designed to take advantage of them. Casings had to be lightweight, yet withstand the pressure generated by burning propellants, as well as the heat, and they had to be made of substances that would not react with the propellant composition, or respond to environmental conditions (rain, dust, heat, cold, vibration) in such a manner as to fail in storage or flight. Light metal alloys (such as titanium alloys) and epoxy composites (boron epoxy, graphite fiber epoxy, Kevlar® epoxy) have been successfully tested at JPL-ETS and have flown missions.

Nozzle materials and engineering design also had to be carefully developed. Nozzles were subjected to the searing heat of the exhaust flames. If their materials were not carefully chosen, the nozzles might melt or burn away depending on the required rocket flight time. If the nozzle throats were too narrow, the resulting high speed of hot gases through them might quickly erode them and cause failures. Too wide a throat might lead to less than optimum thrust. Composite materials such as Kevlar® impregnated phenolics have been found to perform well in nozzles; they char and withstand the motor's heat, unlike metals which melt.

The complexities involved in a successful motor design were numerous, and it was ETS's mission to develop and characterize useful propellants as well as develop and improve solid rocket motor designs. Variations and combinations had to be researched in a systematic manner while responding to missions and funding

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[79]. Insufficient time was available to review the extensive amount of data on such questions as they relate to motor development at JPL. The remarks are a laymen's approach to the problems JPL scientists had to solve.

imposed by Congress and NASA. It could take several years to establish the best propellant formula for a given motor. The solid propellant line was designed to be flexible enough to accommodate a wide variety of materials and test situations. Nevertheless, the solid line's layout, building designs and installed equipment bespeaks a commitment to solid rocket motor technology based primarily on rubber-based propellants and ammonia compounds as oxidizers.

While the Control and Recording Center 4321/E-22 oversaw the test firings of solid motors and liquid-fueled engines, the Weigh and Control Center 4234/E-35 oversaw the production of motor liners and the grinding, mixing and casting of solid propellants. A diagram by JPL employee Bruce H. Morrison outlines the process apart from the buildings in which it took place (see Fig. 23; see the HAER drawings for integrated building and process diagrams). Aside from the fact that Morrison's diagram shows the production of multiple batches for large motors, the production steps remained the same throughout the history of the solid propellant line. The only absent steps in Fig. 23 are the storage of raw chemicals for propellant manufacture and the disposal of wastes.

Most of the detailed process discussions below are based on safety rules, Standard Operating Procedures (SOPs), propellant batch records, historic and contemporary engineering drawings, historic photographs, and other records which come from various periods and refer occasionally to secondary instruments and equipment which moved around among the buildings a lot, depending on the various propellant programs. Some omissions and conflicts between available records exist, and where possible these are declared or resolved after some analysis.

Propellant Ingredient Storage

Safety concerns are manifest in the cultural landscape by the extensive storage complex. Physical separation of buildings containing limited amounts of hazardous materials is a standard safety precaution in this kind of industrial landscape. The isolated storage sheds are located approximately 150 feet apart from each other on the east side of the JPL-ETS complex, away from all permanently occupied buildings. In addition to supporting the solid-propellant research, the storage area also supported the liquid propulsion research.

Ten one-story, open, corrugated metal storage sheds contained solid fuels, solid and liquid oxidizers, and flammable wastes. The open storage sheds are partially enclosed on two or three sides and appear in primarily two sizes--a small 8'-7" x 10'-10" shed and a larger 16'-4" x 40'-6" shed. Three closed

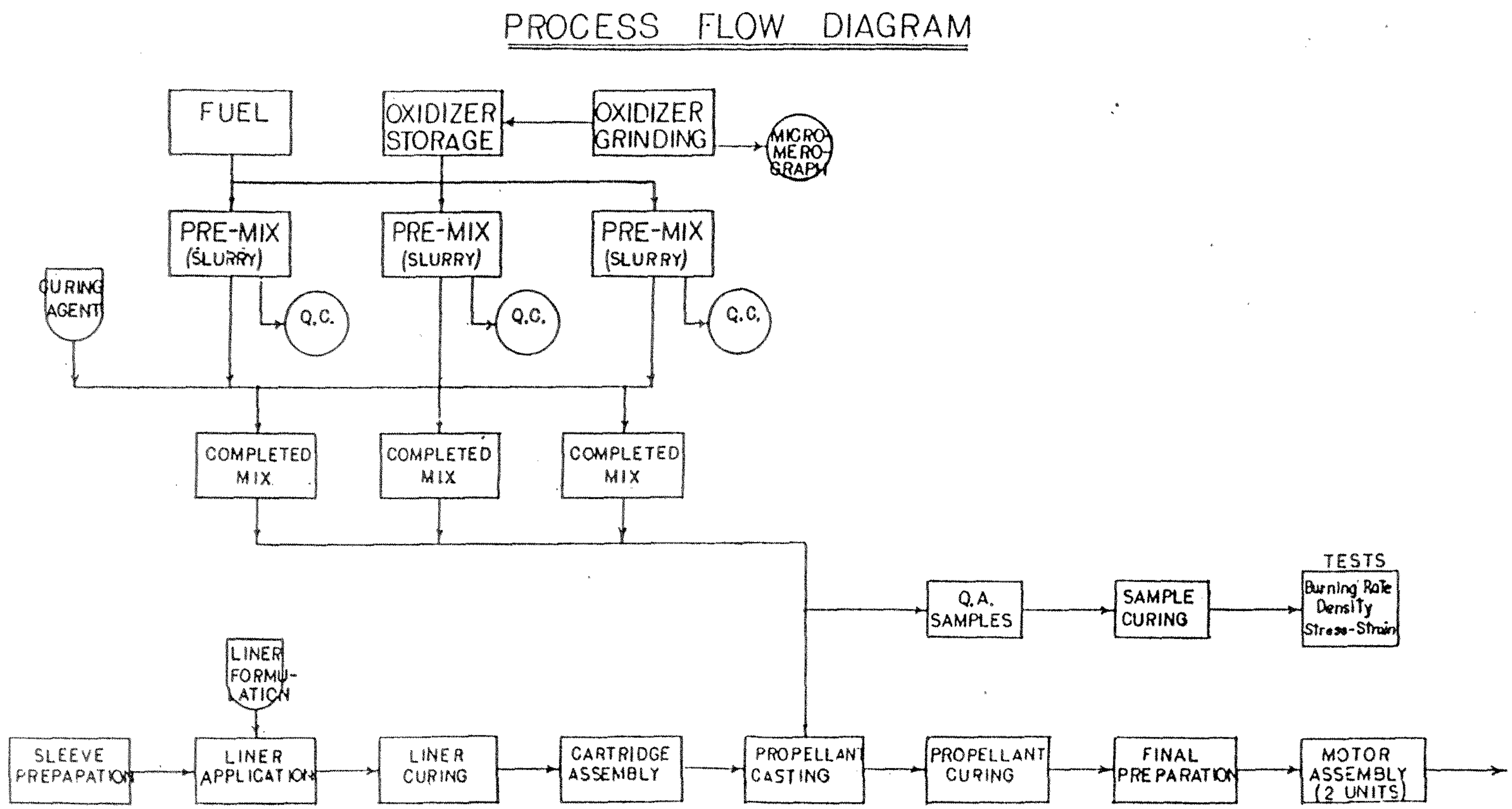

Fig. 23
Basic JPL Solid Propellant Processing Diagram

one-story, ground level corrugated metal storage sheds are present as well. Buildings 4250/E-51 (Solid Oxidizer Storage) and 4251/E-52 (Solid Fuel Storage) were both originally built as 12'-7" x 40'-6" open docks and later converted into closed storage buildings; the second shed at Building 4250/E-51 was built in 1983 and roll-up doors were installed at all three sheds at that time. The sheds are supported by steel I-beam frames bolted to poured-in-place concrete foundations. Concrete hazardous waste retention basins for collecting hazardous material spills were constructed at each of these buildings in 1991. A plumbed emergency shower and eyewash station is present at each building. All three structures are naturally ventilated.

Oxidizers were shipped in fiberboard drums weighing approximately 250 pounds (114 Kg) apiece and stored at ambient temperatures. Safety rules limited the capacity of 4250/E-51 to 50,000 pounds (22,727 Kg) of Class 3 materials and three personnel. All personnel had to wear flame retardant clothing, and they were not allowed to dispense oxidizers or store finished propellants in the structure[80] (HMX [cyclotetramethylenetetranitramine], $C_4H_8N_4(NO_2)_4$), a Class 1.1 high explosive, was occasionally used in some propellant formulations; in 1988, HMX was stored under rigid standard operating procedures in Building 4281/E-82[81]). Oxidizer drums were usually stored and removed by fork-lift; marked trucks delivered the drums to the Weighing & Storage facility (4269/E-70).

A number of additives composed fuels, among them PBAN (polybutadiene acrylic acid acrylonitrile), powdered aluminum, solvents, and other elastomers. These propellant components were all stored in sealed containers at ambient temperatures in separate bays. Safety rules did not permit two or more different materials to be stored in the same bay, and the building was

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80. Bailey, Richard L. Safety Rules, Solid Propellant Engineering, Section 381. Building E-51 (4250); 15 January 1971. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

81. Barry, J. A. 3 October 1988. Section 351, No. 2015 Revision 3, Standard Operating Procedure, Procedure for Receiving and Storage of HMX Oxidizer (typescript), p. 2 of 6. E-33, File 3, Drawers 1 & 2, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

restricted to a maximum capacity of 50,000 pounds (22,727 Kg) of Class 1 materials and three personnel. As in 4250/E-51, personnel had to wear flame retardant clothing, and were not permitted to dispense anything inside the structure.[82]

Oxidizer Weighing and Storage

When propellant ingredients were moved for use, oxidizers were taken to Building 4269/E-70, Oxidizer Weigh & Storage, while fuel components went to Building 4234/E-35, Weighing & Control. Building 4269/E-70 was allowed to hold a maximum of 10,000 pounds (4,545 Kg) of Class 3 oxidizers in its 20′ x 28′ perimeter; four personnel were permitted during operations.[83] JPL specifications for ammonium perchlorate ("AP," NH_4ClO_4) required suppliers to ship AP with a minimum purity of 99.20% (±0.10%) and in a limited range of particle sizes.[84] Other oxidizers used at JPL on an experimental basis were ammonium nitrate (NH_4NO_3), sodium nitrate ($NaNO_3$), and ammonium sulfate [$(NH_4)_2SO_4$]; these were substituted for AP in attempts to remove chlorine from motor exhaust products, but the sacrifice in reduced specific impulse per unit of mass made their use in propellants impractical. A typical propellant formula contained about 70% ammonium perchlorate by weight; this proportion rose when less energetic oxidizers were used.

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82. Bailey, Richard L. Safety Rules, Solid Propellant Engineering, Section 381. Building E-52 (4251); 15 January 1971. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

83. Bailey, Richard L. Safety Rules, Solid Propellant Engineering, Section 381. Building E-70 (4269); 15 January 1971. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

84. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. JPL Spec[ification] GMO-50065-TST, 22 October 1963. Test Specification Ammonium Perchlorate Analysis Methods, p. 6 (typescript). Page 4 states particle size requirements (Tyler sieve standard) as follows: 100% must pass a 16 mesh screen, 89 to 97% a 48 mesh screen, 18 to 50% a 100 mesh screen, 2 to 15% a 150 mesh screen, and only 0.0 to 2% a 325 mesh screen. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

Operators wearing flame retardant clothing opened oxidizer drums and carefully screened the contents; in some cases, oxidizers were weighed and loaded directly into hoppers destined for the Baker-Perkins mixer in Building 4233/E-34. More often oxidizers were sent after weighing to Building 4235/E-36 or 4283/E-84 to be ground to particle sizes required by specific formulas. Weighing of large batches was accomplished by a floor-mounted Toledo scale of 3,000 pounds (1,364 Kg) capacity, while smaller batches were weighed on a scale of 200 pounds (91 Kg) capacity (see Fig. 24). JPL operators attached grounding straps to all scales and other equipment when work was in progress. Scale readouts and other electrical gear related to the scales were installed in explosion-proof housings to minimize the spark hazard from electrical malfunctions as well as to exclude any accumulations of oxidizer dust in the instrument mechanisms. Scales themselves were supposed to be kept scrupulously clean of oxidizer build-up. No organic materials or solvents were permitted in the building during operations, since their presence near powerful oxidizers was an invitation to fire. Oxidizers were transported to the "grind houses" (4235/E-36 and 4283/E-84) in VeloStat®-lined fiberboard drums of 250 pounds (114 Kg) capacity. The liner is an electrically conductive plastic which forms both a moisture barrier and a grounding mechanism for the contents.

Oxidizer Grinding

Building 4235/E-36 was built in 1962-63 as a 14′-8" x 22′-8" reinforced concrete block structure with three rooms; Room 101 was the Grinder Room, Room 102 the Building Equipment Room, and Room 103 the Dust Receiver Room (see Fig. 25).[85] Building 4283/E-84 was built in 1980 to the same floor plan and dimensions as 4235/E-36, except steel frame and Transite board were used to construct the walls instead of concrete (see Fig. 26).[86]

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[85]. Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Bldg. E-36, Grinder Bldg. Plans, Elevations, Sections & Details,** Sheet A-37 (6 of 35), 26 June 1962; JPL Drg. No. E36/1-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.
[86]. California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Propellant Processing Building E-84: Flr. Plan, Elevations & Sections.** Sheet A1, 3 June 1980; JPL Drg. No. E84/3-0. California Institute of

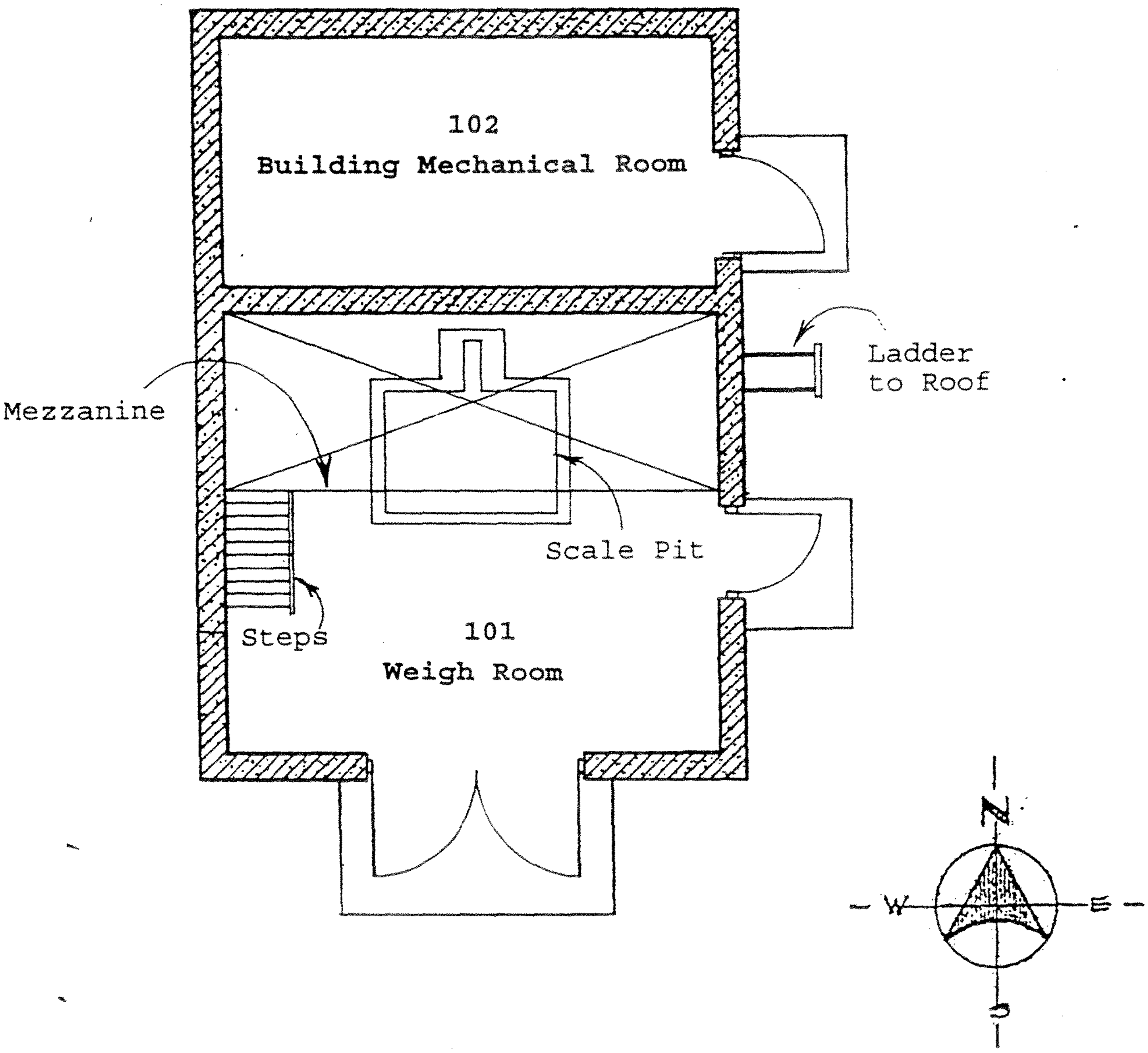

Fig. 24
Plan of Building 4269/E-70, Oxidizer Weighing & Storage

Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

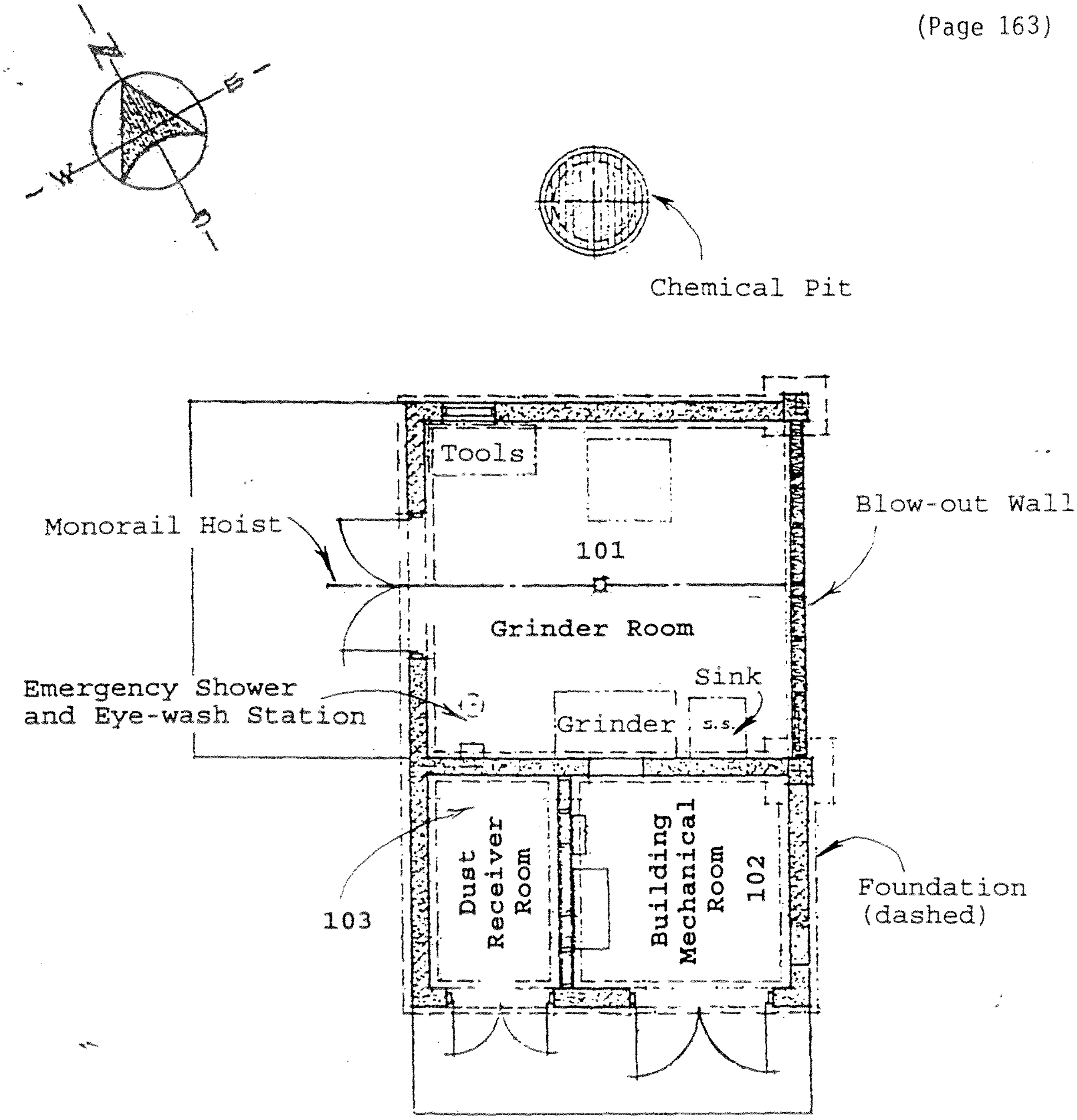

Fig. 25
Plan of Building 4235/E-36, Oxidizer Grinding

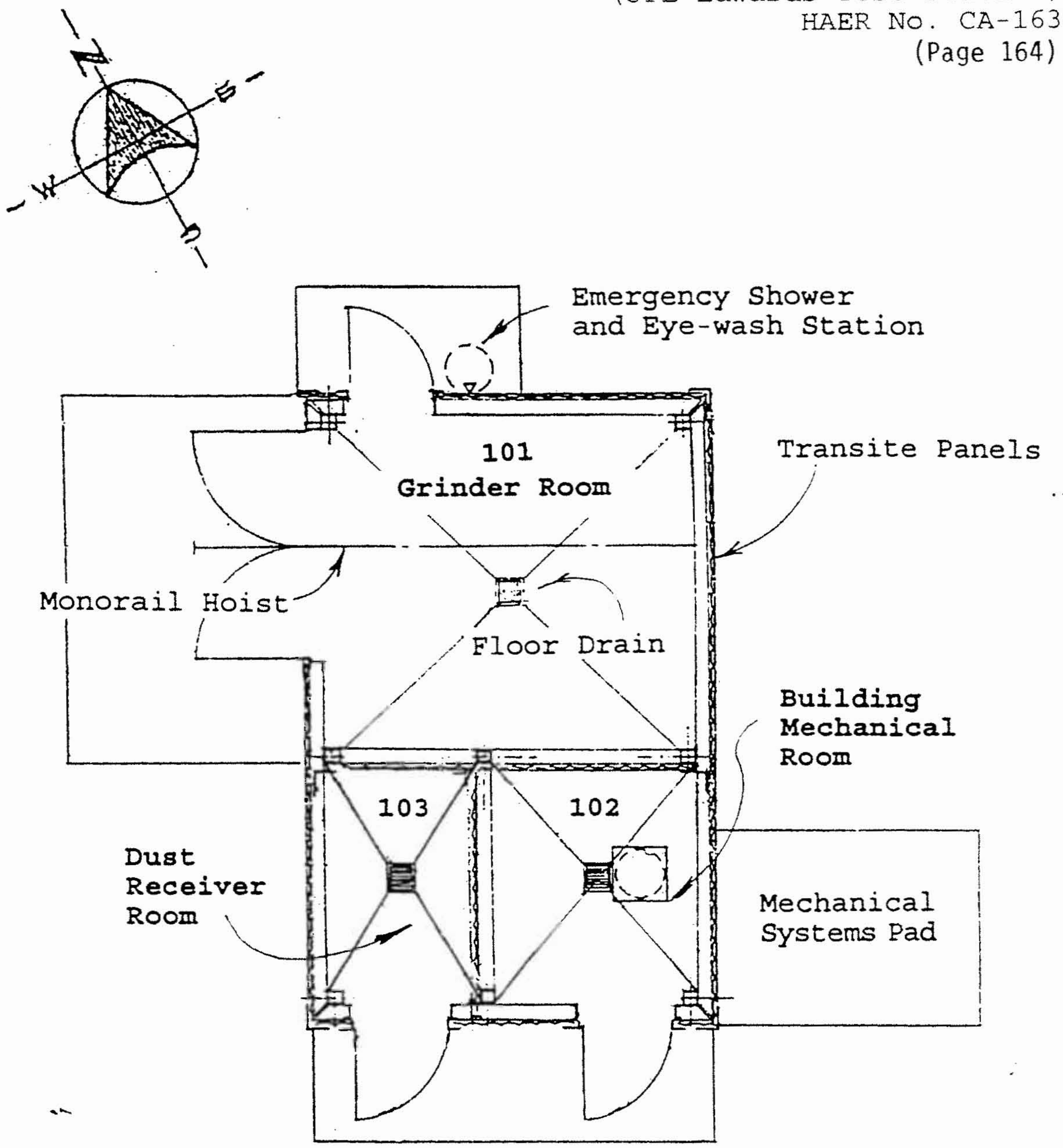

Fig. 26
Plan of Building 4283/E-84, Oxidizer Grinding

Building 4283/E-84 was built to serve as a back-up for 4235/E-36, since occasional explosions and subsequent investigations idled the building for months at a time, threatening development and test schedules.[87] The southeastern wall of the Grinder Room in 4235/E-36 was constructed of 2" x 6" wooden studs with styrofoam insulation and polyethylene covering to act as a frangible or "blow-out" wall in the event of an explosion; 4283/E-84 dispensed with this provision since the 1 9/16" thick "...asbestos sandwich panels w/ explosion clips" walls performed the same function.[88] Both buildings were covered by the same SOP[89] and were rated for a maximum of three personnel, 600 pounds Class 1.3 or 120 pounds Class 1.1 oxidizers.

The grinder used in each building was a Model 1-SH Mikro-Pulverizer™ hammer mill with stainless steel hammers capable of handling a maximum 130 pound charge (59 Kg). Grinding could only take place when the relative humidity stood between 20 and 40%; air temperature and humidity could be adjusted by the environmental system in Room 102 if necessary to permit grinding operations. Operators were required to wear flame retardant clothing and to use respirators if exposed to oxidizer dust. Prior to charging the mill, an electrically grounded 10-mesh screen was installed in the hopper to remove any foreign matter before it entered the hammer chamber. An amber warning light was

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87. Robert L. Ray recounted that a loose nut which fell into a hammer mill caused a fire in E-36. The sprinkler system extinguished the fire.

88. California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Propellant Processing Building E-84: Flr. Plan, Elevations & Sections.** Sheet A1, 3 June 1980; JPL Drg. No. E84/3-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

89. Barry, J. A. 12 October 1990. Section 351, No. 2012 Revision 5, Standard Operating Procedure, Oxidizer Grinding - EF (typescript), p. 1 of 15. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

turned on before any oxidizer was brought into the building. Aluminum scoops (which do not generate sparks if they accidentally strike masonry or metals) and electrostatically conductive brushes were mandatory for transferring oxidizers from drums to the mill hopper. Spills were to be cleaned up with water-dampened cloths and treated as propellant for disposal purposes. Operators had to install a second screen (per propellant formula requirements) which governed the final size of oxidizer particles. They also had to adjust pulleys and belts to achieve the requisite mill speed for grinding the required particle size and quantity of oxidizer. Once the VeloStat® 35-gallon fiberboard receiving drum had been positioned beneath the mill and the dust receiver checked, grounding straps were attached to all machinery. Typical set-up time took about 15 minutes.[90] Personnel were cleared of the building and a red warning light was turned on before grind operations began. The grinder was remotely operated from Building 4234/E-35 and monitored by television and microphones.

During operation, the charge was fed to the mill automatically by a vibrating hopper and repeatedly ground until the required fineness was obtained. It took about 3 hours 20 minutes for a 120 pound charge to make 4 passes through the mill and sift through an 0.020" screen. Oxidizer dust generated by the mill was vacuumed by a 5-horsepower Roto-Clone™ Type N hydrostatic precipitator (dust absorber). All the oxidizers ground in 4235/E-36 or 4283/E-84 were water-soluble compounds, so the hydrostatic preciptator removed them from the air by dissolving the dust in a water spray. Following the completion of a grind, the receiving drum was sealed and removed, then the mill was washed down with domestic water from a hose, and dried with nitrogen gas (GN_2). The grind house had to be kept clean of all oxidizer dust; tools and parts were washed, dried, and kept in a metal cabinet at the close of operations. After washing, drums were dried at 140°F.

Four-ounce samples of every grind were taken and labeled with material, lot number, date, grind number, and purpose for analysis and quality control according to an SOP for sampling

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90. Grind Station Operation, Operational Checkout per SOP 2012, for Lot 5049, Grind No. 195 for 120 pounds of NH_4ClO_4, 28 September 1982. Building E-32, Room 38, File 11, Drawer 3, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

powders and ground material.[91] Samples were delivered to Building 4285/E-86, where particle size and distribution were measured optically by a micromerograph. JPL methodically recorded the characteristics and conditions of every substance at every step in manufacturing a propellant batch, both to ensure quality control and maintain consistency in propellant formulations for meaningful performance analyses. Some formulas called for a bi-modal or tri-modal oxidizer, meaning that specific weights of two or three discrete particle sizes could be required.

Drying and Blending of Oxidizers

Many JPL propellant formulas call for oxidizer particles of a particular size or various quantities of oxidizer at certain specified ranges of particle size. To meet these specifications, portions of several grind batches would be weighed and blended in the tumble dryer/blender in Building 4237/E-38, Oxidizer Drying and Blending. Some propellant formulas also contain additives which are extremely sensitive to moisture prior to casting and curing. For these propellants, the oxidizers must be carefully dried in the equipment at Building 4237/E-38. If HMX were called for, particularly stringent and meticulous procedures were mandated for safety. When 4237/E-38 was built in 1963, JPL installed a Patterson-Kelley Model 304 blender manufactured in Stroudsburg, Pennsylvania. Thereafter other equipment such as explosion-proof electronic scales, an oxidizer particle size classifier, and a VacuDyne® oven were installed. An electrostatically conductive floor covering was also applied to more easily ground personnel and equipment.

Building 4237/E-38 is a standard reinforced concrete block structure measuring 25'-2 5/8" across the front and 22'-7 5/8" along the sides. It has two rooms: Room 101 is the Dryer Room and Room 102 is the Mechanical Equipment Room. The four corners of the structure are reinforced with 12" square steel-reinforced poured concrete columns, and the southeastern facade adjoining Room 101 is a blow-out wall constructed of 2" x 6" timber studs with styrofoam insulation sandwiched between two layers of polyethylene sheeting (see Fig. 27). Inside Room 101 is a mezzanine and stairway built of aluminum, including aluminum

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[91]. Vanderhyde, N. J. 4 January 1989. Section 351, No. 2033 Revision 2, Standard Operating Procedure, Sampling of Powders and Ground Material (typescript), p. 13 of 15. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

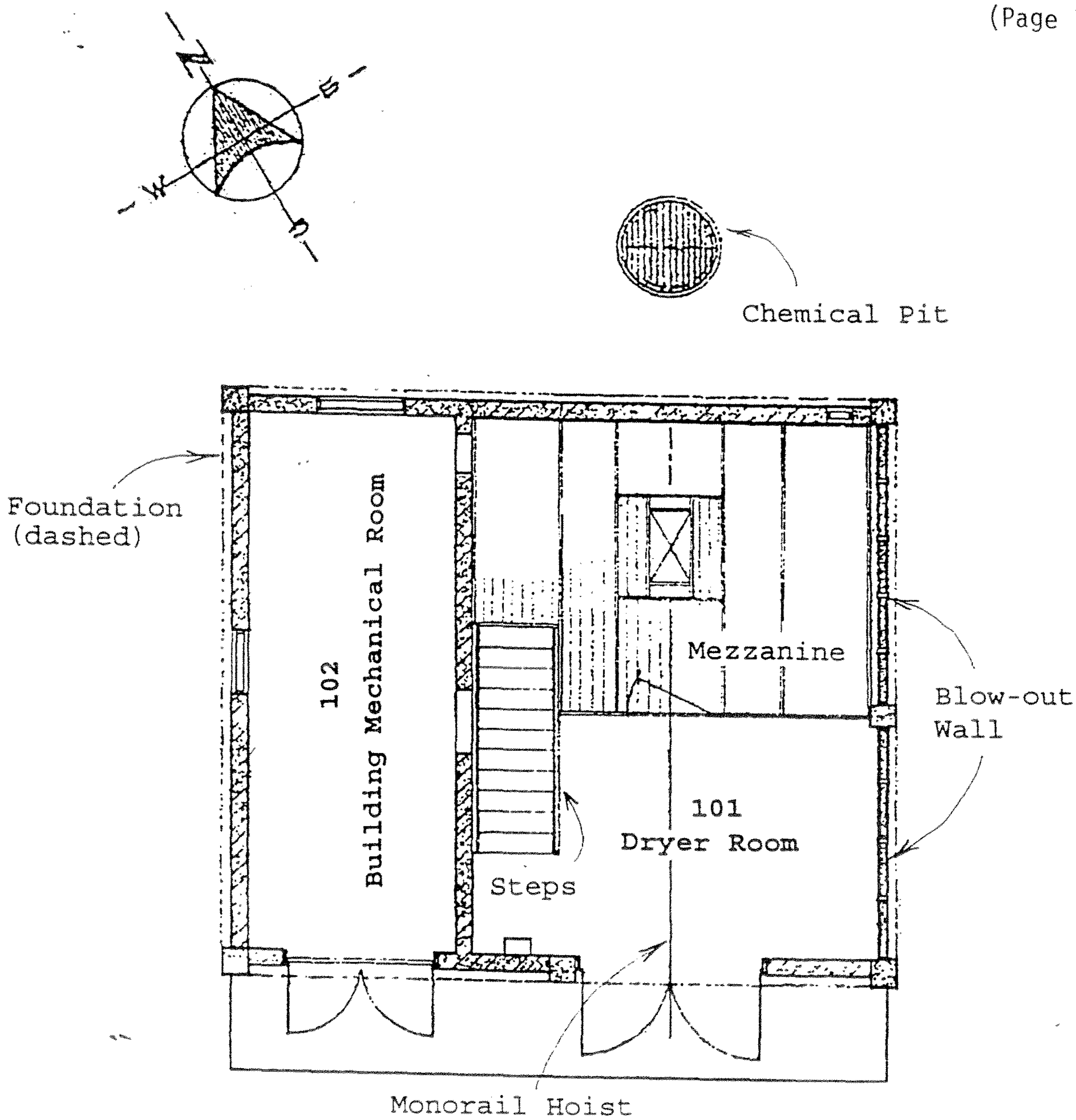

Fig. 27
Plan of Building 4237/E-38, Oxidizer Drying and Blending

handrailings and an aluminum wire-mesh enclosure for the dryer/blender.[92] Aluminum was probably chosen as a structural material because it does not rust (as would steels) in the presence of oxidizer dusts, nor would it emit sparks if accidentally struck by a tool or other object. Building 4284/E-85 was built in 1977-78 as a back-up dryer/blender for 4237/E-38, but the necessary equipment was never installed.

The tumble dryer/blender dried only ammonium perchlorate, ammonium nitrate or sodium nitrate. Only one type of compound was permitted at any time in the building, which was rated for a maximum of 600 pounds (273 Kg) of Class 1.1 oxidizer and three personnel.[93] The blender had to be washed out with domestic water and dried before a different compound could be introduced into it. The presence or storage of greases, oils, or solvents during any operations with oxidizers was expressly prohibited by safety rules, and personnel were required to wear flame-retardant clothing and eye protection. Respirators were mandatory when dust was present. Only non-sparking tools essential to work were permitted in the building, and they had to be accounted for at the beginning and end of set-up procedures to be sure no tool was accidentally dropped in the blender or left aside to cause accidents.

Prior to charging the dryer/blender, electric hot water heaters, a water circulating pump, and a vacuum pump were started in the equipment room. The dryer/blender is equipped with a water jacket that is maintained at 160° to 190°F to dry the unit's contents; a vacuum of 0.3 inches of mercury is drawn in the unit during drying operations. The unit rotates (tumbles) to agitate the contents for drying and blending. To charge the blender, operators lifted oxidizer drums to the mezzanine above the blender by a fork lift vehicle or an air-powered hoist

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92. Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Dryer Building: Plans, Elevations, Section, Details, Door and Finish Schedules,** Sheet A-39, 26 June 1962. JPL Drg. No. E38/1-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

93. Safety Rules, Test & Operation, Solid Propellant, Section 344. Building E-38 (4237); 19 August 1981. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

equipped with a drum turner. Drums had to remain covered while operators moved them, and drums of ammonium perchlorate could not dragged or dropped on the floor due to the compound's friction sensitivity. Personnel, equipment and oxidizer drums were to be electrostatically grounded anytime operators were transferring oxidizer to or from containers and the dryer/blender. Up to 500 pounds (227 Kg) of oxidizer could be added to the dryer/blender at its top, using a JPL-designed funnel. The environmental systems of 4237/E-38 were adjusted to maintain the building interior at a temperature of 80°F ±5°F and a relative humidity of 30% ±10% during drying and blending operations. An amber warning light was turned on while oxidizers were being dried or loaded or unloaded from the unit. When ammonium sulfate was processed, a green light was displayed due to the compound's inert nature.

Before drying and blending began, operators determined that the vacuum in the unit had reached 0.3 inches of mercury, then they closed and locked the aluminum wire caging surrounding the unit. JPL personnel moved to Building 4234/E-35 and resumed control from there. To begin, the unit ran under vacuum for 3 hours at 180°F ±20°F. The water temperature controller was then set to 50°F and a fan or evaporator unit was engaged to begin reducing the temperature of the water circulating in the dryer/blender jacket. When the temperature declined to 120°F, the temperature controller was turned off and the unit ran for 15 hours under vacuum without heat. If a blend of various sized particles has not cooled to 140°F (100°F optimum) by the end of this period, it was run longer under vacuum. At the close of the cycle, dry GN_2 was bled into the dryer/blender to release the vacuum, after which the blend was scooped into electrically grounded VeloStat®-lined fiberboard drums, 250 pounds per drum. Four-ounce samples were taken from each dried charge, sealed in moisture proof containers and appropriately labeled for analysis. Drums were sealed and transferred to Buildings 4269/E-70 or 4250/E-51 for temporary storage if they were not immediately needed for mixing operations.[94]

The VacuDyne® oven was installed to dry a high explosive additive, HMX which is utilized in several JPL formulas (see HAER photo CA-163-FF-2 for a view of a similar oven located in 4284/E-85). HMX is an extremely dangerous Class 1.1 mass-detonating compound which can be easily detonated by electrostatic

[94]. Barry, J.A. Section 351, Standard Operating Procedure No. 2037, Rev. 1: Drying or Blending Oxidizer in the Tumble Dryer, E-38. 2 March 1989. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

discharge, friction, impact, elevated temperatures or any combination of these conditions; it is more powerful than TNT (trinitrotoluene) but its high melting point renders it useful in the high temperature environment of burning propellants. Accordingly, numerous precautionary steps were mandatory during the handling and introduction of HMX to propellant mixes. The primary hazard with HMX is ignition of dry powder by stray static electric discharges, so the first safety measure is to store and handle it while it is wet as far as the propellant production process permits.

In 1988, HMX was shipped to JPL in 200-pound capacity fiberboard drums and stored at Building 4281/E-82. Inside each drum was a sealed polyethylene bag containing four canvas bags, each of which contained 50 pounds of HMX (dry equivalent) wetted with at least 10% (by weight of dry HMX) of a shipping solution to reduce its sensitivity to detonation.[95] The shipping solution commonly contained 40% isopropyl alcohol $[(CH_3)_2CHOH]$ and 60% water; sometimes DOA (di-octyl, adipate $[CH_3(CH_2)_7]_2(CH_2)_4$) was added as a desensitizer, but operators were warned not to count on its presence. Only two JPL personnel were permitted in 4281/E-82 to move HMX in canvas bags. No dispensing or transfer of HMX from the bags to other containers was permitted in the storage area. Personnel were required to wear cotton clothing (to minimize electrostatic spark generation), flame retardant coveralls, eye protection, and wrist and shoe grounding straps. Canvas bags of wet HMX were transported at JPL in a carton lined with a VeloStat® bag. While it could be weighed in this condition at 4269/E-70, it could not be stored or dispensed in that structure. SOPs required HMX to be weighed to the nearest 0.2 pound on grounded scales.

From 4281/E-82, JPL personnel could process HMX in two ways, according to S.O.P. No. 2039.[96] They could mix it with DOA and

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[95]. Barry, J.A. Section 351, Standard Operating Procedure No. 2015, Revision 3: Procedure for Receiving and Storage of HMX Oxidizer (typescript), 3 October 1988. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

[96]. Barry, J.A. Section 351, Standard Operating Procedure No. 2039 Revision 10: Safety Procedure for Drying HMX Oxidizer by VacuDyne Oven Process (typescript), 27 January 1988. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

isopropyl alcohol in a mixer (in an unspecified building[97]) and cast the slurry into VacuDyne® drying trays, or they could transfer it from the shipping containers or canvas bags directly into the drying trays in 4237/E-38.

Personnel entering 4237/E-38 when HMX was present had to wear cotton gloves and clothing, and their flame retardant garments had to be sprayed with an anti-static solution. Conductive leg and wrist straps had to be worn and their anti-static effectiveness confirmed and recorded by using an electrical resistance meter on each operator. All tools had to be of non-sparking materials and effectively grounded. Electrical wiring at all plugs had to be checked for frays, and the area and personnel "snooped" with a static meter to be sure no charges higher than 50 volts were present (as measured from a 2" distance).[98]

Procedures are numerous and highly detailed for mixing HMX and for handling and transferring wet HMX to dryer trays and dry HMX from the trays to appropriate containers.

If a quantity of HMX were to be mixed, the selected drum was weighed to the nearest 0.2 pound in 4237/E-38, and the dry weight of HMX in the container was estimated by a simple formula. All figures were recorded. When the drum was moved to a mixer building, a VeloStat® sheet was laid on the floor near the mixer bowl and the mixer bowl rolled out onto it. The sheet had to be large enough to extend two feet around all sides of the mixer bowl after it was rolled out, and the bowl had to remain grounded to the building ground system. While such operations were underway in the mixer building, the gates at buildings 4232/E-33 and 4240/E-41 were closed and the amber warning light turned on. Properly garbed operators placed the drum of HMX on the VeloStat® sheet, opened it and transferred the required amount of HMX to the mix bowl. The drum was then sealed and returned to 4237/E-38 for weighing (again, all figures were recorded). A solution of

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97. A detailed review of SOP No. 2039 suggests that the mixer used was the 50 gallon Baker-Perkins mixer in E-37 or the 150 gallon Baker-Perkins mixer in E-34. The SOP discusses "...moving the mix bowl forward" and raising the mix bowl to the mixer by remote control in E-35; both are actions that would be taken using a large mixer.

98. Standard Operating Procedure No. 2017 Revision 5: HMX Drying Operation, Safety Checklist per S.O.P. 2017. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

DOA and isopropyl alcohol (mixed in a 1:9 ratio by weight) was added to the mix bowl equal in weight to 10% of the HMX in the bowl, and the bowl was rolled back under the mixer blades. All these operations were monitored by closed-circuit television by another operator stationed in 4234/E-35. When operators in the mixer building had positioned the bowl, they left the building after switching on the red warning light and returned to 4234/E-35. The mix bowl was raised to the mixer blades and the mixing operation carried out by remote control. An average mixing time was 30 minutes at atmospheric pressure, low speed, and a temperature of 80°F. When mixing was completed, the bowl was lowered by remote control before personnel re-entered the mixer building. Before the bowl was rolled out, a new VeloStat® sheet was laid out on the floor and grounded to the building. Personnel scraped the mixer blades clean of HMX using a grounded, conductive, non-sparking spatula. The blades and mix bowl were cleaned of HMX traces with cotton rags or paper towels wetted with anti-static solution; the waste was disposed of in VeloStat®-lined drums. Operators then placed stainless steel or aluminum dryer trays on the VeloStat® sheet after weighing and recording the tare weights of the trays. Operators set weighed sheets of VeloStat® in each tray, cut so that the VeloStat® extended at least 2" above the tray edge on all sides. They then scooped the wet HMX from the mix bowl into the trays and spread it out evenly in a 1" thick layer with conductive, non-sparking spatula. Personnel, trays, scoop and spatula were grounded to the building ground system. After completing this procedure, operators wiped down the entire mixer housing, blades and bowl using DOA wetted cotton rags or paper towels, disposing of the contaminated articles and waste HMX as before. Trays of wet HMX were transported to the VacuDyne® oven in a "...covered van approved for transporting explosives."

If mixing were not required, procedures for transferring wetted but non-desensitized HMX to dryer trays in building 4237/E-38 were similar to those in the mixer buildings. A sheet of grounded VeloStat® was laid out on the floor near the drying oven, and weighed, VeloStat® lined trays were placed in the sheet, one at a time, near the HMX drum. Operators scooped HMX from the drum to each tray using appropriate grounded conductive non-sparking tools, and spread it evenly in the trays.

Once the trays were filled and placed in the drying oven, the oven door was closed and secured with four clamps. A water jet eductor drew a vacuum of at least 2.68 inches Hg (mercury) at ambient temperatures for a minimum of 24 hours. Personnel left the building, switched on a red warning light and closed gates at nearby structures. HMX was then heated by a hot water jacket to 180°F ±20° at a vacuum of 25 inches (mercury) for 96 hours. The oven temperature and other conditions were monitored by instruments and closed circuit television from 4234/E-35. At the close of the drying cycle, HMX was allowed to cool to 120°F and GN_2 was bled into the oven to release the vacuum. HMX samples weighing 20 grams were taken and checked for moisture content. Drying was continued if necessary, otherwise, operators proceeded to transfer HMX from the trays to grounded VeloStat® bags. One tray at a time was removed from the oven and weighed on a grounded balance. Once the weight of a tray was recorded on the HMX Drying Record, an empty VeloStat® bag was placed on the balance, weighed, recorded, and grounded. With the bag still on the balance, the HMX was gently scooped (not poured) into it using grounded, non-sparking aluminum or VeloStat® scoops from the dryer trays until "exactly" 20.00 pounds were transferred to the bag. This was repeated until the dryer tray was emptied. The residual HMX was transferred to the last bag and weighed to the nearest 0.01 pound. During these transfers, the operator, tools, tray and bag were all grounded to each other as well as to the building ground system. The tops of the VeloStat® bags were sealed "gooseneck" fashion, and labels attached with batch number, weight, and other data recorded on them. The bags were placed in a fiberboard drum containing a VeloStat® bag; the drum was lined inside and out with aluminized tape to create a grounding path for discharge of any static electricity. Any spills were swept up with conductive, non-sparking brushes and dustpans and disposed of in VeloStat® bags; residual spills were cleaned up with wet rags. Rags and bags are carefully disposed of as waste propellant in fiberboard containers lined with aluminized tape. All containers were grounded at all times to the building ground system.

Fuel Preparation

As an oxidizer was being prepared to formula specifications, operators in Building 4234/E-35 were weighing the separate ingredients for the fuel slurry. A wide variety of chemicals was employed for fuels, however, a major component was finely powdered aluminum, which constituted about 16% by weight of the final mass of a propellant grain. JPL experimented with various aluminum alloys in powder grain shapes ranging from flakes to spheres to study their combustion behavior in propellants. Finely powdered aluminum can oxidize extremely quickly because of the high surface-to-mass ratio of each particle; it is explosive if airborne, and is even more hazardous when wet. Other additives included plasticizers, burning rate modifiers (such as Fe_2O_3, or iron oxide), anti-oxidants (to preserve rubber life) and substances that modified propellant characteristics such as pot life (time window in which propellant can be cast after a curing agent is added), curing rate, mechanical flexibility, tensile strength, sensitivity to impact and electrostatic discharges, storage life, sterilizability, etc. In addition to substances already mentioned, an inventory of propellant ingredients dated 24 April 1976 listed 593 separate substances ranging from nitrocellulose, to beryllium azide, to castor oil, epoxies, "tire buffings" and napalm soap.[99] Many of the other listed substances are gaseous, or cryogenic, emit hazardous fumes, or otherwise raise peculiar handling problems. The list is an indication of JPL's wide-ranging search for compounds with any usefulness to the production and refinement of successful solid propellants; needless to say, the list expanded as time passed to include numerous complex organic and inorganic compounds sifted from the burgeoning world of commercial and industrial chemistry. A number of these compounds were required in only small amounts for experimentation purposes and could be stored at Building 4234/E-35. More frequently used fuels such as aluminum powder were stored in bulk at 4251/E-52 with smaller amounts kept at 4234/E-35 as "ready storage."

One of hundreds of successful formulas developed at JPL, No. PBAN-Mod. 8 (used in solid rocket boosters of NASA's Space Shuttle), consists of 69.99% by weight of ammonium perchlorate, 16.00% fine aluminum powder, 0.01% iron oxide, and 14.00% PBAN (polybutadiene acrylic acid acrylonitrile, an elastomeric or rubber-like binder that also serves as a fuel component).[100] The final product has a gray color, a density of 0.0641 pounds per cubic inch, and resembles a rubber pencil eraser in consistency. Polyurethanes were commonly used for binders before 1985; in the late 1980s and 1990s hydroxy terminated polybutadienes are used for binders.[101] Polybutadiene rubbers are among the most common rubber compounds, 1,140,000 metric tons were consumed in 1990, mostly in automobile tire formulas.[102]

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[99]. "Propellant Ingredients" (typescript, 23 pages) "Current as of April 24, 1976. Having a total of 593 ingredients with code numbers ranging from 1 through 600." Building E-32, Room 10, File 4, Drawers 2 and 3, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

[100]. Powers, L. B. NASA Marshall Space Flight Center, Huntsville, AL; R. L. Bailey and B. H. Morrison, Jet Propulsion Lab., Pasadena, CA. *AIAA-81-1461: Shuttle Solid Rocket Motor Nozzle Alternate Ablative Evaluation.* New York, New York: American Institute of Aeronautics and Astronautics, 1981:6.

[101]. Robert L. Ray Interview.

[102]. Kent, James A. *Riegel's Handbook of Industrial Chemistry.* 9th ed. New York, New York: Chapman & Hall, 1992:612.

Building 4234/E-35 is in many respects the heart of the solid propellant processing line, since it harbors the control room for remote operation of critical machinery and mixes the widely varied fuel-and-additives components of solid propellant formulas. Building 4234/E-35 was originally constructed as a 51′-6" x 33′-4" steel-reinforced concrete block structure. From the exterior, the building has the same no-frills architecture that has been described above. The interior was partitioned into seven work rooms and a corridor by wooden stud walls (see Fig. 28). The 10′-4½" x 11′-4½" wing room on the southwest corner (added in 1967)[103] had no interior access to the building and served as fuel binder storage. Adjacent to the east of fuel binder storage was the fuel weighing room, followed by the oxidizer room. North of the east-west corridor was the control room in the northwest corner of the building, an equipment room for air conditioning machinery, and to the east of that, an equipment storage space. The eastern end of the building was taken up by a clean-up bay for washing, cleaning and decontaminating laboratory instruments and containers. The building equipment room was the only room other than the fuel binder storage room not to have an interior door to other spaces in the building.

Evidently, accommodations in 4234/E-35 became inadequate. An open storage shed with a sheet metal roof was added to the southeastern corner at some point, and judging from the safety rules of 15 January 1971, some of the room functions had been modified between 1971 and 1983. In 1983-1984 the interior was extensively renovated, and two new rooms were added to the eastern end of the building (See HAER photo CA-163-N-7). The control room was housed in a trailer until work was completed.[104] The new control room (Room 101) expanded about 250%, swallowing up the old fuel weighing room to occupy a space

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103. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering. **Bldg. E-35 Addition: Storage Room Addition.** Sheet A, 24 August 1967; JPL Drg. No. E35/9-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

104. California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Addition to Weigh & Control Bldg. E-35, Temporary Rack & Console Move,** Sheet E-3, 30 March 1984; JPL Drg. No. E35/20-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

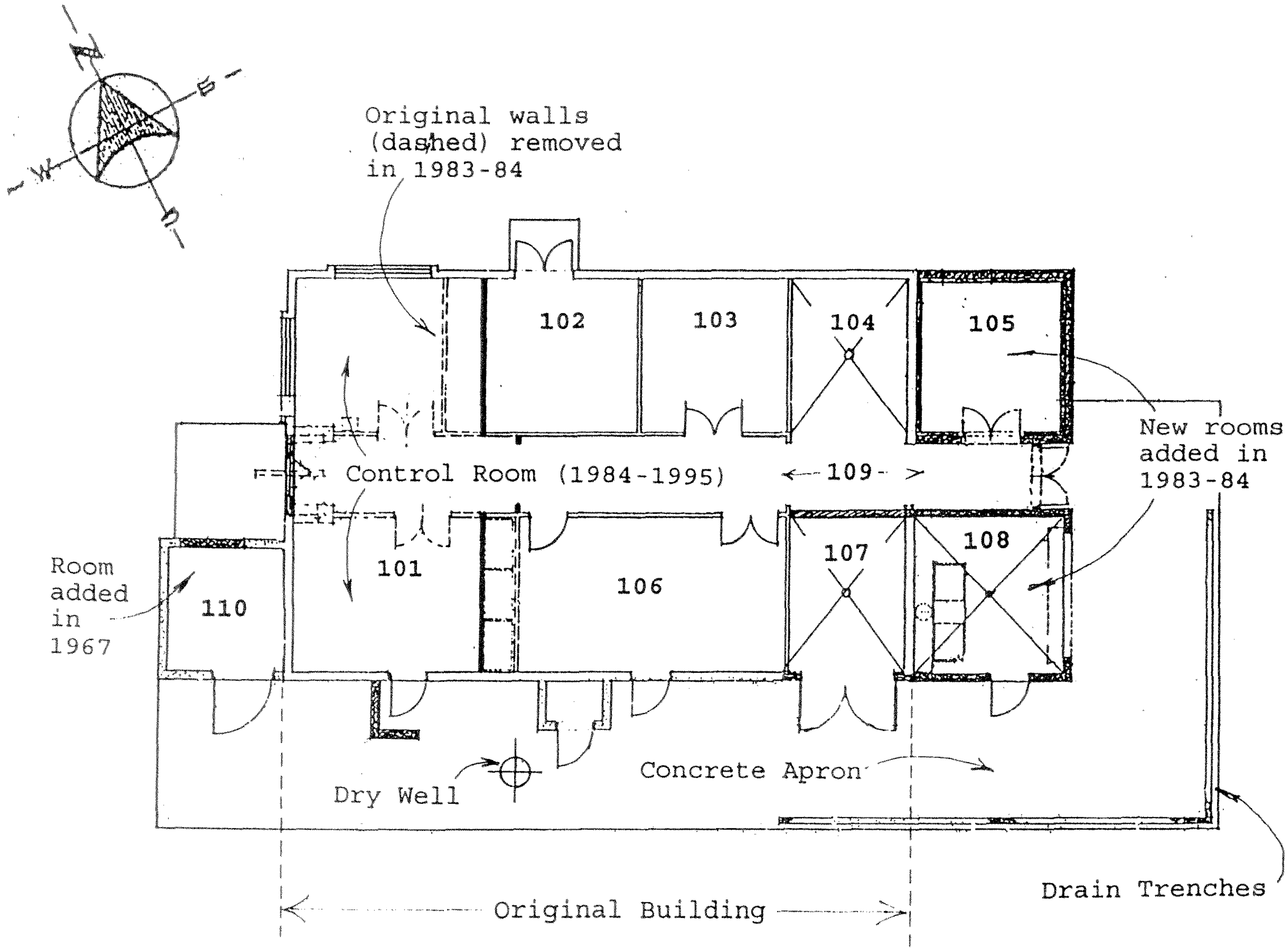

Fig. 28
Plan of Building 4234/E-35, Weighing & Control

across the western end of the building. The equipment room retained its function and was renumbered as Room 102. The equipment storage room was renumbered as Room 103 and used for additives storage. The northern end of the old cleaning bay retained its function and was renumbered as Room 104. To the east of Room 104 was a new insulated room (105) designed to dry and store laboratory hardware at 140°F. The oxidizer room became Room 106, the new weigh room. The fuel binder room retained its old function, while the southern end of the old clean-up bay became Room 107, a physical property laboratory later converted to solvent storage. To the east of Room 107 where the shed wing had stood was a new cleaning room (108) with a roll-up door on the eastern exterior wall. A new concrete apron was constructed on the south side of the building, retaining access to a dry well, but covering over a former chemical pit.

Available evidence for the handling of propellant components at 4234/E-35 is limited.[105] Flame retardant clothing was required for any hazardous operation. The simultaneous presence of "incompatible" materials (such as a fuel and an oxidizer) in a room was prohibited. All floors and equipment were to be cleaned after each operation, and rubber gloves, safety goggles and breathing apparatus were to be worn when handling certain substances like TDI or cleaning solvents. When aluminum powder was dispensed, grounding wires had to be connected to containers. Solvent containers (cyclohexanone, $CO(CH_2)_4CH_2$) were to be grounded in the cleaning bay. In 1995, the rooms in 4234/E-35 were rated for maximum quantities and personnel as follows:

Room 101:	0 lbs propellants	5 personnel
Room 102:	0 lbs propellants	5 personnel
Room 103:	unknown	5 personnel
Room 104:	unknown	unknown
Room 105:	50 pounds Class 1.3	5 personnel
Room 106:	70 pounds Class 2	5 personnel
Room 107:	5 pounds Class 1.1	3 personnel
Room 108:	10 pounds Class 1.1	5 personnel

In 1995, the control room was partially dismantled, but intact enough to see the layout of controls and instruments (see HAER photo CA-163-N-3 and N-4). In the renovations of 1983-84, the room had been considerably enlarged, and steel plates covered floor trenches dug to accommodate cabling for the controls and instruments. The room retained two horizontally elongated windows originally intended for observation of the propellant

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105. Specific details are limited to the 15 January 1971 safety rules for E-35.

line by operators, but their line of sight is now blocked by revetted barricades, which were built to protect 4234/E-35 from blasts at nearby structures. Explosion-proof, grounded scales still rested on heavy marble benches in Room 106, though it appeared from a "ghost" on the floor that another bench had been in place there until recently. The weighing room floor had a conductive coating to disperse static electric charges. The dense marble benches helped to damp vibrations and reduce erroneous readouts from sensitive instruments. Readouts were printed out on paper tapes as well as recorded by hand, both to verify that an ingredient had been weighed to the proper quantity according to procedure, and to check against human error recording a reading (see HAER photo CA-163-N-6). Electrical equipment such as scale meters and fluorescent lighting were housed in explosion-proof fixtures. Other rooms were visited for this report, but they were largely empty.

After the components for a fuel slurry were prepared at 4234/E-35, operators transported them to a mixer along with a curing agent. If quantities were small enough, they were hand-carried in Seal-Rite® containers; otherwise they were transported by a vehicle. Propellant components were added to the mixer in sequences detailed by a solid propellant mixing schedule specific to the formula at hand.

Motor Casing and Liners

All solid propellants have to be contained in a casing designed to withstand the heat and internal pressure generated by burning propellants. Typically casings were insulated by a rubber layer which lay between the casing and propellant. JPL personnel prepared casings for propellant casting in the Liner Lab (Building 4332/E-33). Sometimes they prepared casings lined with rubber by other companies or contractors, at other times they formulated their own insulation compounds, applied them to empty casings and baked the lined casings in oven rooms or an autoclave.[106]

According to Robert L. Ray, a career JPL-ETS employee in solid propellant engineering and testing, early ATS and Syncom motor casings were made of titanium (for strength and lightness) and lined by non-JPL contractors with a rubber insulation that was incompatible with propellants. JPL also experimented with rubbers of its own formulation; typically, ethylene propylene di-monomers (EPD) were used for case insulation. It was cut into pie-shaped pieces 1/8" thick, applied to casing walls, and then

[106]. Robert L. Ray Interview.

vulcanized in an autoclave (see HAER photo CA-163-L-2). If a propellant were cast into a rubber-lined casing with no other preparations, it would fail to adhere to the rubber. Such propellant "pull-aways" resulted in motor burning times that were faster than intended, sometimes with explosive results. A liner was a preliminary coating applied over rubber insulation, having properties that would make it adhere to both the insulation and the propellant. Liner formulations contained a binder plus a filler, which consisted of substances like asbestos ($Mg_3(Si_2O_5)(OH)_4$) in the 1960s and 1970s; silica (SiO_2) and other refractory substances were also used. After asbestos was banned as an environmental hazard, phenolic (a plastic) microballoons were substituted. One liner formula consisted of 18% phenolic microballoons.

JPL employees washed insulated casings in baths of TDI (toluene 2,4-di-isocyanate, $CH_3C_6H_3(NCO)_2$), a solvent which prepared rubber surfaces for the liner materials (TDI was also used as a curing agent for propellants, and sometimes propellants were cast into insulated casings after the TDI wash). TDI was kept in three stainless steel wash tanks in Room 103; drums of TDI had vent valves on them set to release vapors to the atmosphere if pressure exceeded 5 pounds psi. SOPs required personnel to wear flame retardant clothing, rubber gloves, goggles and breathing equipment (Scott Air Packs) when handing TDI or other solvents in 4232/E-33.[107] Two people were required to work together during TDI rinse operations, and any spilled TDI had to be immediately cleaned up with a 5% ammonia and water solution. All floors, equipment and accessories had to be cleaned up after every operation. After the TDI wash, liner materials which had been ground, mixed or blended in Room 102 were applied to insulated casings and partially cured in the 4232/E-33 oven rooms or in a 5′ x 8′ autoclave.[108] The interior surface of the lined casing was then machined smooth (probably in 4243/E-44).[109]

The Liner Lab itself was a single story 70′-7-3/4" x 20′-7-

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107. Bailey, Richard L. Safety Rules, Solid Propellant Engineering, Section 381. Building E-33, Room 102; 15 January 1971. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Report on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

108. It was not clear from Mr. Ray's accounts where the autoclave was located in E-33.

109. How the asbestos-impregnated shavings were disposed was not determined.

5/8" steel-reinforced concrete block building following the standard architectural and construction description given above (See HAER photo CA-163-L-3 for 1962 unedited construction plans; see also Fig. 29). The Liner Lab contains ten work rooms numbered 101 to 110, all clustered around Room 107, the mechanical equipment room (This room numbering system was current in 1995; the room numbering system shown for 4232/E-33 in the HAER drawings was the one current in the safety rules for 1971). At the time of documentation in 1995, 4232/E-33 had been used for offices for a number of years and no longer contained process equipment.

Materials and casings were transported into the storage room (101) through steel double doors on the southeast side of the building. Doors from Room 101 lead to the Liner Room (102) to the northwest and to toilet and change rooms on the northeast side (108 and 109 respectively). At a later date, Room 101 was divided into two rooms, the one in the building's southern corner becoming a bay with one side open to the atmosphere (compare HAER photo CA-163-L-1 with Fig. 29). Subsequent renovations to the building were minor. JPL employees prepared liner formulations in the liner room (102), which in 1963 contained a small mill, two mixers, a blender, two fume hoods and several cabinets. Presumably the mill ground refractory additives to varying degrees of required fineness, the blender prepared mixtures that contained no gritty or insoluble additives, and the mixers combined all of a liner formula's components for the final preparation step. The formulations were made in small batches to minimize fire and exposure hazards. Records were kept of every batch for analyses of performance.

Once liner materials had been applied, the casings were heated for several days in one of the 6' x 6' ovens (Rooms 104 to 106) to partially cure the liners. Standard operating procedures required personnel to wear leather or asbestos gloves when handling any casings or dried hardware from the ovens. Once liners were removed from the ovens, they could either cool and stand by in storage until needed or they were taken warm to one of the mixer buildings where propellant would be cast into them. Further assembly of casings with caps and other components were necessary in some situations prior to casting.

Propellant Mixing and Casting

When a fuel slurry, oxidizer, motor casings and sample molds were ready, they were brought together at a mixer for the final combining of ingredients and the casting of grain and samples. JPL housed five mixers ranging in capacity from 1 pint to 150 gallons in three different buildings. Building 4233/E-34 housed

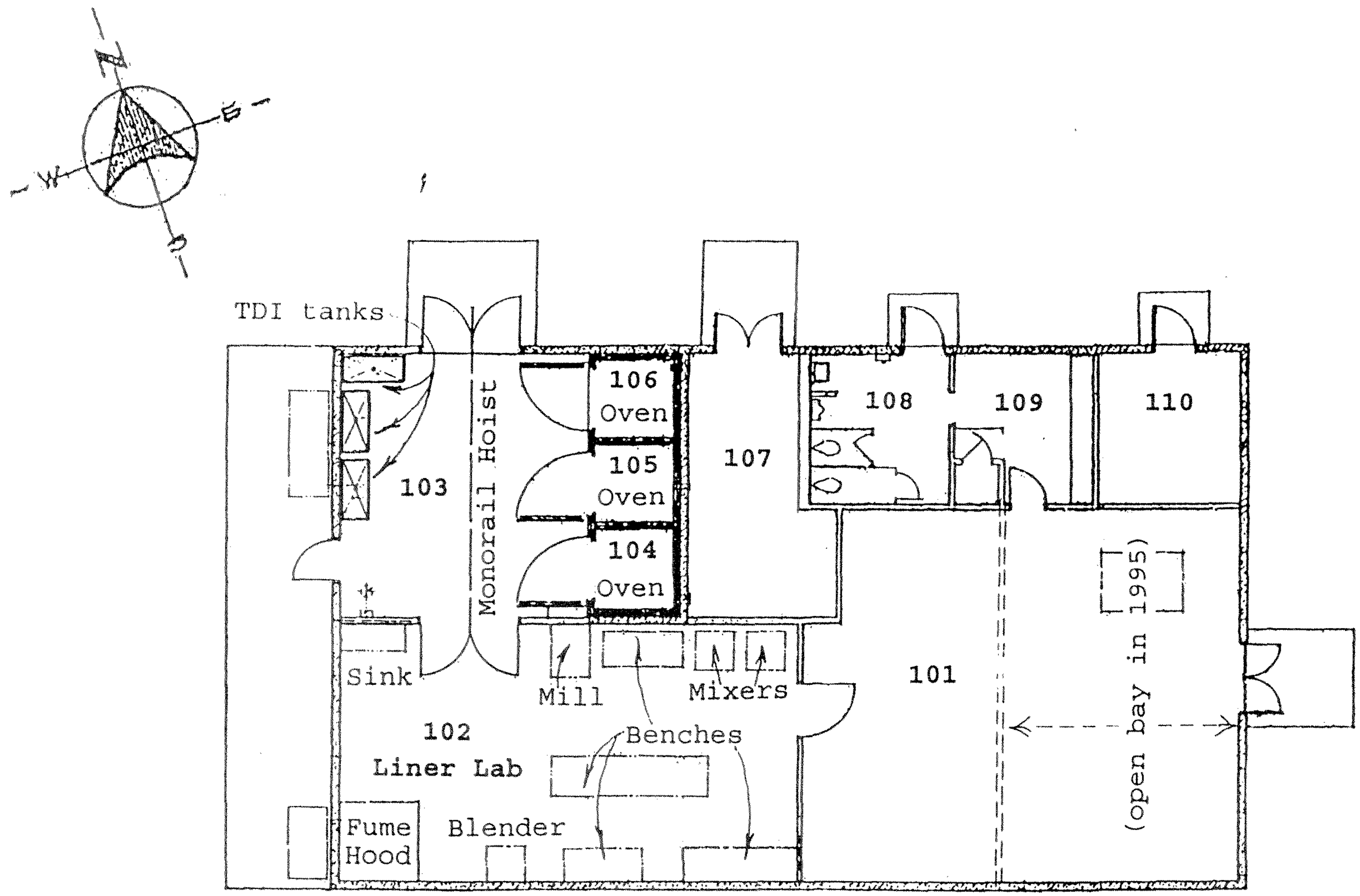

Fig. 29
Plan of Building 4232/E-33, Liner Lab

the 150-gallon Baker-Perkins Size 16-PVM vertical mixer, serial number 53371, fitted with a jacketed mixing can fabricated from #304 stainless steel alloy.[110] This massive unit weighed about 32,000 pounds and was powered by a 5-horsepower 3-phase alternating current motor (see HAER photo CA-163-M-4 for overall elevations of the unit and its 1963 installation plan). Building 4236/E-37 housed a 30-gallon Baker-Perkins Size 12-½ PVM vertical mixer in Room 101 (see HAER photo CA-163-P-2). Two Baker-Perkins mixers were located in Room 102--a 1 gallon capacity model 4-PU and a 1-pint capacity model 2-PX (see HAER photo CA-163-P-3). Building 4243/E-44 housed a 5-gallon Baker-Perkins model 8-PI mixer in addition to a grain trimmer and mandrel puller. The capabilities of these machines varied somewhat, with only minor differences in their operating procedures. The Baker-Perkins mixers in 4236/E-37 and 4243/E-44 are not original to their buildings; they replaced earlier Bramley mixers of similar capacities.

The mixers were adapted to process chemicals from commercial food processing models. The manufacturers added piping for fire suppression systems, and the machines could mix and cast propellants under vacuum to eliminate the entrainment of air bubbles in propellant grain. The mix can or "pot" was equipped with a water jacket to maintain mix temperatures at about 140°F to 170°F; mixing generated heat because of the viscous nature of propellants. Operators added ingredients by hand to small mixers whereas the larger machines were equipped with a hopper ("tote bins") which mechanically added ingredients under remote control. Loaded tote bins could be rolled into conditioning buildings and heated to bring their contents up to the temperature of the mix before operators mounted the bins on a mixer. Remote controls were built in to the mixers, and instruments (such as infrared detectors) for monitoring the machines and the mixes were incorporated for connection to the control room at 4234/E-35. The mixers were equipped with two counter-rotating stainless steel paddles mounted in a hub which also rotated during mixing. The hubs and paddles were driven by an internal planetary gear system which caused one paddle to rotate several times faster than the other. The paddles cleared the walls of the mix pot in the 150-gallon machine by a ¼", which left a thin layer of badly

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110. Jet Propulsion Laboratory interoffice memo, W. Thurston to Floyd Anderson, 29 July 1963, with attachments including a letter from J.E. Baumann of Baker Perkins, Inc. Chemical Machinery Division to Paul Lesniak of JPL and a final inspection report. Memo on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

mixed propellant on the walls of the pot. JPL discovered that by reversing the paddle rotation briefly this layer could be dislodged and incorporated into the mix, thus producing the necessary homogenous mass. A specific grinding action is maintained during mixing: particles of fuel and oxidizer grind each other down somewhat. JPL determined that this was beneficial, since smaller particles fill voids, and due to their larger surface-to-mass ratio they react more quickly; the action also increases the density of the propellant.[111]

As might be expected, the larger mixers produced propellant batches for large motors or extensive series of test motors, while smaller mixers produced batches for more experimental formulas, some of which required expensive ingredients. JPL personnel also used smaller mixers for liner compounds as well as propellants, the 5-gallon mixer in Building 4243/E-44 often served this purpose. Some motors were so large that several batches from the 150-gallon mixer were required to cast the grain; scaled-down test versions of the solid rocket boosters for NASA's "Space Shuttle" contained 5,000 pounds of propellant. For jobs of this size, extra mix pots were borrowed from other facilities and batches were stored in them overnight in various buildings until sufficient propellant accumulated to cast the motor. In these cases, curing agents were not added until the "last minute" (see HAER photo CA-163-P-4 for an image of the casting operation for a 48" diameter Char motor).

Transportation of such large batches of live propellant was strictly limited to 5 miles per hour or less.[112] Moving a live loaded cartridge could proceed no faster than a man's gait (3 miles per hour). For all such movements a "buddy system" was used; one man walked beside the loaded trailer to set the pace for the tow driver.[113] The Section 381 Operational Methods & Safety Procedures manual required that gasoline-powered vehicles, electric carts, and small three-wheeled trailers be used for transporting solid propellant on JPL property. All such vehicles were equipped with grounding straps, and loads were securely tied down and grounded. No riders were allowed in trailers or truck

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111. Robert L. Ray Interview.
112. JPL Edwards Facility, Processing Schedule for Multi-propellant Batches, Revision 1 - November 1984, B. H. Morrison, Step 26 (unpaginated).
113. JPL/Edwards Facility, Processing Schedule for Multi-propellant Batches, Revision 1 - November 1984, B.H. Morrison, Steps 39 and 54 (unpaginated). Record on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

beds when propellants were present. Drivers had to display amber warning lights and/or explosives signs when actually transporting a propellant container or loaded motor.[114]

Operators at mixers had to follow safety procedures scrupulously. They wore flame retardant clothing and safety goggles as a matter of course; respirators were required whenever propellant dust or low concentrations of isocyanate curing agent vapors were present. Breathing air was provided in pressurized tanks for emergency purposes. Anti-static spray solutions, cotton clothing, and wrist and leg grounding straps were required for mixing any HMX formulations. Identity badges, rings, watches, pens and pencils had to be removed from their persons and clothing above the waist as precautions against anything falling into the mix pots. Operators were required to check out the operational status of the mixer thoroughly, including vacuum pump, water pump and environmental systems, fire suppression system and safety equipment associated with the mixer before they began any hazardous operations. Ambient conditions in the mixer room had to be 80°F ±5° and 30% ±10% relative humidity before propellants could be introduced into the mix pot. As with other hazardous operations, a minimum of two personnel had to be present for any activity, and all procedures were monitored via closed circuit television by personnel in 4234/E-35.

Propellant ingredients were never simply introduced to the mix pot all at once. The pot itself had to be raised to the mixer head, latched, evacuated and the temperature set at 180°F for at least one hour to dry any moisture out of it. Ingredients were then introduced in a sequence specified by the mixing sheet, usually starting with the binder, the main liquid component. After part of the binder had been delivered into the pot, personnel raised it to the mixer head and left the building, switching on the red warning light before any mixing was done. Once operators were clear of the structure, the pot was evacuated and the mixer run for 5 to 10 minutes at low speed. When the mix cycle concluded, operators returned to the structure, released the vacuum and lowered the pot. They then had to clean the blades with non-sparking, conductive tools, and add the next amount of specified ingredients. If necessary, they also reset the mixer speed. The pot was then raised into position, and operators left the building while the second mix cycle ran.

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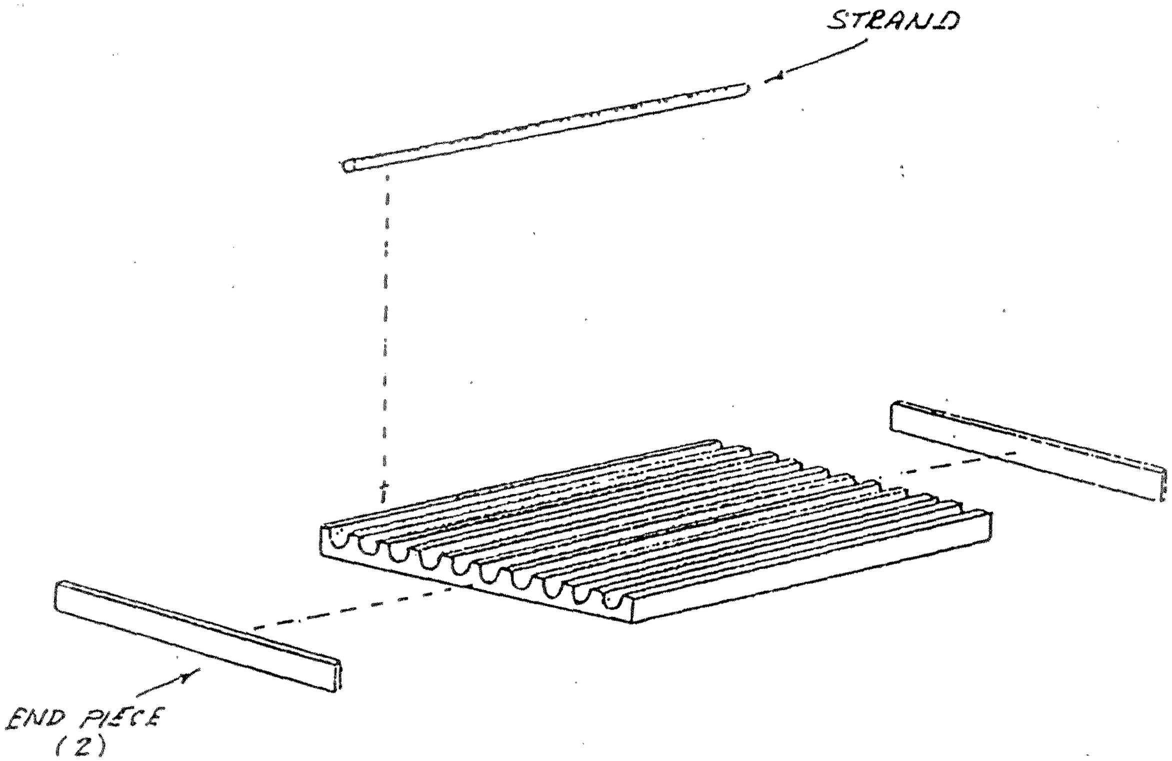
114. Bailey, Richard L. Operational Methods & Safety Procedures for Section 381, 14-15, 1971. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Record on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

Mixing cycles could be as little as 5 minutes or as long as 30 minutes, depending on the nature of the ingredient and the size of the batch; time for the vacuum pump to evacuate the pot and for operators to release the vacuum and lower the pot had to be added to the mix time for each cycle. This procedure might be repeated eight or ten times during the mixing of a single batch of propellant, hence some batches might require a day or two to complete. After the binder was stirred, an anti-oxidant might be added and mixed in, followed by aluminum powder. Depending on the size of the batch, an oxidizer (whether AP or HMX) might be added in one or two steps. If different types or particle sizes of oxidizer were called for, these were each added in separate steps and mixed into the batch. The temperature of the pot jacket and the propellant was constantly monitored and recorded, as were all machine settings and mix times. The last ingredient added was the curing agent (usually an isocyanate compound like IDPI, or isophorone di-isocyanate), since that began the chemical reaction that turned the binder in the mix into a firm rubbery substance. Just prior to this step, an "end of mix" viscosity reading was taken and recorded. To accomplish this, a small sample was removed from the batch and taken to a Haake RotoVisco RV12 rotary viscosity meter in 4234/E-35 (later moved to 4284/E-85). A reading of 5 to 10 kilopoises was considered good; 50 kilopoises was too thick. Following the introduction and mixing of the curing agent, the batch might have a "pot life" of anywhere from 30 minutes to 3 hours. During this period, all casting had to be made with the batch, or the propellant would congeal too much to be castable.

During the last mixing cycles, personnel made the requisite motor casings and sample molds ready for casting. In addition to casting grain, samples were always cast for quality control tests and analyses. Typically, sample castings included tensile testing coupons (referred to as "dog bones" by JPL staff in paperwork because of their shape), burn rate strands and bulk propellant blocks (see Fig. 30). Mandrels were installed along the center axis of motor casings and secured. Usually mandrels were coated with a mold-release compound so they could be more easily pulled from the grain after curing was completed. Mandrels were made of materials like Lucite®, or Teflon®-coated aluminum. Sometimes the assembled motor casings and mandrels were preheated and brought to the mix houses prior to casting of propellants. Preheating was used to partially cure a recently applied liner coating, or to bring the assembly up to the temperature of the propellant being cast into it.

Casting was usually done under vacuum (about 4mm Hg) in order to avoid entraining air bubbles into a motor grain. To accomplish this, the mix pot was removed from the mixer and a



NOTE. SCRAPE EXCESS PROPELLANT FROM TOP OF MOLD.

Fig. 30
Burn Strand Mold as depicted in Standard Operating Procedures

pressure dome affixed to the open top. A chamber containing a motor casing was connected to the bottom of the pot, and the entire assembly evacuated before the valve in the bottom of the mix pot was opened to release propellant into the motor casing. Sometimes the motor casing itself served as the vacuum casting chamber. Bulk propellant blocks and dog bones were cast in special Teflon®-coated molds[115], while burn rate strands were cast to shape in grooved molds ("Figure 1" on page 13 of Standard Operating Procedure No. 2018 Revision 4 displays a burning rate strand mold; see Fig. 31 in this report.) Bulk propellant blocks were "...normally...cast and cured in ½ gallon milk cartons lined with aluminum foil."[116] The casting of viscous propellants was assisted by the installation of a pressure plate on top of the propellant in the mix pot prior to the attachment of the pressure dome. Compressed air could then be introduced between this plate and the dome, and the plate would squeeze the propellant out the dispensing valve on the bottom of the mix pot into the evacuated casting chamber. Casting was conducted as quickly as was prudent, and the mix pot was sent off to be cleaned before the propellant hardened. If personnel did not begin cleaning in time, the job could end up taking months, using acetone and scraping tools to remove all traces of propellant from the pot![117] Waste propellant and the cloths used to wipe down equipment were disposed of as propellant waste and stored for eventual destruction at the burn unit (4249/E-50).

Freshly cast grain and samples were transported promptly to be cured in Buildings 4238/E-39, 4239/E-40 and 4240/E-41, following the safety guidelines for transporting live propellants reviewed above.

The buildings and sites housing the mixers differed from

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115. Barry, J. A. Section 351, Standard Operating Procedure No. 2055 Revision 3: Manufacture and Testing of Physical Property Samples (typescript), 16 January 1992; p. 3 of 33. Record on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.
116. Barry, J. A. Section 351, Standard Operating Procedure No. 2018 Revision 4: Preparation of Cured Propellant Burn Rate Strands (typescript), 8 March 1990; p. 6 of 17. Record on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.
117. Robert L. Ray Interview. Mr. Ray recalled that it took about three months to clean a large pot when the propellant in it wasn't cleaned out in time.

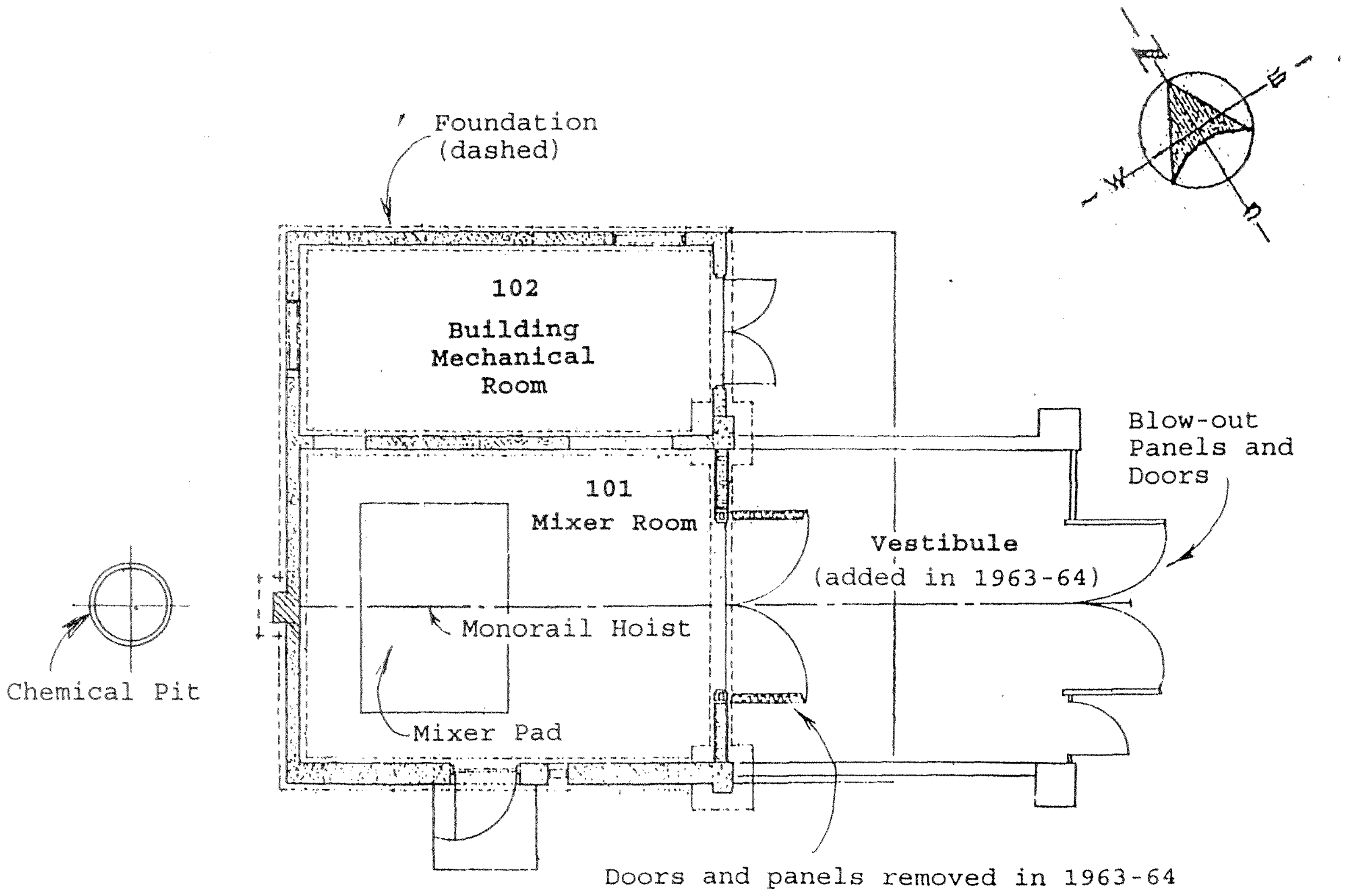

Fig. 31
Plan of Building 4233/E-34, Mixing & Casting

each other. All the buildings began as two room structures with the workspace designated Room 101 and the building equipment room as Room 102. Building 4233/E-34, built in 1962-63 to house the 150-gallon Baker-Perkins mixer, was originally measured roughly 26'-10" x 21'-8". The 20'-2" x 15'-2" mixer room was a 22' high space equipped with a 3-ton air hoist for lifting mixer pots, machinery components, motor casings and the like. The southeastern wall of the room, including the high double doors, was built of wooden framing and insulation to act as blow-out panels in the event of an explosion (Interestingly, this would send gases and smoke roughly eastward, in the same direction as prevailing winds). Adjoining the mixer room to the northeast was the building equipment room which contained the electric water boiler, air conditioning equipment, vacuum pumps, electrical distribution panels and other equipment necessary to the mixer's operation. In 1982, a 16'-2" vestibule was built onto the southeastern wall of the mixer room and the double doors and blow-out panels moved to the new southeastern facade (see Fig. 32). The addition provided more sheltered workspace for personnel inside to cast large motors. Earth-filled revetted steel barricades were constructed to the immediate northeast and southwest of 4233/E-34 to contain the effects of any explosions and prevent debris from striking the main administration building (4231/E-32) or the weigh and control building (4234/E-35). In 1995, 4233/E-34 was rated for a maximum of 5,000 pounds (2,273 Kg) of Class 1.1 material and five personnel.

Building 4236/E-37 was built in 1962-63 and measured 21'-6" x 27'-8 3/8". Its construction and appearance follow the architectural descriptions given above for the design of the solid propellant line. The mixer room is the same size as the original mixer room for 4233/E-34, but the overhead is only 14'-4" high, given that a smaller 25-gallon Bramley mixer was originally installed here (see Fig. 33). Like 4233/E-34, the southeastern wall of the mixer room contains a set of tall double doors and is built to be a blow-out wall. A 1-ton air hoist serves to lift heavy equipment. Adjoining the mixer room to the northeast is the building equipment room which houses machinery analogous to that in 4233/E-34. Building 4236/E-37 appears never to have undergone any renovations or enlargements. In 1995, it was rated for a maximum of 600 pounds (273 Kg) of Class 1.1 materials and five personnel.

Building 4243/E-44 is a multi-purpose structure whose mission has changed many times. It has always housed a mixer, however, as part of the E-42/E-43/E-44 Preparation Complex. Like 4233/E-34 and 4236/E-37, 4243/E-44 was built in the first construction phase of the solid propellant line. Initially it was a two-room building measuring 24'-3 5/8" x 26'-2"; Room 101

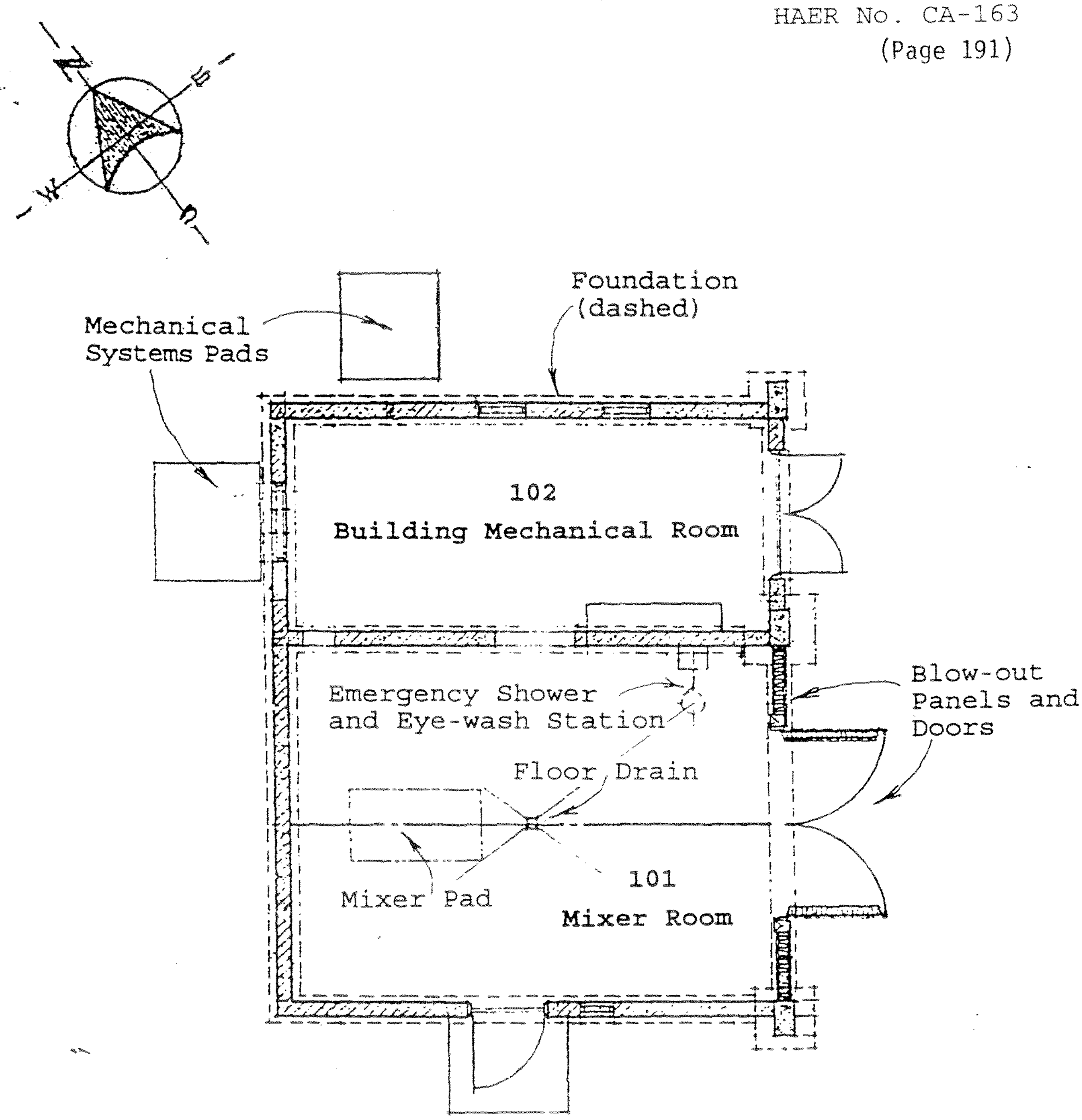

Fig. 32
Plan of Building 4236/E-37, Mixing & Casting

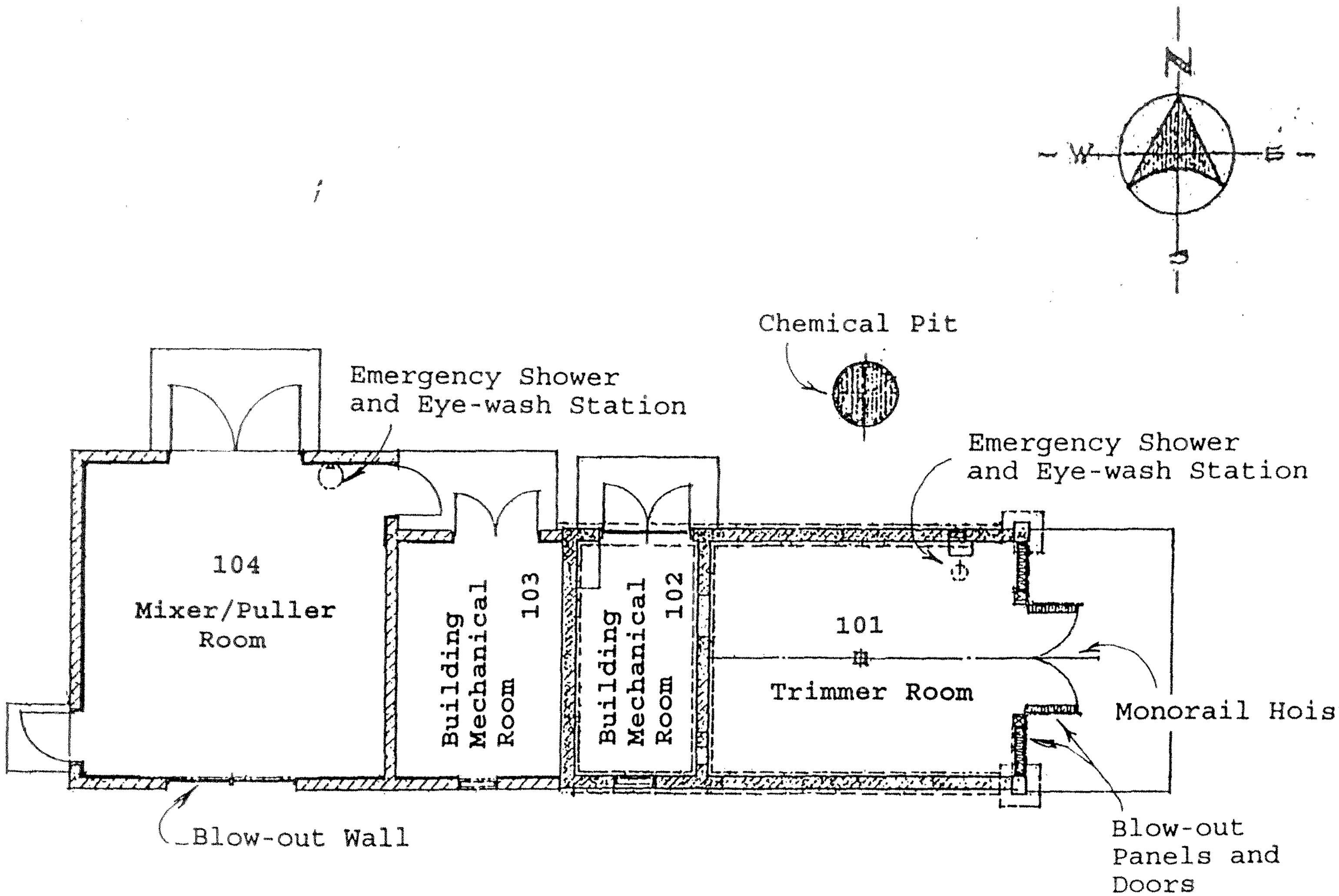

Fig. 33
Plan of Building 4243/E-44, Propellant Preparation

took up the eastern two-thirds of the structure and was designated for "propellant preparation" (mixing) in the engineering drawings. A 5-gallon Bramley mixer was the first machine to be installed, later replaced by a 1-gallon Baker-Perkins machine. The western end of the building was designated Room 102, the building equipment room. Like 4233/E-34 and 4236/E-37, the side of the preparation room having double doors and blow-out panels faces nearly east; a 1-ton monorail air hoist is suspended from the overhead to assist in moving heavy equipment. At a later date, the building was in effect doubled in size and function by the addition of another workroom (Room 104) and a building equipment room (Room 103) to the western end of the original structure (see Fig. 34). Design work was performed by Ben Beckler & Associates, Architects and Engineers of North Hollywood, California.[118] Room 103 adjoined but did not connect internally with Room 102. Room 104 was 20'-0" square and had a 19'-4" ceiling, higher than Room 101. Like Room 101 an overhead monorail air hoist was installed. The southern side of Room 104 incorporates an 8' wide blow-out panel, while double doors give access on the northern side. The rating posted on the building in 1995 was for a maximum of 1,000 pounds (455 Kg) of Class 1.1 materials and four personnel.

Building 4285/E-86 was built in 1977 with an 8'-0" diameter by 19'-0" deep casting pit designed to preheat casings (see HAER photo CA-163-GG-3), but the equipment was never installed due to changes in programs and funding. Building 4285/E-86 was adapted for other purposes, though the casting pit remained in place in 1995.

Curing

Three buildings-- 4238/E-39, 4239/E-40 and 4240/E-41-- were erected in 1962-63 to serve as curing ovens for newly cast grain and propellant samples. Cast propellant could come from buildings 4233/E-34, 4236/E-37, or 4243/E-44. On occasion they were used to dry freshly cleaned hardware or preheat motor casings for propellant casting. Each building was limited to a maximum of 600 pounds (273 Kg) of Class 1.1 propellants and three personnel. All are two-room buildings measuring 14'-8" x 20'-0" and following the general architectural description outlined previously (see Fig. 35). A heavily insulated 5'-4" wide by 12'-0" high steel door on the southeast facade of each building gives entry to the curing chamber, which has a concrete floor and is equipped with sprinklers to combat fires. The windowless walls are finished in ¼" thick asbestos board, behind which lies 8" of

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[118]. The engineering drawings are undated.

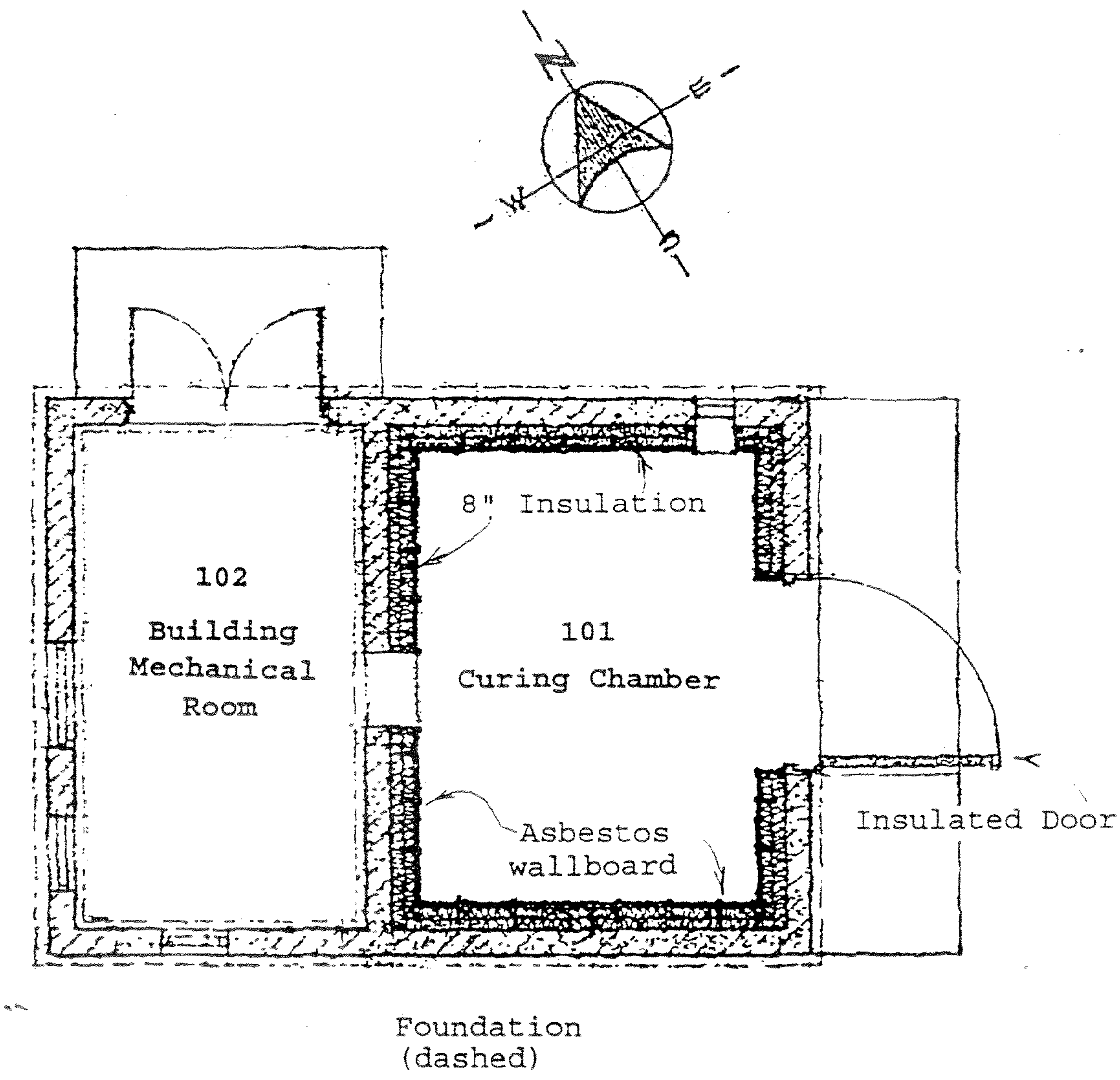

Fig. 34
Plan of Buildings E-39/40/41, Propellant Curing

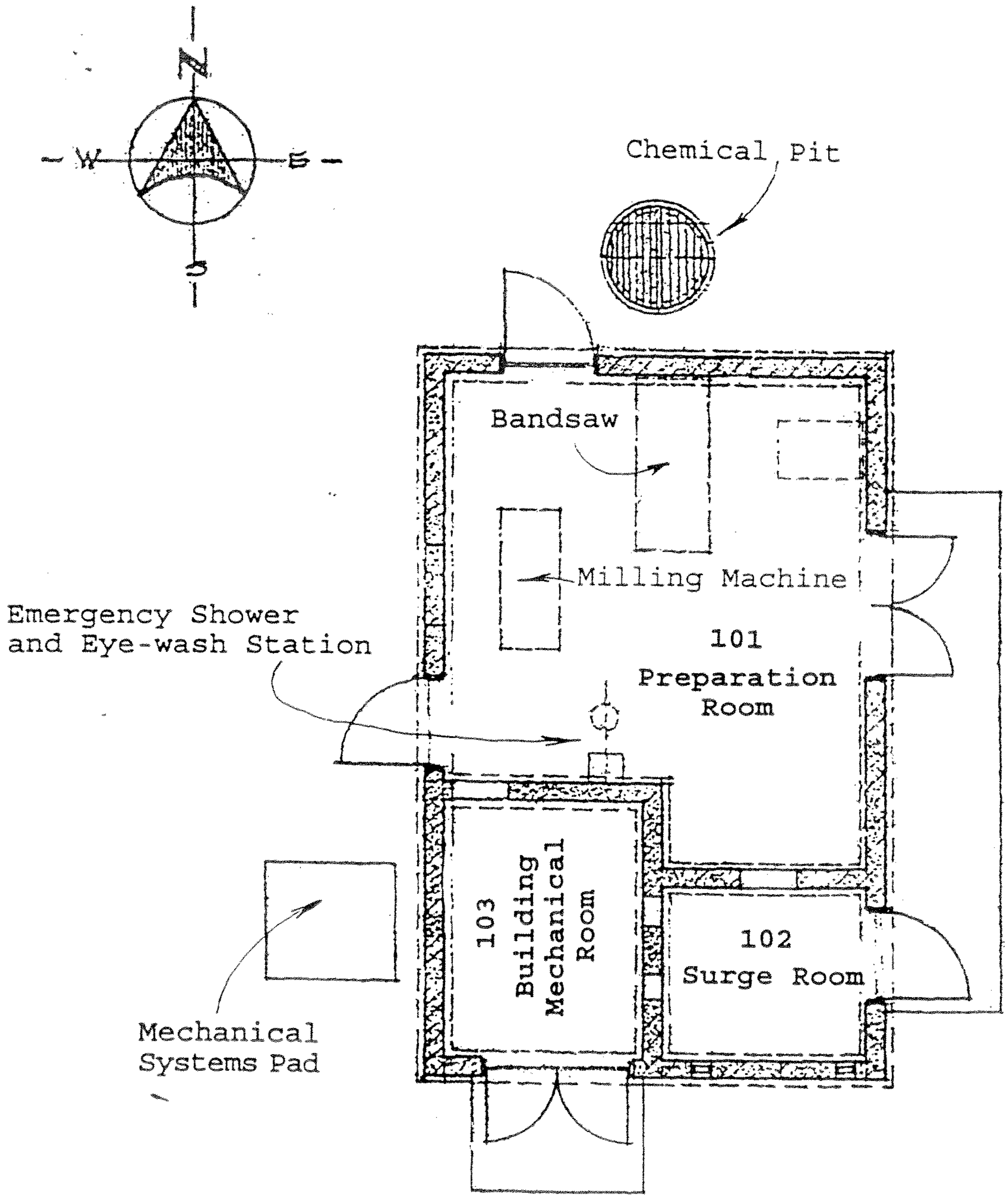

Fig. 35
Plan of Building 4241/E-42, Propellant Preparation

fiberglass insulation. Freshly cast motors and samples were placed in the curing chambers and left for 2 weeks at 140°F so that the curing agent and binder had the optimal time to complete the chemical reaction that converted the binder into rubber. Heat was supplied by hot air produced in the building mechanical room; air was exhausted from the curing chamber through a wall vent with a grill in the northeastern facade; this purged the chamber of any solvent fumes from motors or drying hardware. Access to the mechanical room was from the north facade, there is no interior door between this room and the curing chamber.

Personnel entering the curing chamber had to wear flame retardant clothing and safety goggles. Casings and samples had to be properly supported so that no spillage occurred, and propellant scraps were not allowed to accumulate on the floor. A recorder in the curing chamber kept track of the temperature, and an amber warning light was displayed whenever curing was performed.[119] When curing was completed, further processing was necessary to prepare and condition propellants for tests.

Preparation

The preparation buildings-- 4241/E-42, 4242/E-43, and 4243/E-44-- as a group carried out several functions with Building 4242/E-43 as their control center. Personnel in Building 4241/E-42 sawed, cut and milled propellant samples to the requisite shapes and sizes for physical tests, whereas personnel in Building 4243/E-44 worked on cast motors. In addition to mixing liner and propellant formulations, 4243/E-44's

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[119]. Bailey, Richard L. Safety Rules, Solid Propellant Engineering Section 381, Building Nos. E-39, E-40, and E-41, all dated 15 January 1971. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Record on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

tools removed mandrels from motor grains and trimmed and shaped the grain to final design size. The three buildings were built in the same phase of the solid propulsion line's development, but each are of a different size and layout. As with all the other buildings thus far, operators set the machines up with samples for sawing or milling, but actually performed the work from a remote location in Building 4242/E-43, monitoring progress via closed-circuit television and audio equipment.

Building 4241/E-42 is a 16'-0" x 25'-4" three-room structure. Room 101 holds a Kalamzoo Model 8-C-D bandsaw with Teflon®-coated saw blade, a milling machine manufactured by Index, and a workbench with electrically grounded, explosion-proof electronic scales as well as selected hand tools (see Fig. 36). The machine tools were outfitted with sprinkler systems to extinguish any fires that might occur as the result of sawing or milling propellants. Three types of propellant test samples were made here: "dog bones" (or tensile bars), burn rate strands, and special specimens cut from bulk propellant. Safety Rules from 19 August 1981 declare that the propellant limit for this room is 1,000 pounds (454 Kg) and the personnel are limit to four. As at other buildings, the fire suppression (or deluge) and other safety systems had to be checked out periodically.

The "dog bones" were machined under remote control by a vertical milling machine to produce a precise shape and size suitable for tensile tests (see and HAER photo CA-163-S-1). Figure 36 shows a dimensioned drawing of a "dog bone".[120] The "dog bones" were ordinarily milled from cast and cured propellant slabs approximately 9/16" by 1-1/16" by 5" in size, but slabs could also be cut from cast and cured bulk propellant on the bandsaw. The SOP for manufacture and testing of samples indicates that a maximum of six "dog bones" should be milled, three at a time in a specially fabricated brass vise mounted on the milling machine table. (If less than three blocks were required, brass spacer bars were substituted for absent propellant blocks). The milling cutter operated at 300 revolutions per minute, and several set-ups were necessary to produce the final product. The operator took special care not to tear or crack any samples, since such defects would upset the tensile tests. Chips of scrap propellant were caught by a water-

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[120]. Barry, J. A. Section 351, Standard Operating Procedure No. 2055 Revision 4: Manufacture and Testing of Physical Property Samples (typescript), 16 January 1992; p. 13 of 33. Record on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

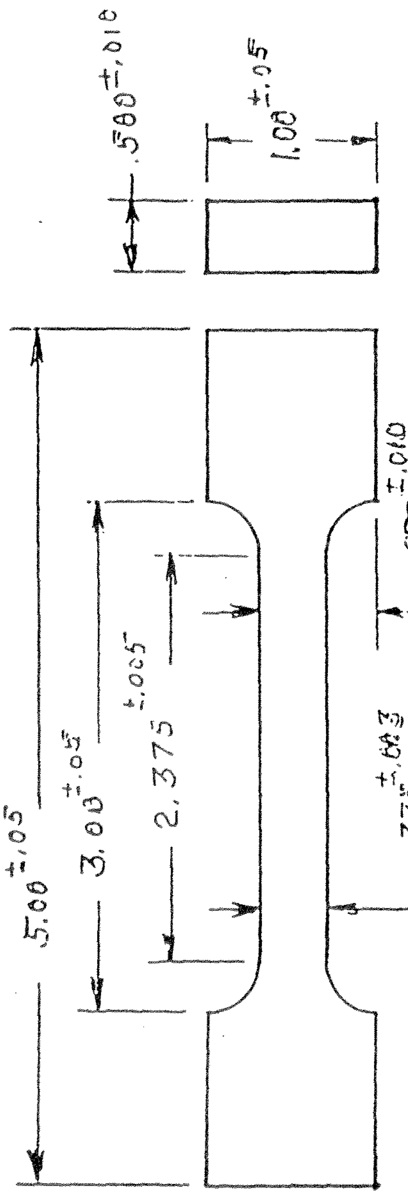

Fig. 36
Dimensioned Diagram of
Standard JPL Propellant Coupon ("Dog bone")

bath vacuum machine operating in conjunction with the milling machine, and waste was disposed of according to SOP. The tensile tests on these bars had to be made the same day the bars were milled. In addition to wearing flame retardant clothing and goggles, the milling machine operator had to ground himself to the machine during the times he had to manually set up and adjust the machine and vise in the presence of propellant chips and dust.

Burn rate strands could be produced by casting them in a special mold, or they could be cut from a propellant block. In the first method, cast strands were cut to 6" length by hand using an "X-Acto knife™"; in the latter, strands were cut to 0.3" diameter by 6" lengths with a special round cutter mounted on the milling machine table. The milling table was operated by hand (see Fig. 37). Further operations required that holes be drilled in the burn strands for the insertion of ignition wires. Some samples were also coated with an inhibitor; the inhibitor was made up and heated in a bread pan for 12 minutes at 140°F to 180°F in a small air circulating oven. The operator then laid the strands in the bread pan and coated them using a brush, or else dipped them. Following this was a 4-hour fast-cure at 140°F to 160°F or a 16-hour normal cure at 140°F minimum temperature. Strands were then placed in a pan and covered with aluminum for transportation to the Building 4267/E-68, Ignition Laboratory.

Rough sawing of propellant blocks and preparation of special test samples was accomplished by remote control on the bandsaw after the samples were set up by hand; the blade speed of the saw was typically 96 feet per minute, but this varied considerably depending on propellant characteristics. Chips and dust were vacuumed up by a water-bath vacuum; operators made final clean up with an anti-static brush. Further specialized shapes could be cut by hand or on the milling machine. In all operations, an amber light was displayed outside when hand operations were in process, and a red light when remotely controlled procedures were under way. Extra care was taken when preparing samples containing HMX. Extra filters were installed on water-bath vacuums; these were disposed of as HMX in sealed containers per SOP.

Room 102 is a propellant magazine (or ambient oven) termed the Surge Room, because it "absorbed" temporary surges in the volume of propellants being processed. It was rated for 200 pounds (91 Kg) of Class 1.1 materials and a maximum of two personnel. Completed motors and samples sufficient for only one day's work were kept here during daylight hours--no overnight storage was permitted. Room 103 served as the building equipment room and occasionally as ready storage of motors and propellant

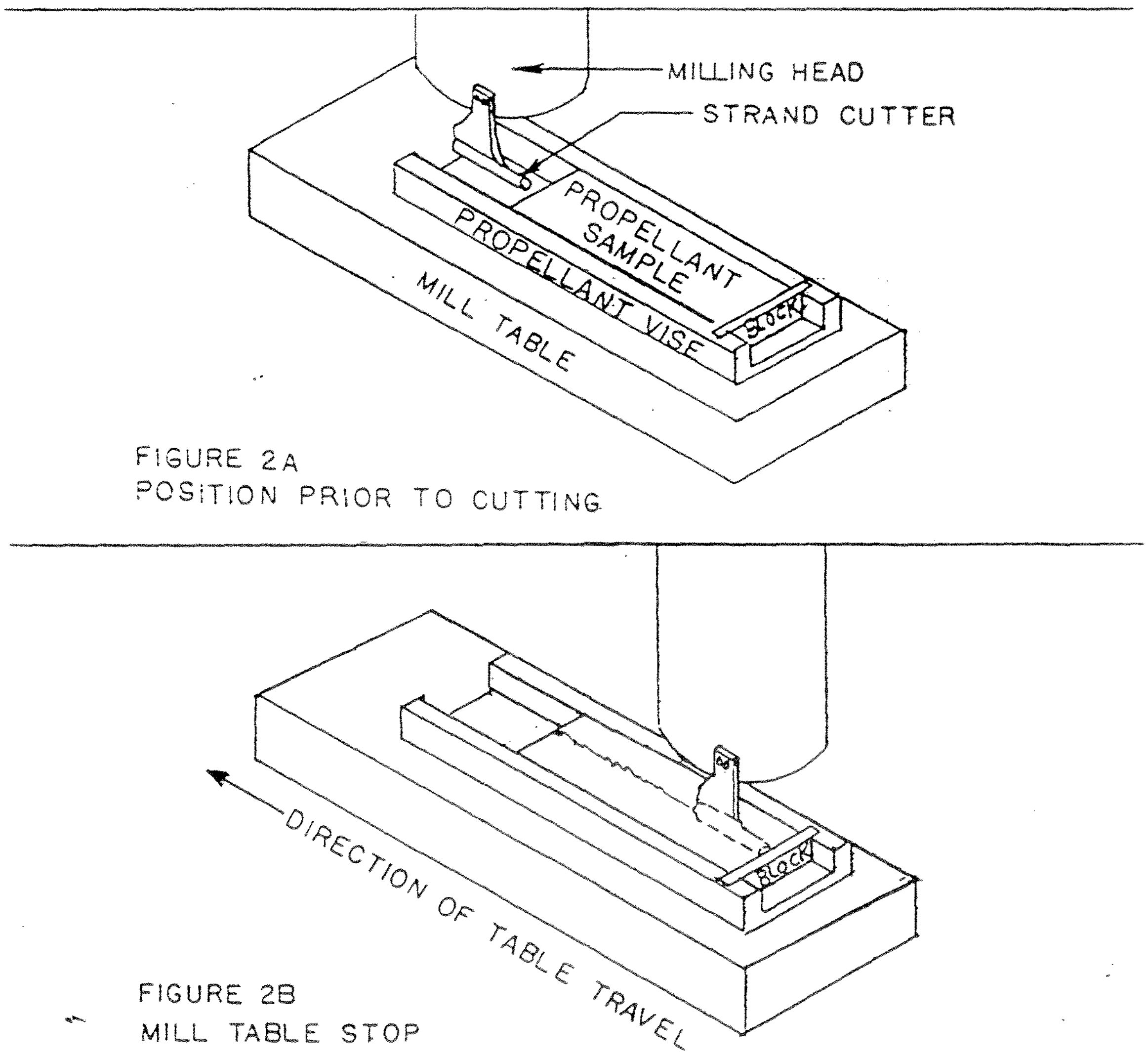

Fig. 37
Diagram Showing Process of
Cutting Burn Strands from Propellant Blocks

samples.

Building 4242/E-43 is 9'-4" x 14'-8" concrete block structure that served as the control center for the preparation buildings. In it were the controls for operating the machinery and warning lights at 4241/E-42 and 4243/E-44, as well as television and audio monitoring equipment. An area rest room was included, along with the privilege of smoking in the building. Propellants were not allowed in this building, but there was no restriction on the number of personnel (see Fig. 38). Protective blast barriers were constructed in 1964.[121]

Building 4243/E-44 is described above under mixing. In addition to mixers, 4243/E-44 also contained a mandrel puller in Room 104 and a specially designed vertical lathe for trimming grain in Room 101. "The remote mandrel puller consists of a fixed structural steel frame and a hydraulic cylinder mounted on this frame such that a force may be applied to remove the mandrel from the rocket motor. A hydraulic power supply furnishes hydraulic fluid to the pulling cylinder at pressures up to 1000 psi."[122] An operator simply mounted a rocket motor in the frame, attached proper grounding wires and restraining hardware, engaged a clevis in the bottom of the hydraulic ram with a pin, and left the building for the actual pulling operation. When the procedure was competed, operators returned to remove the mandrel to storage, removed the rocket engine for further treatments, and vacuumed up any propellant dust for disposal.

The trimmer was a vertical lathe specially designed to turn the ends and bores of propellant grains; its manufacturer has not been identified. "Since manually trimming of live charges is both slow and dangerous, a machine was designed to do this operation remotely...There are two unique features on this remote charge trimmer: (1) The propellant grain is trimmed in a

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[121]. California Institute of Technology, Jet Propulsion Laboratory. **Barricade #3 @ Bldg. E-35, Edwards Test Station, Edwards, California.** 23 March 1964; JPL Drg. No. E35/8-1. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

[122]. Freeman, R. J. Section 351, Standard Operating Procedure No. 2068: Manufacture and Testing of Physical Property Samples (typescript), 18 October 1988; p. 3 of 17. Record on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

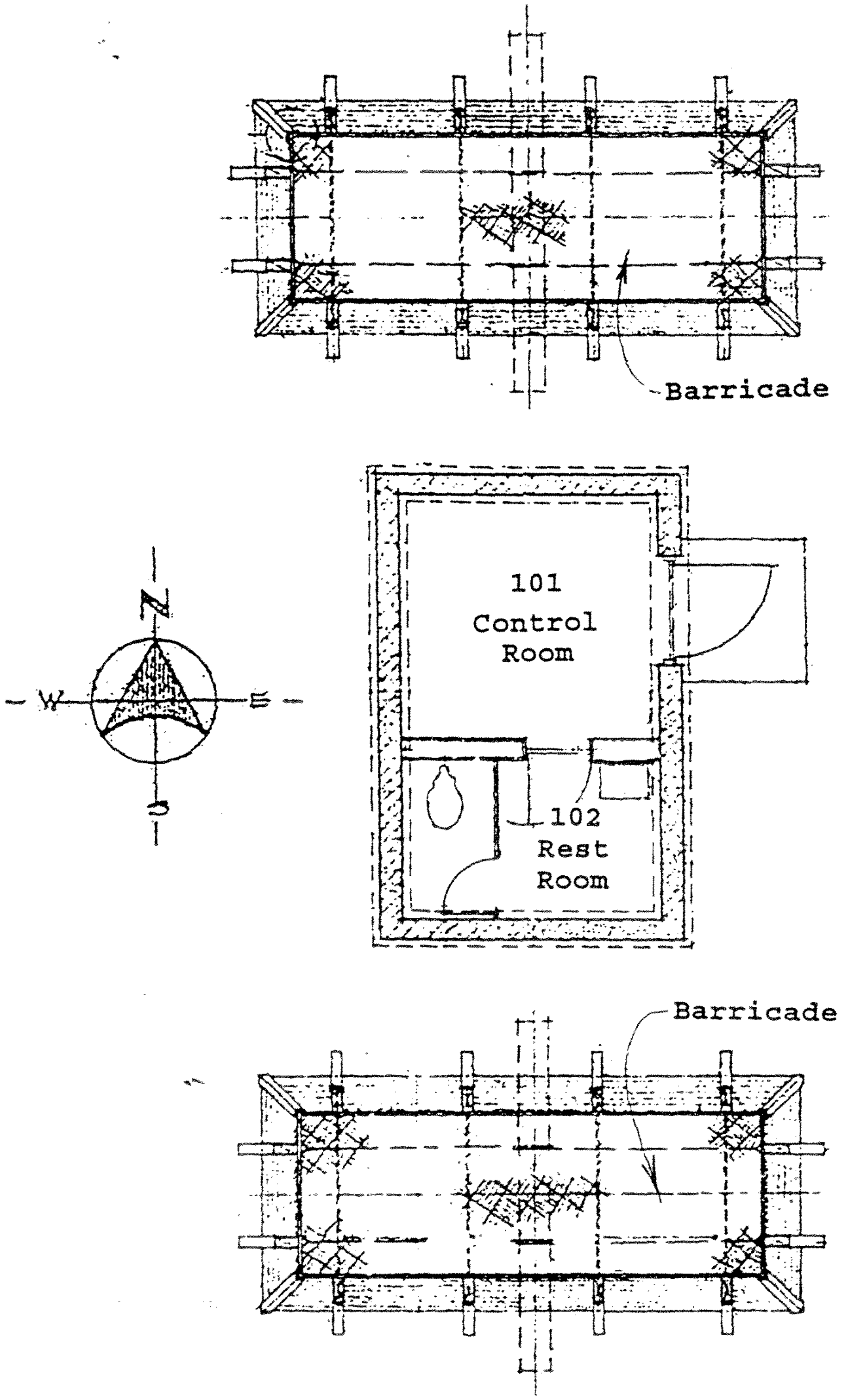

Fig. 38
Plan of Building 4242/E-43, Preparation Control

vertical position (2) The propellant grain can be trimmed to a desired contour."[123] (See HAER photo CA-163-T-1 for a view of this machine; photo CA-163-T-2 shows the manually operated machine that it replaced.) The machine could turn propellant grain from 8" to 14" in diameter, and specially contoured bore turnings could be effected by a hydraulically operated template follower connected to the turning tool. A metal template shaped to the desired contour was mounted in the machine, and a follower was engaged to trace its edge and adjust the cutting tool accordingly. D. Bailey's manuscript instructions on the machine's settings indicate that it could turn a 10" diameter charge with only 0.005 inches' out-of-roundness and a 0.030" taper along the 24" length. The SOP for this machine indicates that this machine was later used intensively for trimming standard BATES grains (for Ballistic And Test Evaluation System). BATES grains were cast to fit twelve-inch diameter flanged tubes made of steel in various lengths (as opposed to actual motor casings used in design tests).[124] Motors were always trimmed with the nozzle end down. When personnel were finished with the machine for the day, all parts were washed down with acetone and "Kimwipes™." The used wipes were deposited in the propellant collection drum along with all floor sweepings.

The trimmer was powered by explosion-proof motors and hydraulic systems. It produced waste ribbons of propellant which dropped via a chute into a VeloStat® lined 30-gallon fiberboard drum. A closed circuit television camera could be mounted to view up the waste chute and verify that cutting was proceeding based on the continuing appearance of a waste ribbon. A mirror was also mounted inside the machine that permitted the television camera to capture an image of the cutting tool at work. The tool was operated remotely from 4242/E-43 once correct setup had been personally verified by the operators.

Conditioning

Following preparation, JPL personnel subjected motors and assorted propellant test specimens to long periods at temperatures varying from -40°F to +200°F. This step was somewhat analogous to "soaking" a liquid-fueled engine in the

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123. Bailey, D. "Settings for Remote Charge Trimmer, E-44" (handwritten manuscript), 9 March 1964; p.1. E-32, Room 35, File 1, Drawer 2, JPL Edwards Facility Collection. Manuscript on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

124. Robert L. Ray Interview.

test cells of the liquid propulsion area of ETS. Motors and samples were exposed to different temperature ranges for extended time periods to see how various propellants withstood conditions simulating storage or inactive periods in outer space. Samples could be tested at various points in the conditioning cycle, and motors test fired to evaluate the effects of the treatment on the chemical and structural stability of propellants.

The safety rules and the propellant and personnel limitations were the same for each building.[125] Safety rules were substantially the same as for the curing buildings, but the allowable propellant quantities were considerably higher. Each of the conditioning structures could contain up to 10,000 pounds (4,340 Kg) of Class 1.1 materials (Class 1.3 at 4245/E-46), and maximum of four personnel could be present in the building at one time.

The conditioning treatments took place in Buildings 4244/E-45 through 4248/E-49, all of which are two room structures. Room 101 is the conditioning room, and Room 102 is the machine room for environmental systems. Each structure subjected its contents to a specified temperature range. Buildings 4244/E-45 and 4248/E-49 were designated to handle conditioning (or "storage" as it is referred to in the engineering drawings) at ambient temperatures. Building 4245/E-46 operated at a temperature range from -40°F to +20°F. Buildings 4246/E-47 and 4247/E-48 operated from +100°F to +200°F, though because of a fire, 4247/E-48 was used only for waste storage in 1995. Because of the differences in environmental mission among some of the buildings, their structure and dimensions varied slightly, though specific construction details and their architecture were common to all.[126]

Building 4244/E-45 is a 16'-6" x 26'-0" poured reinforced

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125. See Safety Rules, Solid Propellant Engineering Section 381, Building Nos. E-45 through E-49, all dated 15 January 1971. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

126. Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California. **Edwards Test Station Complex - Phase II, Typical Structural Sections & Details--Bldgs E-33 to E-49**, Sheet S-2, 26 June 1962; JPL Drg. No. E33/8-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

concrete structure with 6′ x 10′ steel double doors ¼" thick opening to the conditioning room on the southeast side (see Fig. 39). The apron to the conditioning room doors was fitted with a steel grate for cleaning one's shoes. The mechanical room doors open on the northwest side; the machinery inside supplied air movement into the conditioning room and out through a vent over the conditioning room doors.[127]

Building 4245/E-46 is a 17′-4" x 30′-8" concrete block structure. A single 7′-0" x 10′-6" insulated steel door opened into Room 101 from the southeast side, while Room 102 was entered from the northeast side of the building (see Fig. 40). Not only were the walls of Room 101 heavily insulated, but the floor structure was honeycombed with air ducts to promote thorough, even heating of the room (see HAER photo CA-163-II-1 for a photo of 4245/E-46 when the floor was under construction). Hot air was supplied from Room 102 through underground 12" diameter Transite (pressed asbestos) ducts, from which branched 2-1/8" diameter copper pipes that conducted air from the 12" ducts to the spaces under the floor. The rooms in 4245/E-46 were of nearly equal size.[128]

Buildings 4246/E-47, 4247/E-48 and 4248/E-49 were each 17"-4" x 24′-0" concrete block structures in which Room 101 enclosed over twice the floor are of Room 102 (see Fig. 41). Each conditioning room had 8" of fiberglass insulation and finished

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[127]. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Propellant Storage Magazine, Floor Plan Sect's & Elev's,** no date; JPL Drg. No. E45/1-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

[128]. Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Magazine Bldg: Mechanical Plans, Sections, Refrig[eration] Piping for Bldg. E-46,** Sheet MP-21, 26 June 1962; JPL Drg. No. E46/3-2. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

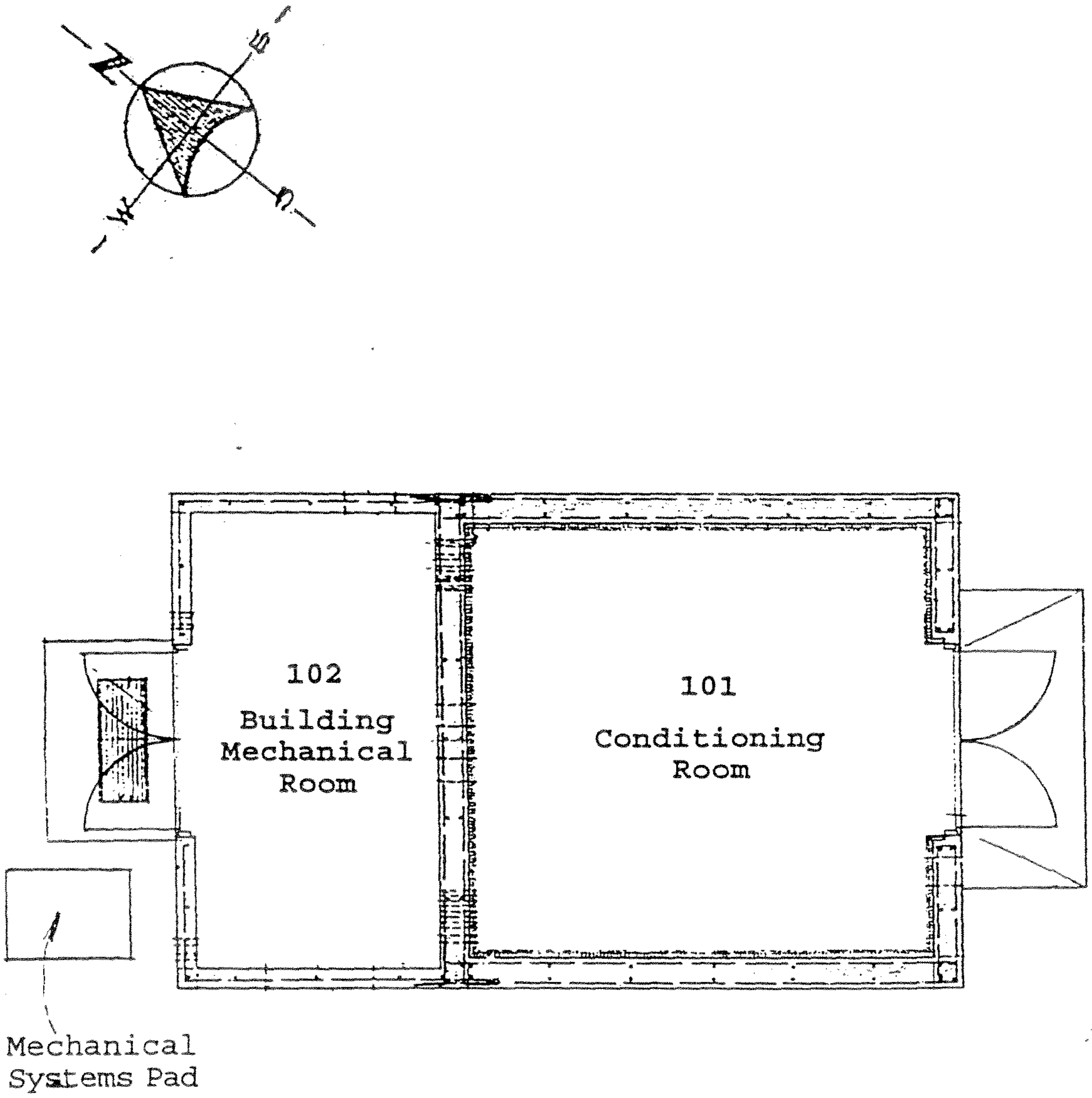
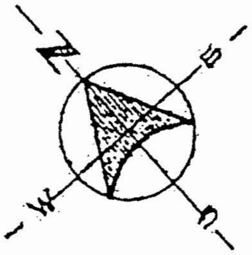


Fig. 39
Plan of Building 4244/E-45, Propellant Conditioning



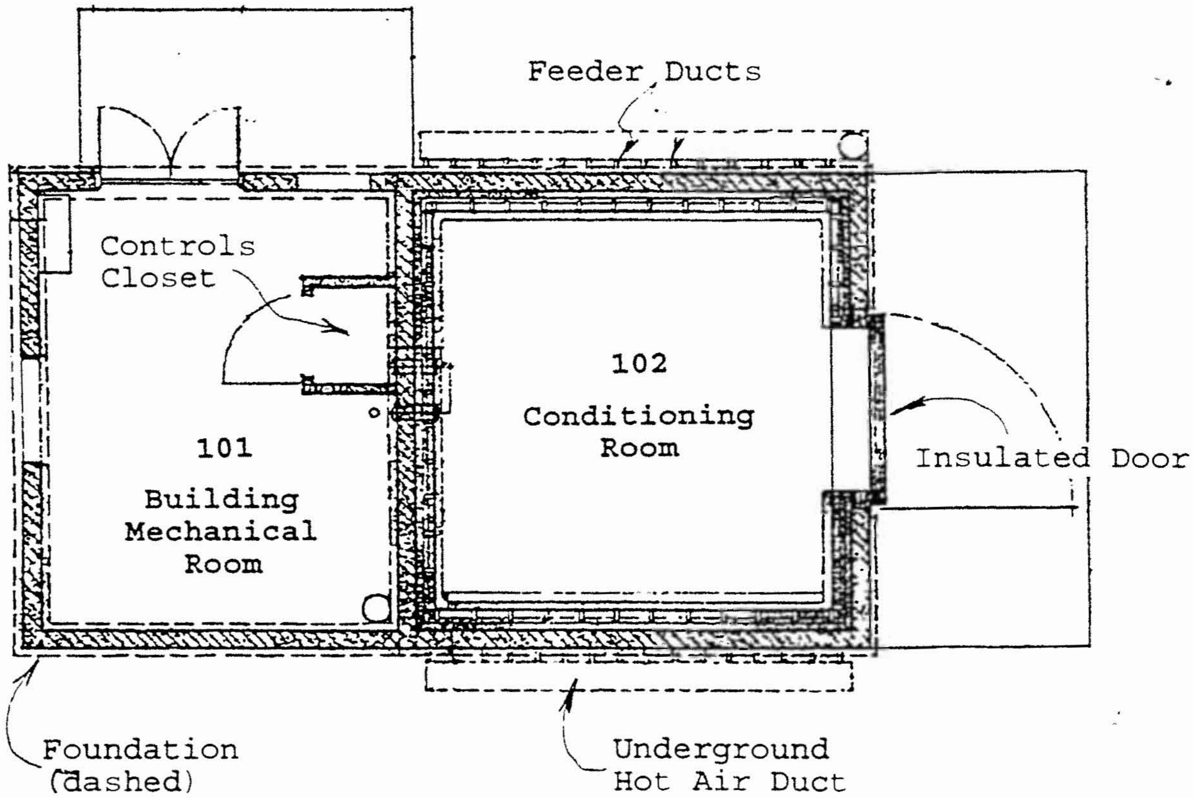


Fig. 40
Plan of Building 4245/E-46, Propellant Conditioning

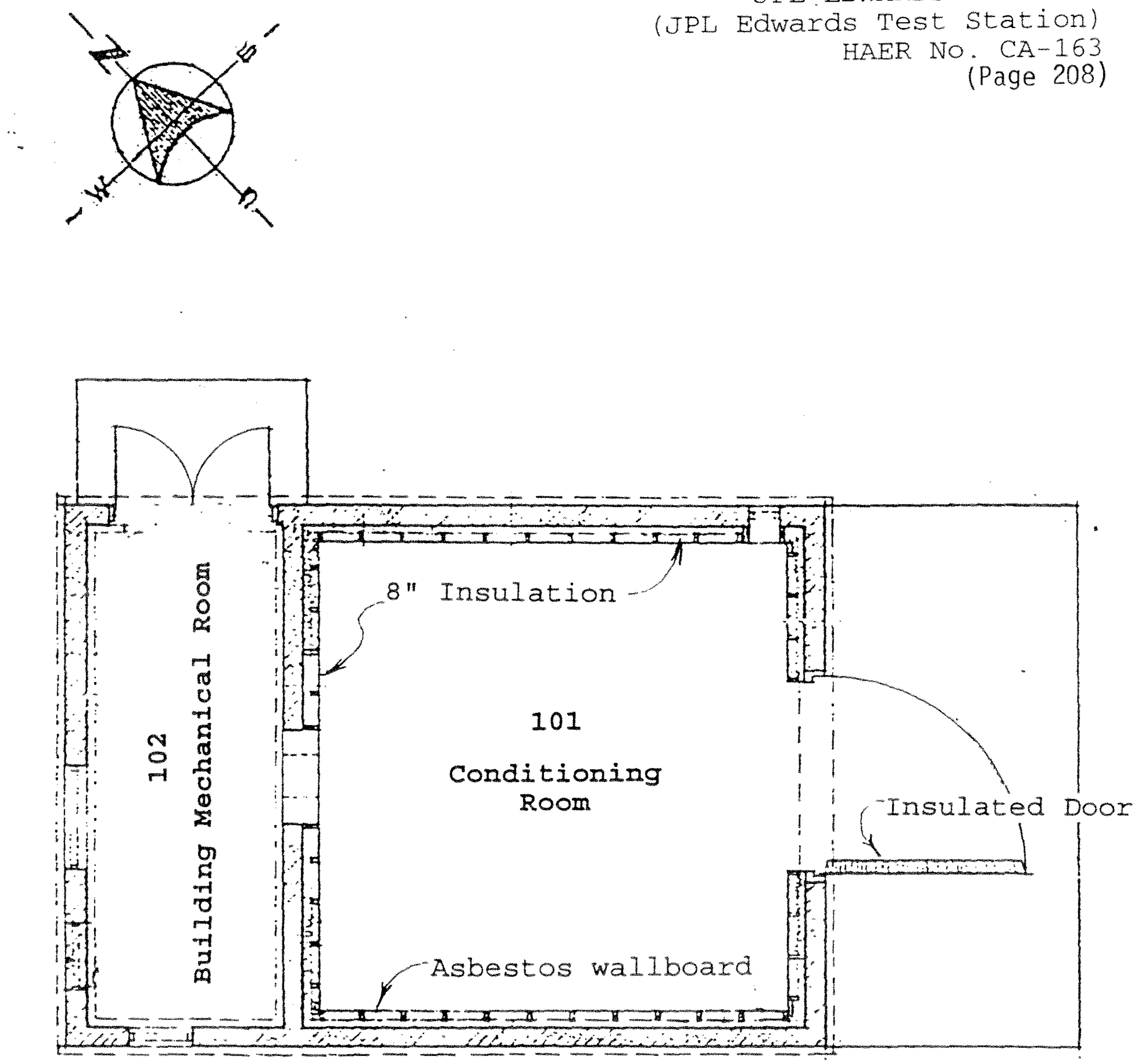


Fig. 41
Plan of Building E-47/48/49, Propellant Conditioning

surfaces of 3/16" thick cement asbestos board.[129] Buildings 4246/E-47 and 4247/E-48 were originally built with hot water boiler units.[130] Later, these units were removed, and electric "Cal-rods" substituted for heat sources. The roof of 4247/E-48 burned during a conditioning cycle; according to Robert Ray, the fire occurred after working hours and burned for a long time because the facility guard could not see it from his guardhouse.

Sterilization

At one time, NASA programs called for an extreme conditioning process for solid propulsion motors. NASA ordered heat sterilization of spacecraft destined to land on other planets in order to ensure the spacecraft could introduce no microbial contamination to an alien world. NASA specifications required a motor for a Viking (Mars) spacecraft to withstand seven cycles each 54 hours long at 275° for propellant type approval and five 54 hour cycles at 257°F for flight approval.[131] An autoclave in Building 4272/E-73 subjected JPL

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129. Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Magazine: Floor Plan, Elevations, Section & Schedules for Bldg's E-47, E-48, E-49,** Sheet A-46, 26 June 1962; JPL Drg. No. E47/1-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

130. Robert L. Ray Interview.

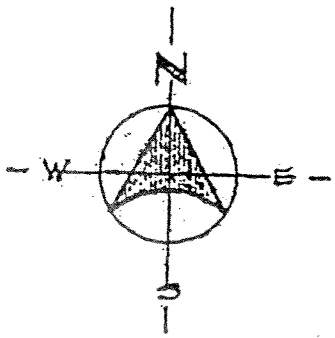
131. Anderson, F. A., S. H. Kalfayan, and C. A. Wilkins. "Heat Sterilizable Propellant Development." 1980 JANNAF Propulsion Meeting, Vol. 5; Laurel, MD: Johns Hopkins University, Applied Physics Laboratory, Chemical Propulsion Information Agency, 1980:181.

motors to repeated long cycles of 275°F heat to develop propellant formulas which would withstand this sterilization process while retaining all other required characteristics. At these elevated temperatures, JPL looked for loss of propellant mass, shrinkage, slumping, and chemical decomposition of the binder, oxidizer and/or insulation. Special treatments were investigated. During the sterilization tests, motor grains were weighed, measured and X-rayed for internal faults. JPL discovered that dissolving, recrystallizing and regrinding ammonium perchlorate with a phosphate dopant (ammonium phosphate monobasic, $NH_4H_2PO_4$) made the oxidizer much more stable at high temperatures; the use of unsaturated polymers such as polybutadienes as binders made for stable, dependable binders. One particular propellant formulation survived 17 sterilization cycles and fired successfully, demonstrating that the propellant formula developed for it was more than up to NASA's demands for the interplanetary program.

The Safety Rules for Building 4272/E-73 bill it as an Environmental Conditioning Building limited to 10,000 pounds (4,545 Kg) of Class 1.1 propellants and three personnel; it could subject propellant and loaded motors to temperatures from -90°F to +400°F using a large autoclave. It was built of reinforced concrete block in 1965 and measures 19'-4" x 22'-0"; engineering drawings bill it as the "Sterilization Facility" and the Real Property Records term it the "Sterilization Laboratory." Operators placed motors in the autoclave, using gloves whenever they were not at ambient temperatures. Flame retardant clothing had to be worn at all times. Temperatures and cycle times were dependent upon the test program requirements (see Fig. 42).

Physical Properties Tests

A consistent program of propellant development required methodical testing and quantification of a propellant formula's characteristics in each step of its manufacture. These tests were of many kinds. Propellant could be weighed, measured, X-rayed, pulled apart, struck, scuffed, zapped with electric sparks, compressed, and burned under controlled conditions. Uniaxial tensile tests measured the tensile strength of propellants using a model 4505 Instron machine; these tests were conducted in room 107 of 4234/E-35 until they were moved in 1978. Photographic evidence from JPL archives indicates that tensile tests were conducted in Building 4285/E-86 in 1989 (see HAER photo CA-163-GG-2). X-ray images were once made in a test bay at 4271/E-72, Test Stand "E", but these were later moved to the newly constructed X-Ray facility where a more powerful X-ray machine was installed. Tests that might result in ignition or those that actually burned propellants were conducted at



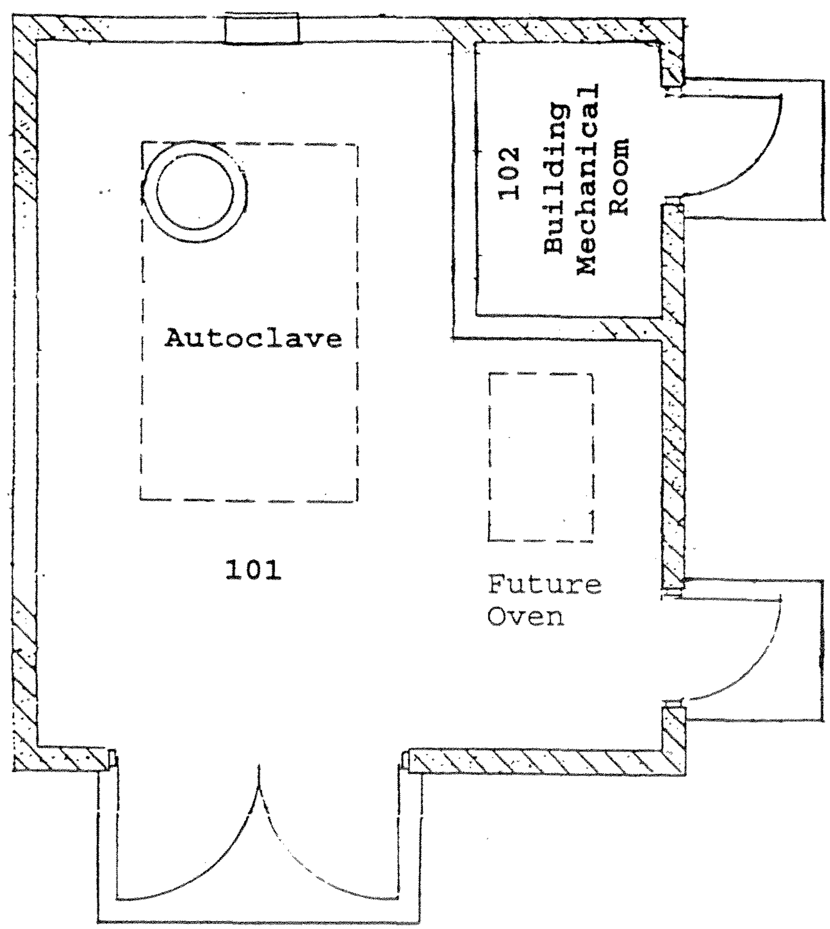


Fig. 42
Plan of Building 4272/E-73, Sterilization Facility

4267/E-68, the Ignition Lab. All tests employed complex correction factors for scaling the results up to full-size motors; such scaling is "...not a linear process."[132] Tests made at Test Stand "G" (Vibration Facility) and Test Stand "E" were necessarily of full-sized motors, so correction factors were unneeded there.

Non-combustion Tests

Building 4234/E-35 is discussed above; Building 4282/E-83, Technical Services Facility, was constructed in 1982 as a 40'-0" x 22'-8" two-room concrete block structure. It was almost immediately enlarged in 1983 to a 70'-8" x 44'-8" structure containing seven rooms (see Fig. 43).[133] Room 101 was dedicated to instrument calibration, Room 102 to instrument repair, Room 103 to transducer calibration. Room 105 was designated a clean room, and Room 106 as the dressing room access to the clean room; Rooms 105 and 106 were in the original structure. Room 106 was a chemical laboratory with a storage area designated as Room 107. The balance of rooms (108 to 111) were for a lavatory, janitorial closet, corridor and entry vestibule. Two exterior "bottle storage" areas were constructed on the eastern facade.

Viscosity Tests

The SOP for use of the Haake Rotovisco RV12 Viscometer[134] indicates that operators must wear fire retardant coveralls, safety glasses and rubber gloves when handling propellants and ensure that all equipment is properly grounded. Propellant is transported from the mixer to the viscometer in a stainless steel beaker stored inside an insulated VeloStat® 1 quart container. The viscometer cup is filled with approximately 10 grams of

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132. Robert L. Ray Interview.

133. California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Addition to Technical Services Facility E-83, E.T.S. Floor Plan, Schedules and Details,** Sheet A-2, 19 June 1981; JPL Drg. No. E83/15. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

134. Rivkin, S. N. Section 251, Standard Operating Procedure No. 2067, Revision 2. "Viscosity Measurements of Solid Propellants using the Haake Rotovisco RV12 Viscometer," 25 October 1988. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

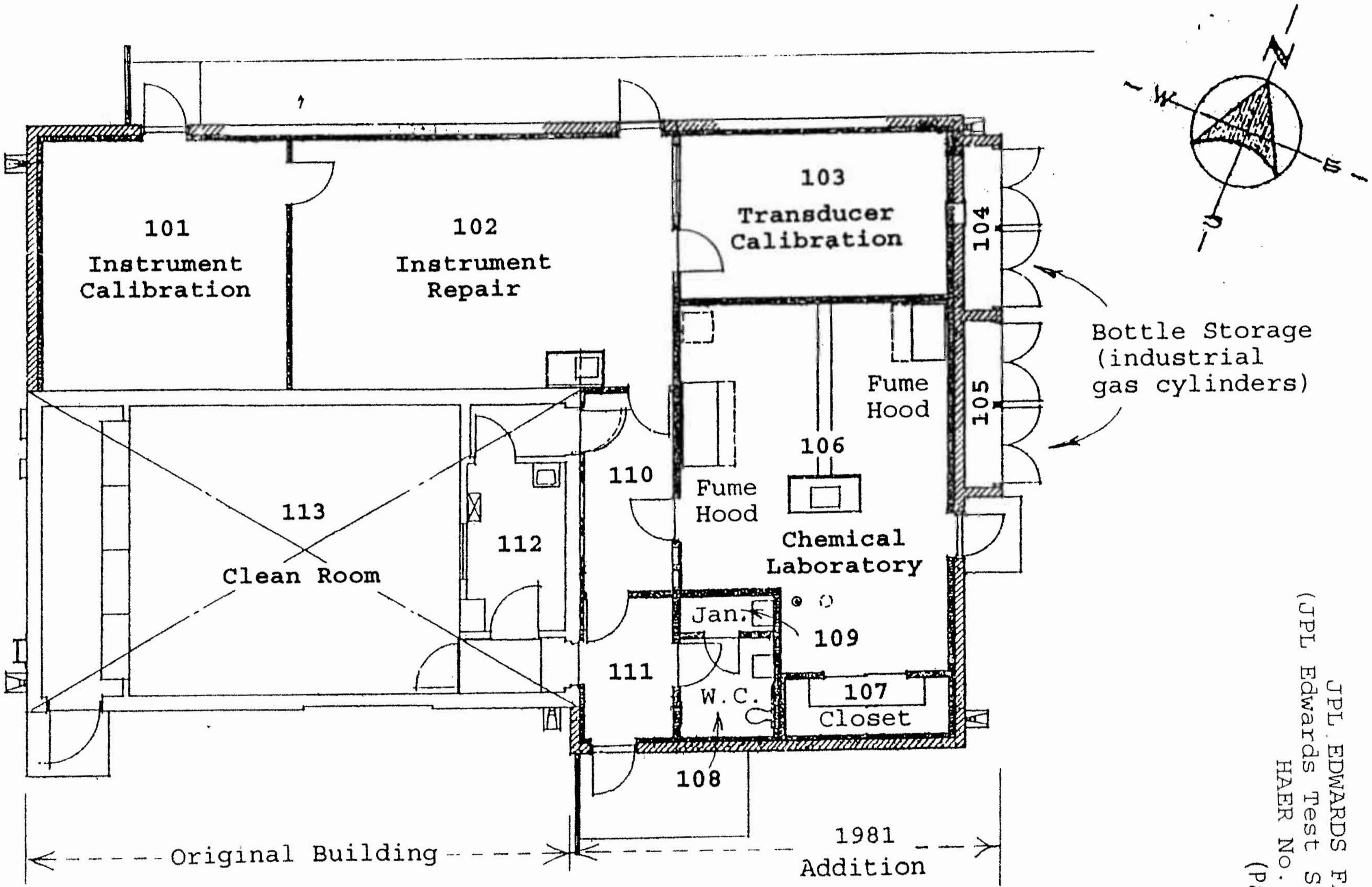

Fig. 43
Plan of Building 4282/E-83, Technical Services Facility

propellant before it is inserted under a rotor; excess propellant is taken to 4284/E-85. If the propellant is still at mixer temperature (120°F to 140°F, depending on propellant formula), the test can begin immediately; otherwise operators must wait until the viscometer bath brings the propellant up to temperature. A standard measurement cycle takes 20 minutes.[135]

For clean-up, the rotor and cup are removed from the viscometer and the propellant sample emptied into a waste container. Using rubber gloves, operators clean the cup and rotor with a spatula and acetone- or cyclohexanone-soaked disposable towels. Used towels are disposed of in the same container as waste propellant.

Tensile Tests

The Instron machine is a computerized device which will chart the elongation of a propellant coupon in response to the duration of the test and the tension applied to it.[136] The machine also has a conditioning chamber which can subject the sample to temperatures from -100°F to ambient during the tests. Liquid nitrogen was used to cool the chamber. A tensile test could last several hours. "Dog bones" were tested until they broke, and then the parts could be packed for scrap or stored for future analysis depending on the propellant engineer's wishes.

Peel Tests

The Instron machine discussed above was also employed for peel tests which measured the strength of the bond between a propellant and liner combination using a climbing peel test attachment.[137] Operators made samples for peel tests by cutting

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135. The copy of SOP No. 2067 used for reference indicates a 17 minute cycle on page 8 of 12, but this figure has been crossed out by hand and "20" superimposed above it.

136. Clay, M. B. Section 353, Standard Operating Procedure No. 2085: Testing of JANNEF Bars on 4505 Instron Under Cold Conditions (typescript), 14 February 1991; M.B. Clay. Section 353, Standard Operating Procedure No. 2087: Testing of JANNEF Bars on 4505 Instron Under Ambient Conditions (typescript), 14 February 1991. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

137. Shiraishi, L. R. Section 353, Standard Operating Procedure No. 2082: Manufacture and Peel Testing of Propellant/Liner/Insulation (PLI) Interface Test Samples (typescript), 7 February 1990. Records on file in temporary storage, Dryden Flight Research

6" x 6" squares of insulation. Operators wore cotton gloves, cleaned the insulation pieces with acetone and baked them for at least one hour at 140°F. The insulation was then affixed to molds using tape with adhesive on both sides. Operators applied an 0.06" layer of liner compound to the insulation using a trowel. The molds were then baked for 24 hours at 140°F. After baking, operators transported the molds to a mixer and vacuum cast a layer of propellant over the liner. When the combination was cured, the propellant/liner/insulation sandwich was milled to ¼" thickness on the milling machine in 4243/E-44 and cut into strips 1" wide. Each mold produced a sandwich from which four 1" strips could be cut. The propellant sides of three of these strips were bonded to sandblasted aluminum strips and the fourth strip used for visual inspection. For each test, operators installed a strip in the peel test apparatus (see Fig. 44), measured the width of each strip to the nearest 0.001", and recorded the force required to peel the sample apart at ½" per minute. In addition to recording the visual appearance of each peeled sample, operators derived the peel strength with a formula, using data from the machine and the strips. Disposal of tested samples is not discussed in the SOP for this operation.

Specific Gravity Tests

Measurements of a propellant's specific gravity (ratio of propellant density to the density of water) were made with a Model SPY-3 Quantachrome Stereopycnometer.[138] Personnel wore fire-retardant clothing and rubber gloves when handling the 1" x 1" x 1" propellant samples required for this test. Operators used a special cell from the stereopycnometer, which was carefully weighed with and without a sample. The loaded cell was installed in the machine, and an inert gas was introduced at a recorded pressure. Operators measured the gas volume and calculated the propellant density. Tested samples were shipped to 4247/E-48 for disposal as hazardous waste and the sample cell cleaned with acetone.

Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

138. McComb, J. Section 353, Standard Operating Procedure No. 2083: Determination of the Density of Cured Solid Propellants Using the Quantachrome Stereopycnometer (typescript), 19 March 1991. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

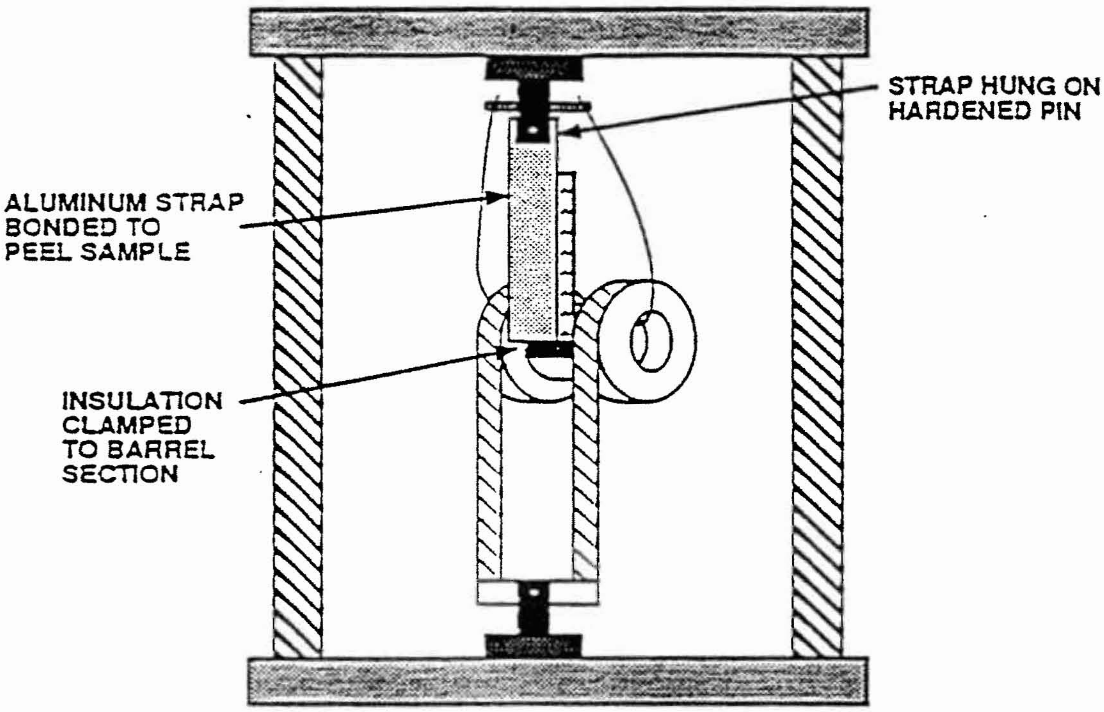

Fig. 44
Diagram of Peel Test As Performed on Intron Machine

Combustion Tests

Combustion testing of propellant samples occurred in Building 4267/E-68, Igniter Laboratory; the building's Safety Rules refer to this structure as "Igniter Laboratory and Small Motor Assembly."[139] This 14'-0" x 25'-8" concrete block structure contained two rooms and an exterior test bay (see Fig. 45). Room 101 was the laboratory where some tests were set up and igniters and small motors assembled. Room 102 was the exterior bay where hazardous material tests were conducted; all tests in this bay were remote controlled from Room 101. Room 103 was simply the building mechanical systems room. Room 101 was limited to 20 pounds (9 Kg) of Class 1.1 materials and four personnel, whereas Room 102 was allowed up to 80 pounds (36 Kg) of Class 1.1 materials but only two personnel. Flame retardant clothing and safety goggles were required attire, and personnel handling explosive materials were also required to wear grounded wrist straps to dissipate any static electrical charges. Grounding bars were located at the entrance to Room 101 for personnel to touch upon entry.

JPL test engineer Robert L. Ray related that JPL staff designed and prepared many types of igniters at the Igniter Laboratory (4267/E-68) instead of purchasing them from commercial suppliers. These "homemade" devices were tested in pieces of pipe set up in the test bay. The test bay was also the site of continuity checks and test firings for electric squibs and similar devices. Most igniters consisted of boron potassium nitrate pellets [$BK(NO_3)_2$], although triethylaluminum [$Al(C_2H_5)_3$] and triethylboron [$B(C_2H_5)_3$] were also used. Raw materials for the igniters as well as assembled igniters themselves were kept in the Igniter Magazine, 4261/E-62.

Burn Rate Tests

Burn rate tests for Class 1.1 and 1.3 propellants were made using an instrument called a "Crawford Bomb," which consisted of a sealed Hastelloy[140] chamber submerged in a water bath. Each

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139. Bailey, Richard L. Safety Rules, Solid Propellant Engineering, Section 381. Building E-68, Room 101; 15 January 1971. E-32, Room 7, Shelf 2, JPL Edwards Facility Collection. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

140. Hastelloys are a group of nickel-molybdenum-chromium-iron alloys with at least seven commercial compositions; the particular alloy used in JPL's Crawford bomb was not determined.

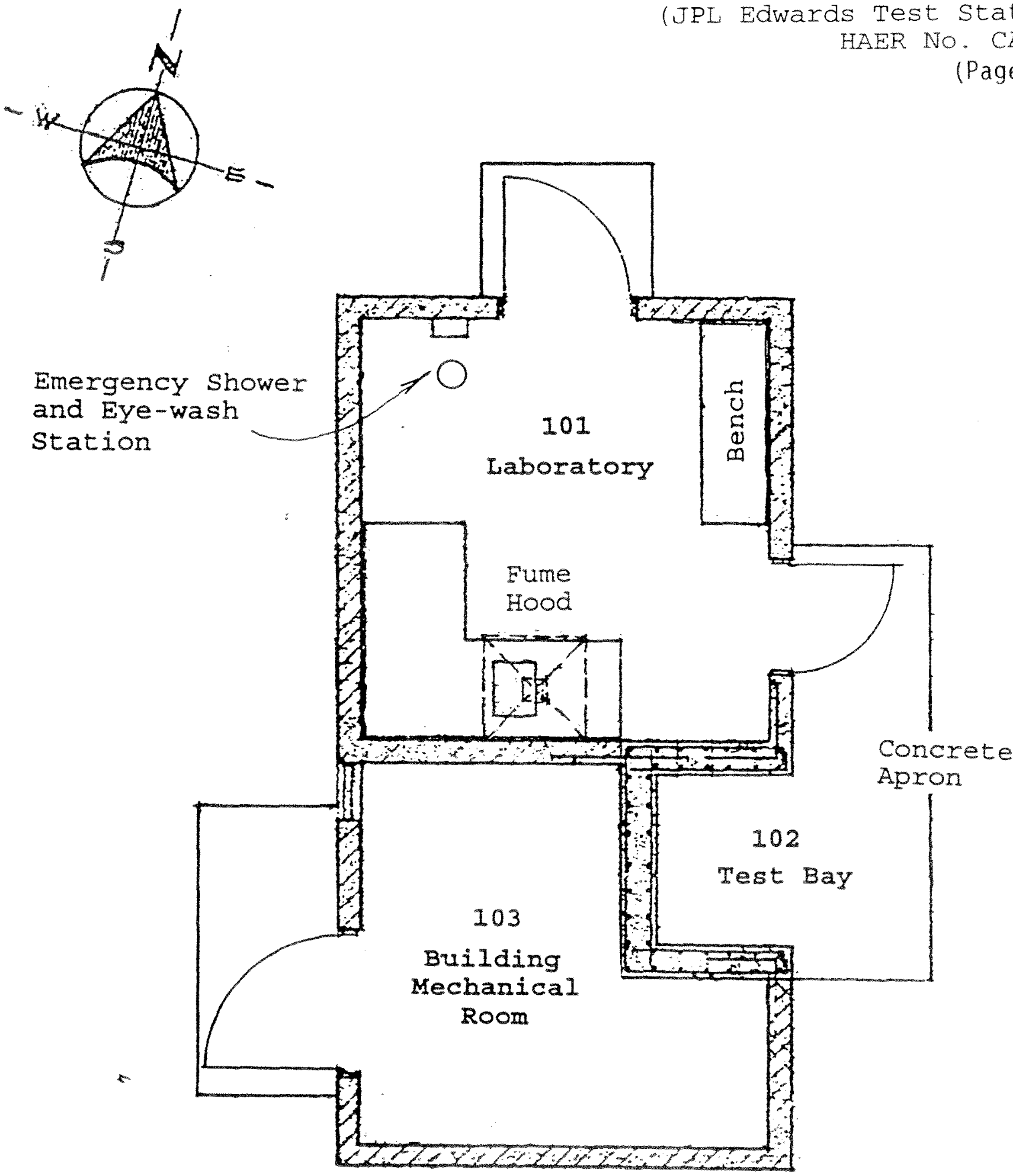

Fig. 45
Plan of Building 4267/E-68, Igniter Lab

test consumed three 0.3" diameter by 6" long strands of propellant. Tests were conducted at pressures ranging from 13.6 to 2,000 pounds per square inch absolute (psia)[141] for Class 1.3 strands, and up to 1,500 psia for Class 1.1 strands, depending on the test parameters requested. Different propellant formulas burned a different rates depending upon the ambient pressure; determination of these factors was important for propellant and motor design, since propellants in an actual motor burn while the unit is under pressure producing thrust. The pressure in the Crawford bomb was altered by introducing GN_2 from the high pressure lines serving JPL Edwards. The temperature could be varied from -50°F to +200°F. JPL's Crawford bomb was a Model 535 unit manufactured by Atlantic Research Corporation.[142] The propellant strands were prepared for the tests by drilling a hole in one end for an ignition wire, and two more holes 5" apart for timing wires. The timing wires indicated when the burning zone in the strand passed the measured points along the strand. Several instruments were connected to the Crawford bomb, including pressure gauges, pressure transducers, a plotter, and various remotely controlled valves. Burn rates could be monitored by the pressure transducers or acoustic emission equipment; in the first case, all three strands were fired simultaneously whereas in the second, only one strand was fired at a time. Each test took approximately 30 seconds. When tests were completed, high pressure gas was bled from the bomb, and the unit allowed to cool before it was opened and residues cleaned out.

X-Ray

The use of X-rays to inspect the internal structure of industrial products has a long history in American industry. Equipment and techniques similar to those in industry were used to examine motors and propellant grains at ambient temperatures for structural integrity in Building 4286/E-87, the Radiographic Inspection Facility. Defects invisible to the naked eye, such as voids in a grain, "pull-aways" of grain from the liner, or

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[141]. 13.6 pounds per square inch absolute (psia) is atmospheric pressure at JPL Edwards Facility. A reading of zero psia is a vacuum. Most pressure readings are pounds per square inch gauge (psig), where zero on the gauge is equal to ambient atmospheric pressure.

[142]. Ray, R. L. Section 353, Standard Operating Procedure No. 2044, Revision 2. Operation of the 3-Strand Crawford Bomb at Edwards Facility (typescript), 11 March 1992. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

failures in parts of the casing or nozzle were immediately detectable. Procedures called for a motor to be X-rayed with the motor rotated along its vertical axis to a principal orientation. After the first X-ray image was made, the motor was rotated 90 degrees about its vertical axis and a second image made. This ensured the detection of most faults. Images were also made with the motors in other positions. Motors could be X-rayed during conditioning, before and after tests at the Vibration Facility (Test Stand "G", 4271/E-72) and during other phases of motor production.

Building 4286/E-87 was a 25'-4" x 39'-4" concrete block structure built in 1981 to accommodate a 1-million electron volt X-ray machine purchased from the Lockheed Aircraft Corporation. This unit was considerably more powerful than the one previously used at Test Stand "E" (4259/E-60). It was housed in the 26' tall "high bay" of the facility, which was separated by a 4' thick concrete shielding wall from the "low bay" where the control room and film processing room were located (see Fig. 46).[143] The high bay contained a travelling bridge crane from which was suspended a scissors frame and rotary platform for the X-ray unit. This arrangement permitted operators to set the X-ray unit in a wide variety of positions. A 14' wide by 18' high roll-up door in the northwest facade of the high bay gave trucks access to the building for motor delivery and pick-up.

Due to the high energy radiation produced at 4286/E-87, the facility was surrounded by a fence which enclosed several acres of land to keep personnel and intruders from entering a radiation danger zone. The building was also located at the northwestern boundary of the Edwards Facility and oriented so that the shielding wall was between the X-ray unit and the entire JPL Edwards Facility enclosure to the southeast. Operators closed the vehicular gate to the facility before an X-ray image was made, and switched on a red warning light. During the period X-rays were emitted, an air horn sounded at one-second intervals. Once exposed, X-ray film was developed in the film processing room for immediate inspection. Further images could be made on

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[143]. Ben Beckler & Associates Architects & Engineers, 4227 Lankershim Blvd. North Hollywood, California 91602. California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Radiographic Inspection Facility, Floor Plan, Sections & Elevations** Sheet A, 25 June 1979; JPL Drg. No. E87/4-0. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

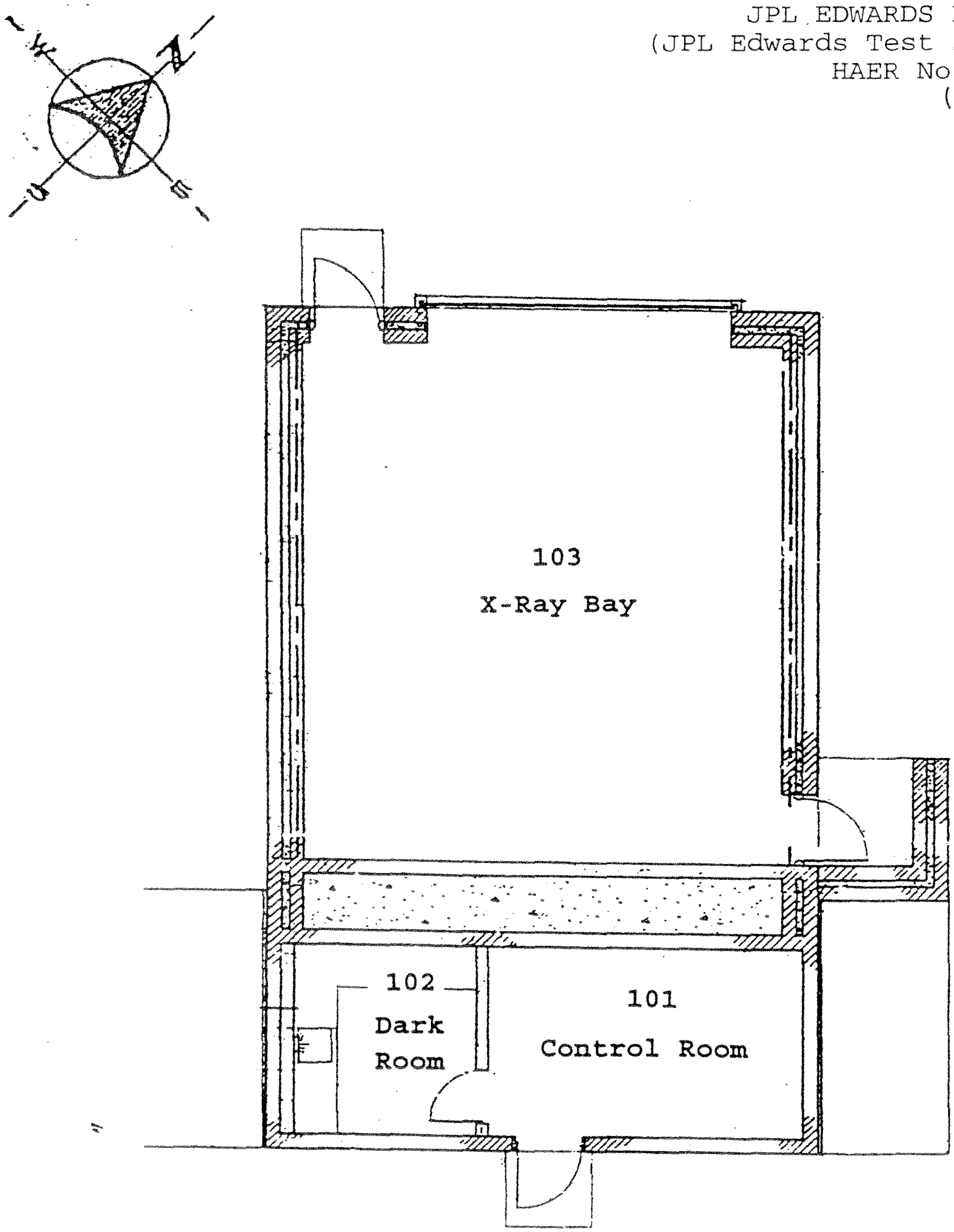

Fig. 46
Plan of Building 4286/E-87, Radiographic Inspection Facility

the spot if necessary to clarify questions.

From 4286/E-87 a motor could be returned to the process step from which it had been taken, delivered to test preparation, or delivered to Test Stand "G" or Test Stand "E".

Motor Assembly

Prior to vibration tests or test firings, JPL personnel assembled inert parts of motors in Building 4260/E-61, designated the "Inert Assembly Building." It contained an office, area rest room, a small machine shop, and X-ray film processing facilities used when X-rays were conducted at Test Stand "E".[144] This 26'-8" x 28'-0" concrete block structure was built in 1962 as part of the JPL solid line's first wave of construction. It was connected to JPL's tunnel system by an outside entrance (see Fig. 47). Small parts were made here as necessary for the assembly of inert parts. No propellants were ever admitted to this structure.

The final assembly of live motors was carried out in Building 4268/E-69, Weigh & Test Preparation. This 20'-8" x 39'-0" concrete block structure consisted of two rooms: a large work room containing a monorail hoist, horizontal steel erection plate, and a 2,000 pound capacity floor scale, and a building mechanical room (see Fig. 48). The work room was rated for a maximum of 2,700 pounds (1,227 Kg) of Class 1.1 materials and six personnel. Apparently no structural modifications were made to the building since its construction, however, a solvent recovery still was installed sometime before 1989 to aid in environmental clean-up and the recovery of contaminated solvents.[145] No more than one motor could be processed at a time, and it had to be electrically grounded whenever it was moved from one metal fixture to another. Personnel wore flame retardant garments, eye protection, and wrist and leg grounding straps whenever they handled parts of live motors (see HAER photo CA-163-CC-2 for

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144. Jet Propulsion Laboratory, Pasadena, California. "Control and Energy Conversion Division, Facility Utilization ETS, Edwards Test Station, Edwards California, June 1981, unpaginated.
145. Barry, J. A. Standard Operating Procedure No. 2069, Revision 1. Operation of the Recyclene R RX-35 Solvent Recovery Still (typescript). 8 March 1989. E-33, File 3, Drawers 1 & 2, JPL Edwards Facility Collection. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

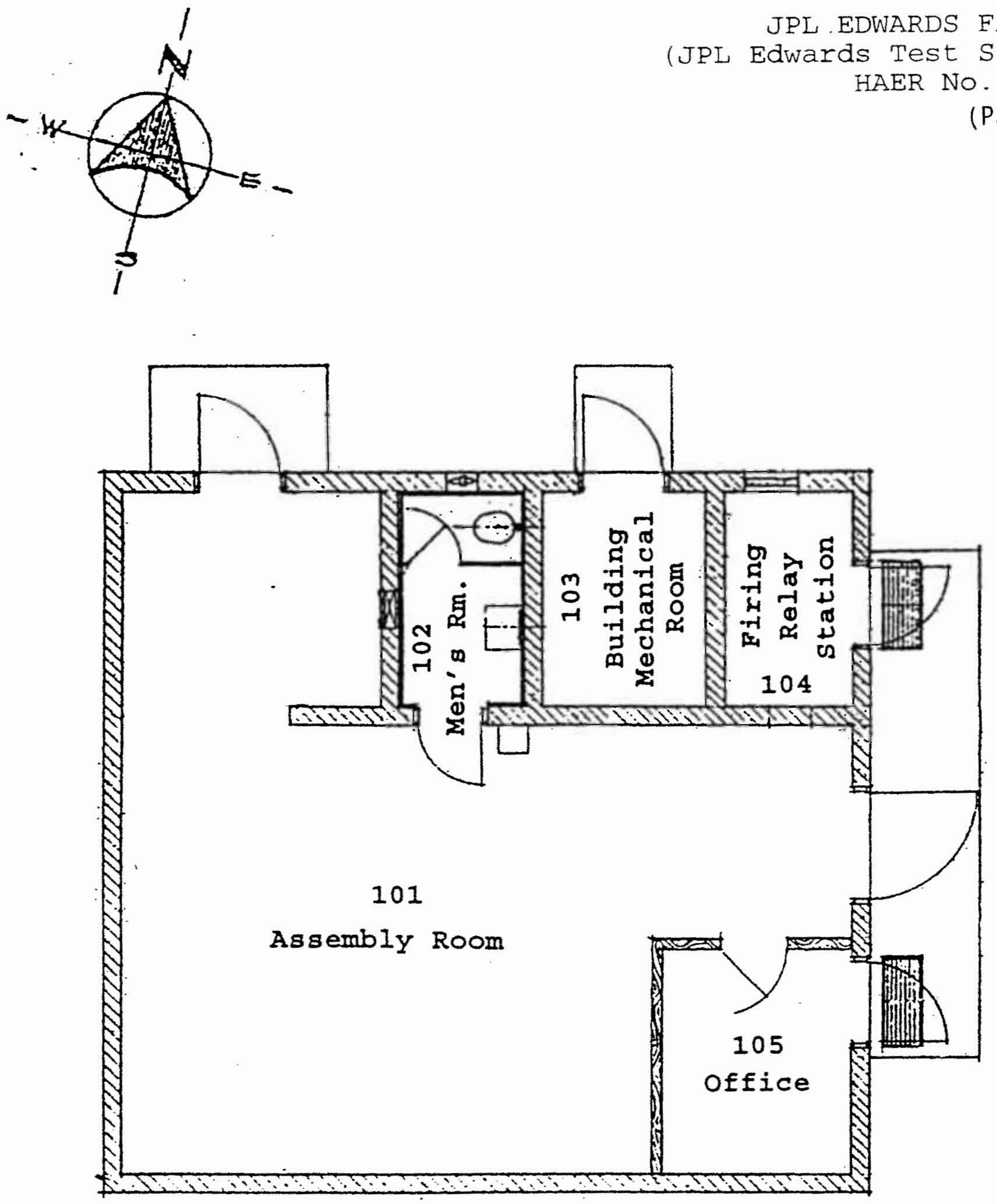

Fig. 47
Plan of Building 4260/E-61, Inert Assembly Building

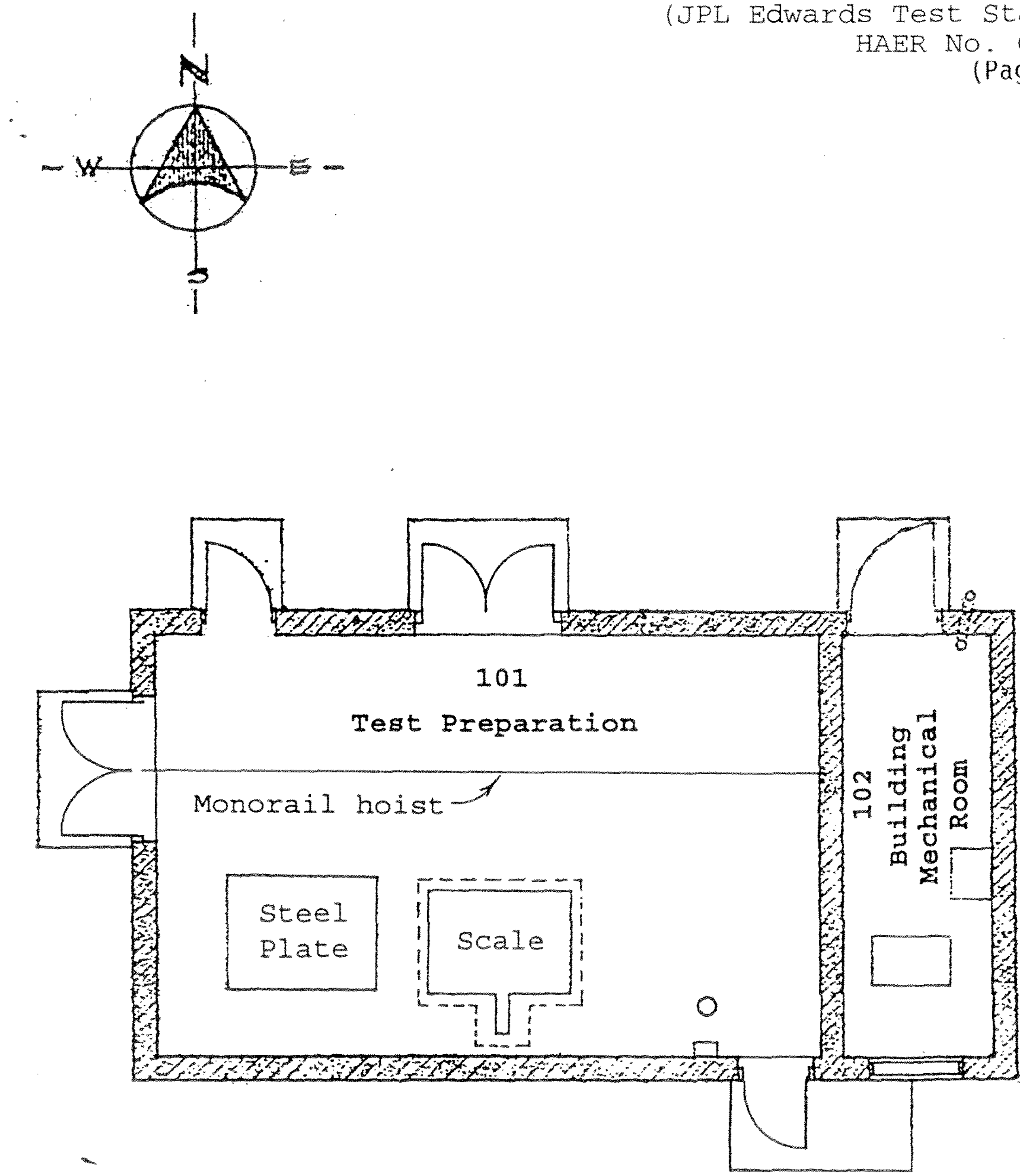

Fig. 48
Plan of Building 4268/E-69, Weigh & Test Preparation

image showing assembly of BATES motors).[146] Any scrap accumulated from last-minute trimming and fitting could not exceed 5 pounds, nor could it be stored overnight on the premises. Personnel hand-trimmed grain to required setbacks and weighed and measured them for records. Next, they assembled motor heads to casings, installed boron wafer igniters, installed the grain (in phenolic paper wrappers) in the casing, and then attached the nozzle. The procedures outlined for assembling some motors (such as the 25-pound BATES motor) were applicable to assembly at Test Stand "E" as well as at 4268/E-69. Assembled motors were stored on three-wheeled "bomb carts" in Building 4268/E-49 with VeloStat® coverings on the nozzle openings until needed for tests.

The Igniter Magazine, Building 4261/E-62, is a 13'-8" x 12'-8" steel reinforced concrete building with a flat blow-off roof constructed from 2" x 6" wooden rafters and ½" thick plywood. It contains two rooms labeled 1-A and 1-B, each with two outward-opening, electrically grounded steel doors. The first exterior door opens to a small vestibule, which itself has a steel door leading into the magazine space proper. By the handle of each exterior door is mounted a steel bar with a visible grounding cable and a sign "Caution: Grounding Bar - Touch Before Entering" (see HAER photo CA-163-AA-1). All wiring for electric lighting passes through exterior mounted steel conduit to minimize the risk of explosion initiated by malfunctioning wiring. The magazine was originally constructed in 1962-63 as a one-room 6'-8" x 12'-8" structure with 8" thick concrete walls (Room 1-A). Room 1-B was added in 1975 when a three-room addition was contemplated.[147] The addition has 12" thick walls, reflecting a change in Air Force regulations for the construction of buildings containing explosives (see Fig. 49). The building is posted for a maximum of 100 pounds (45 Kg.) of Class 1.1 materials. Each room contained a grounded steel cabinet in which igniters,

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146. Ray, R. L. Procedure No. 353-90-E69-5, Revision B, 5 September 1990. Assembly Procedure for 25# BATES Motors, p. 5 of 9. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

147. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Addition to Building E-62,** Drg. No. E-62/4-1, 12 Dec 1964. This drawing shows original the single bay building design dated 7 Dec 1960 (Drg. No. E-62/1-0), plus an additional three bays, only one of which was added. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

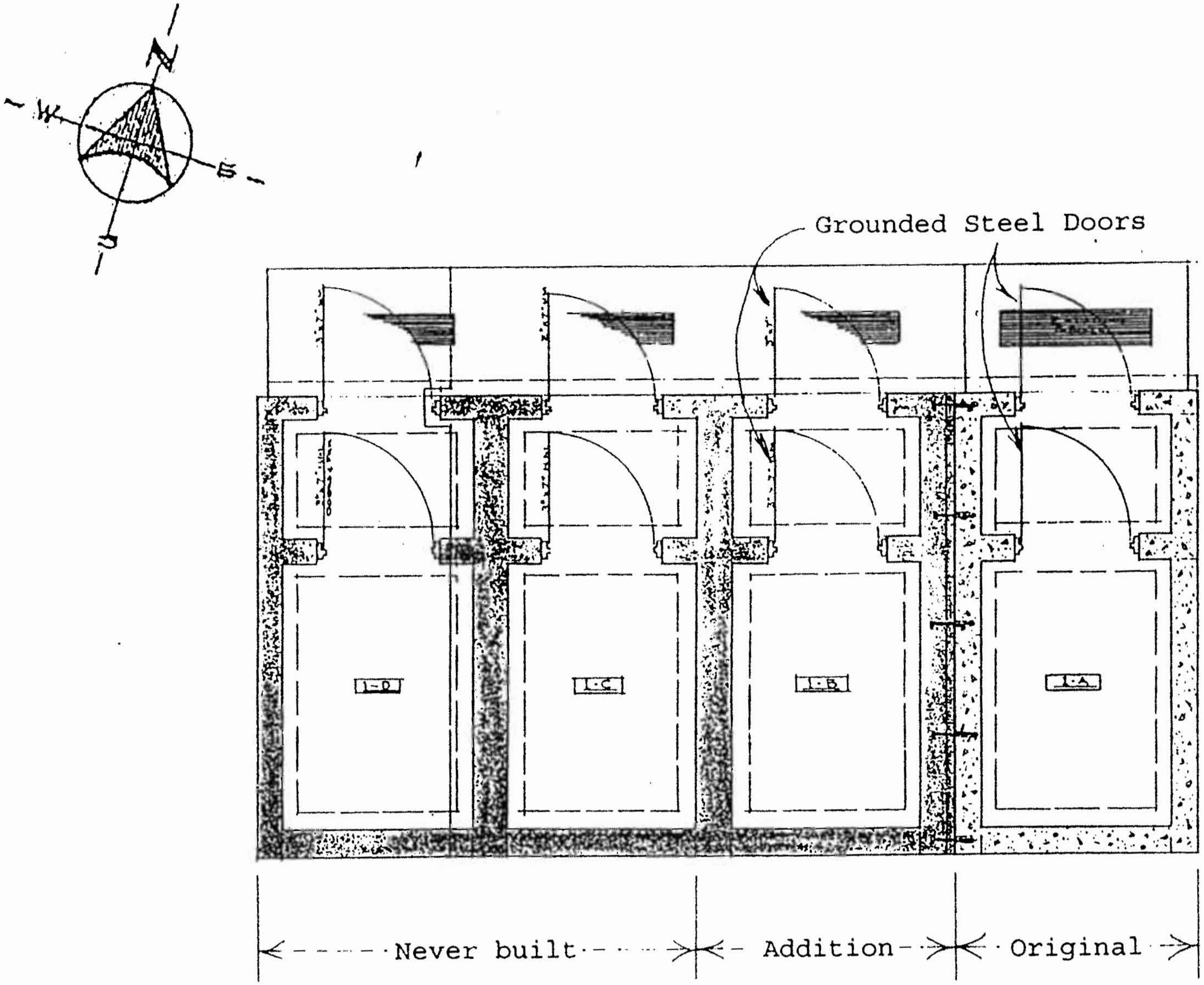

Fig. 49
Plan of Building 4261/E-62, Igniter Magazine

electric squibs, and other explosive devices or their constituent chemicals were kept in metal drawers. JPL personnel had to wear flame retardant clothing when inside and carry igniters in metal boxes to minimize the possibility that the devices might be "touched off" by radio frequency radiation.[148]

Test Stand "G": Vibrator

Because spacecraft containing solid motors rode larger rockets into earth orbit or beyond, their motors were subjected to considerable vibration during launch. JPL staff built Test Stand "G" 4271/E-72 in 1964 to determine motors' ability to withstand launch conditions by simulation in vibrator. Building 4271/E-72 was a 28'-0" x 45'-0" concrete block structure with three rooms; the vibrator was installed in a 26' tall high bay, while the equipment room and amplifier room were located in the low bay (see Fig. 50).[149] The vibrator itself (see HAER photo CA-163-EE-2) was "...a MB-C210E Electrodynamic Exciter having a maximum sinusoidal force output of 28,000 lbs. and a no-load-peak acceleration sine wave of 80 gs" ("80 gs" means 80 times the force of gravity).[150] The vibrator was connected to a steel table on which motor assemblies could be mounted along with associated instruments (see HAER photo CA-163-EE-3). Because live motors were tested here, the east elevation of the vibrator room was equipped with blow-out panels and blow-out 10' x 26' double doors. Personnel were not allowed inside the building

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[148]. Bailey, Richard L. Safety Rules, Solid Propellant Engineering, Section 381. Building E-62; 15 January 1971. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

[149]. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Vibration Test Facility Bldg E-72, Floor and Roof Plans, Sections, Details & Door Schedule,** Sheet A1, 21 May 1964; JPL Drg. No. E72/2-5; California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Vibration Test Facility Bldg E-72, Exterior Elevations,** Sheet A2, 21 May 1964; JPL Drg. No. E72/3-3. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

[150]. *The Jet Propulsion Laboratory Edwards Facility*, Jet Propulsion Laboratory, California Institute of Technology, no date; quotation derived from a JPL photo caption in this notebook. unpaginated. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

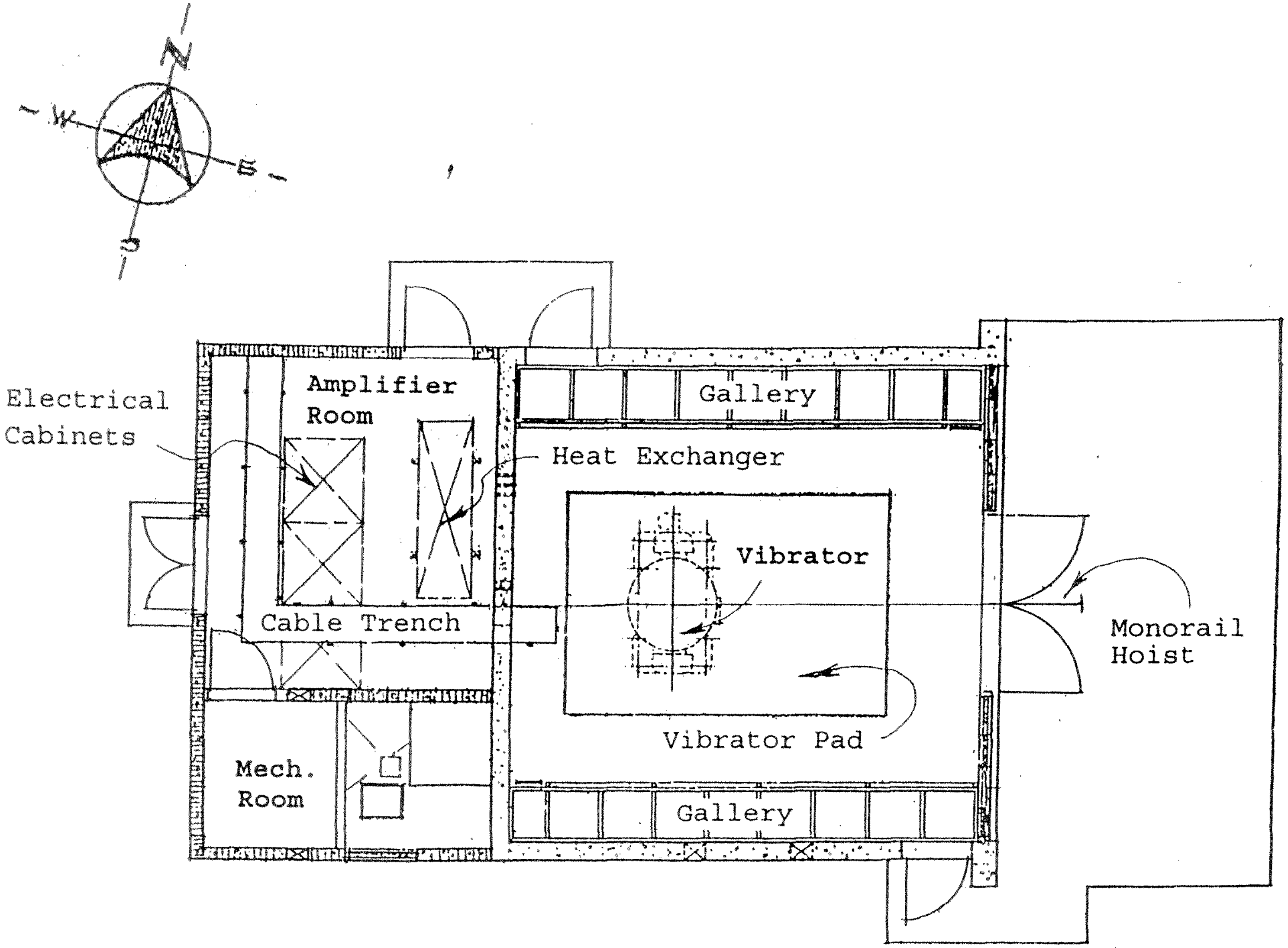

Fig. 50
Plan of Building 4271/E-72, Test Stand "G" (Vibrator)

during tests, and could not re-enter it until 15 minutes after a test's conclusion. In 1967, new catwalks were installed on the north and south walls of the vibrator room[151]; no other major changes to the building interior were discerned.

In 1988, JPL converted the vibrator facility to an Autoclave & Insulation Layup Facility. A new 5' x 8' autoclave was purchased to support NASA programs, and only 4271/E-72 had the electrical power supply to support the autoclave.[152] As partial justification for the conversion, JPL Edwards staff said that the vibrator had not been used in 15 years, and there were no plans for its future use. The autoclave cured rubber insulation materials at temperatures up to 400°F and pressures up to 400 pounds per square inch.[153] Normally, parts to be cured were placed in vacuum bags and left overnight under -25" Hg vacuum.

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151. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Vibration Test Facility Bldg E-72, Floor and Roof Plans, Sections, Details & Door Schedule,** Sheet A1, 21 May 1964. California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

152. Jet Propulsion Laboratory, Edwards Facility Interoffice Memorandum 351EF-88-1212, 28 January 1988 from G.L. Root to W.A. Menard. Handwritten approval by Menard for the conversion request is dated 5 February 1988. "Real Property Record - Buildings," a series of cards on each structure at JPL Edwards Facility, recording construction, alterations and costs. Records on file at AFFTC/CE-RE (Real Estate), Edwards AFB, California.

153. Ray, R. L. E-72 Autoclave Processing Checklist. 351-88-E-72-1, Revision D, 19 June 1990; p. 25 of 26. Records on file in temporary storage, Dryden Flight Research Center, Edwards AFB, California, part of the JPL Archives Collection, Pasadena, California.

After this period, heat, pressure and CO_2 gas were applied as required by a parts processing plan. Contents of the autoclave had to cool below 200°F before the autoclave could be shut down. The levels of oxygen and CO_2 were carefully monitored inside and outside the autoclave. Building doors were opened if oxygen levels inside the building fell below 19.5% due to CO_2 vented from the autoclave.

Test Stand "E"

Test Stand "E," built in 1962, is a 15' x 70' steel-reinforced poured concrete structure with a four-bay plan. The test stand consists of two individual atmospheric, (one vertical and one horizontal) solid-propellant rocket motor firing cells, and instrumentation room, and a third test cell used as an X-ray inspection cell until 1981 (see Fig. 19, page 86). The two rocket motor cells are located on the north half of the test stand, and the X-ray inspection cell is on the south half of the test stand. The north bay is open on the east facade; it contains a large metal work bench and a 2-ton steel I-beam monorail hoist. A remote camera is trained on the work bench. A corrugated metal sheathing covers the north bay. The adjacent south bay has tall concrete walls and an upper divider for separating equipment and tests. It has a metal roof, and is open on the east facade. The center bay was used for vertical and horizontal rocket motor firings. An octagonal tiedown is on the ground. Openings through the west walls convey instrumentation and utility cables into the tunnel system. These test cells normally handled motors that produced between 1,000 and 10,000 pounds thrust direct, and 5,000 pounds thrust reverse. Maximum thrust capability was 50,000 pounds.[154]

The center bay is an integrated workshop and office space; it is enclosed with a shed roof. An off-center door accesses a workspace that connects Test Stand "E" to the tunnel system on the west facade of the test stand. The tunnel corridor that accesses the tunnel system extends past the west facade. Two doors flank the tunnel on its north and south facades. The adjacent bay to the south, the former X-ray test cell, is now a storage space. Two perpendicular 1-ton monorail hoists extend through the bay. One monorail hoist extends past the east facade. A large storage tank is located on the south facade of the test stand; the nozzle extends through the wall into the X-ray inspection cell. A pair of double doors pierce the east facade of the south bay, and a door is on the south facade of Test Stand "E." A one-story, 10' x 10' concrete block addition

154. Koebig and Koebig, Inc.

is attached to the west facade of the south bay. It housed a generator and monitor; a door on the south facade of the addition accessed the equipment. Two fully enclosed wooden plank blast barriers (native soil and cribbing) are located on the north and south facades of Test Stand "E." The north blast barrier has been extended and encased in a metal sheathing.

Test Stand "E" was first used to support NASA's commercial satellite and spaceflight program, such as Syncom and ATS. Solid-propellant kick motors, used to place Syncom and ATS in geosynchronous (geostationary) orbit around the earth, were tested at Test Stand "E" in the 1960s.[155] Nozzles and a 10,500-pound solid-propellant motor, under development for the space shuttle program, were tested on Test Stand "E" in the late 1970s.[156] The two test cells were modified to accommodate testing of 48-inch motors for the space shuttle program. In later years, propellant configurations for the ASRM was tested at Test Stand "E." The last test firing at Test Stand "E" was conducted in April 1994.

Waste Disposal and Clean-Up

The accumulation of scrap propellant, used propellant samples, and propellant contaminated wastes and solvents was stored at two sites on JPL grounds: 4247/E-48 and 4258/E-59. Eventually, this accumulation had to be disposed of, and the JPL solution was to burn it. Clothing and coveralls were cleaned by contractor. The incinerator at Building 4249/E-50 was originally equipped with a propane-fired furnace for destroying waste materials (see HAER photo CA-163-V-1), however, Kern County waste disposal rules changed in the 1970s to permit open pit burning of this type of waste. The 1971 Safety Rules for 4249/E-50 indicates that propellant wastes were kept in their sealed containers and placed in a feeding chute which led to the incinerator. A maximum of 50 pounds (23 Kg) of propellants could be burned at any one time. Loading the incinerator was to be done remotely from behind the 4249/E-50 barricade, however, loose scrap material (such as was kept in VeloStat® bags) could be put in the incinerator directly. A maximum of 25 gallons of solvent waste could be disposed of in an open tank to the east of the incinerator. Scrap motors to be burned out were bolted to steel plates in the pit; no more than five such motors could be disposed of simultaneously. Only one kind of burn activity could

155. Gibbons and Tibbitts, 2.
156. National Aeronautics and Space Administration and Jet Propulsion Laboratory. *The Edwards Facility*. JPL 400-304. Pasadena, California: Jet Propulsion Laboratory, November 1987:2.

be done at one time, and whenever burns were underway, all personnel had to be behind the barricade, and all containers and brush for a 100-foot radius had to be cleared from the site.

After open-pit burning was sanctioned, burns were conducted whenever JPL personnel had the time to do it. Kern County rules required a burn at least every 90 days to prevent a hazardous accumulation of flammables, but JPL personnel preferred to wait until at least 200 or 300 pounds of waste had accumulated before disposing of it. This minimum quantity assured that all waste would be burned up. A maximum of 1,000 pounds was permitted during a single burn.[157]

Facility Administration

With the construction of the first phase of the solid propellant line in 1962-63, JPL also constructed an Administration Building 4231/E-32 (see Fig. 51). The administration and communications wing was constructed first in 1962, with future expansion anticipated. The initial wing was a 40′ x 80′ structure which provided only offices and a room for telephone network equipment. The second phase, called "supporting facilities" for E-32, were designed by Austin, Field & Fry and constructed by the Army Corps of Engineers in 1965-66. These facilities provided numerous amenities in addition to more office space. Included were a conference room, cafeteria, photography laboratory, a machine shop, and several shops and bays for road vehicles, for a total floor area several times the size of the original wing. The internal connections between these two buildings were awkward for personnel, because the two structures met at the tips of two opposed corners. A third phase, "Modifications ′66," followed hard on the heels of the support facilities. This addition provided a continuous corridor which served the whole building and added still more office space. The machine shop originally included a vertical milling machine, a shaper, an Hendey 14" engine lathe, a bandsaw, surface grinder, radial drill, and heat treatment oven (see HAER photo CA-163-K-4). These tools were large enough and of sufficient variety to produce almost any kind of specialized parts for use in both the solid and liquid propellant operations at the Edwards Facility. Absent in either available photographs or engineering drawings is evidence of welding equipment, or equipment for producing composite materials (e.g., graphite or Kevlar® fibers embedded in a phenolic or other plastic matrix). The precise kinds of parts made in this shop, and which projects it supported were not investigated for HAER.

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157. Robert L. Ray Interview.

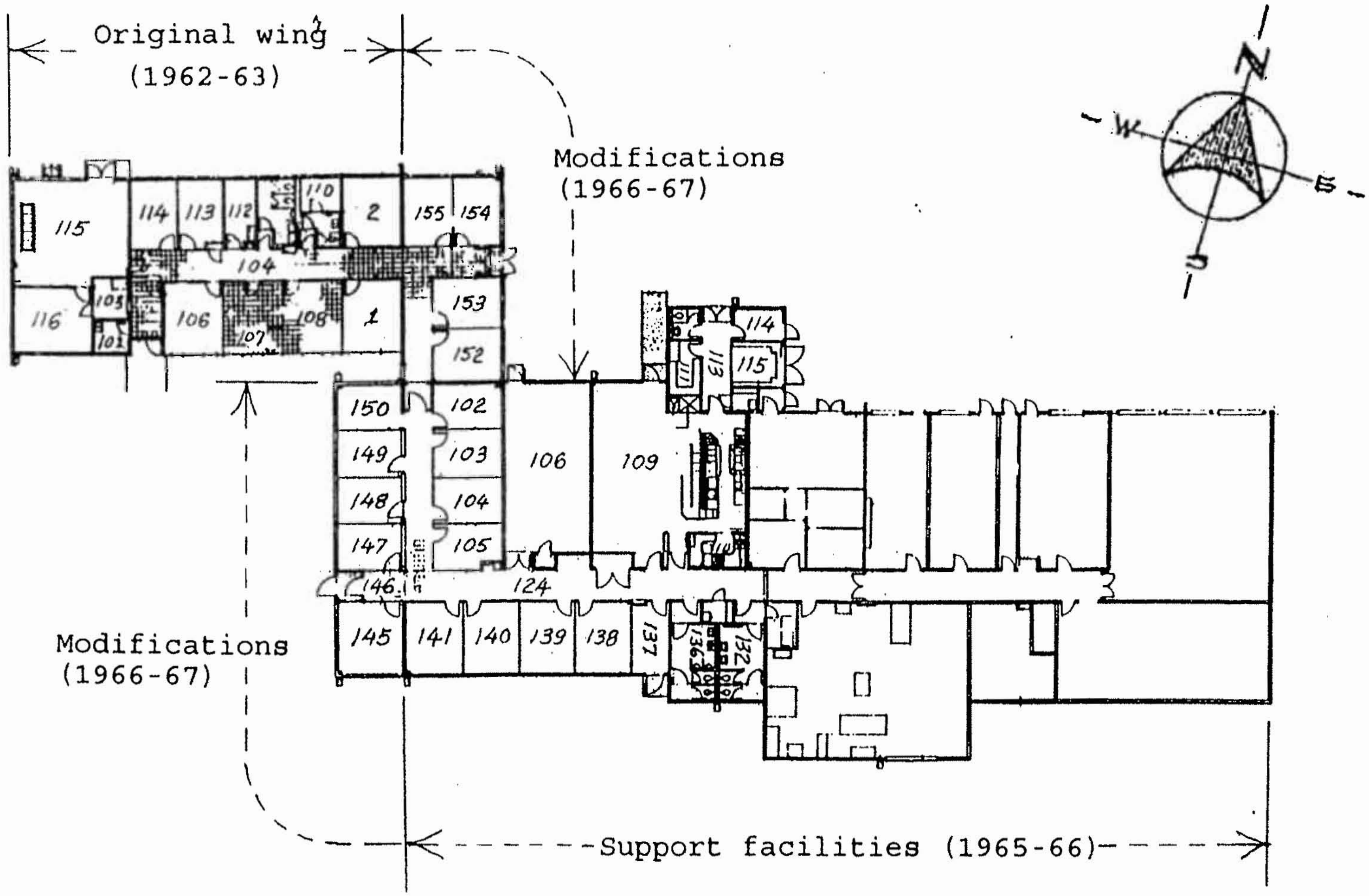

Fig. 51
Plan of Building 4231/E-32, Administration Building & Shops

The administration building and its support facilities are the sole structure at JPL Edwards Facility where any architectural "flavor" appears, and even here, it is reserved for the public entrance on the south side of the original wing. The rest of the building's numerous facades are built of reinforced concrete block and retain the stark, rigorously functional design characteristic of the solid propellant line buildings.

Chemical Names and Formulas

Acetone: CH_3COCH_3

Aluminum: Al

Ammonium nitrate: NH_4NO_3

Ammonium perchlorate: NH_4ClO_4

ammonium phosphate: $NH_4H_2PO_4$

Ammonium sulfate: $(NH_4)SO_4$

Asbestos: $Mg_3(Si_2O_5)(OH)_4$

Boron potassium nitrate: $BK(NO_3)_2$

Carbon dioxide: CO_2

Cyclohexanone: $CO(CH_2)_4CH_2$

DOA (di-octyl adipate): $CH_3(CH_2)_7]_2(CH_2)_4$

Fluorine: F_2

Gaseous nitrogen: GN_2

Helium: He

HMX (cyclotetramethylenetetranitramine): $C_4H_8N_4(NO_2)_4$

Hydrogen: H_2

IPDI (isophorone di-isocyanate): $C_{12}H_{18}N_2O_2$

Iron Oxide: Fe_2O_3

Isopropyl alcohol: $(CH_3)_2CHOH$

Mercury: Hg

Nitrogen: N_2

PBAN (polybutadiene acrylic acid acrylonitrile): $(C_{10}H_{11}NO)_x$

silica: SiO_2

Sodium nitrate: $NaNO_3$

TDI (toluene 2,4-di-isocyanate): $CH_3C_6H_3(NCO)_2$

TNT (trinitrotoluene): $C_7H_5N_3O_6$

Triethylaluminum $Al(C_2H_5)_3$

Triethylboron $[B(C_2H_5)_3]$

Water: H_2O

PROJECT INFORMATION

This HAER report had its genesis in a Phase II cultural resource evaluation of the Jet Propulsion Laboratory Edwards Facility conducted by Scott M. Hudlow, Architectural Historian, Environmental Services Department, Applied Technology Division, Computer Sciences Corporation, Edwards Air Force Base, California. The Phase II study determined that the JPL Edwards Facility was eligible as a National Register of Historic Places historic district, and that the Air Force Flight Test Center closure plans resulted in adverse effects which merited mitigatory HABS/HAER documentation under Sections 106 and 110 of the National Historic Preservation Act. This addendum was prepared to document the JPL solid propellant manufacturing and testing line, since this portion of the facility has great historic significance in its own right, was little used, and personnel who could be interviewed for the record were retiring. At the time of this writing, there are few people nationwide training in the art of solid propellant development, hence there was an additional urgency to document the solid propellant line while personnel knowledgeable in its history and operations were available to assist in the documentation. The historical background and sources from Mr. Hudlow's work were adapted by Richard K. Anderson, Jr. to meet the HAER report format and HABS/HAER standards as required by the Phase III cultural resource documentation project conducted by Mr. Hudlow. Mr. Anderson also included in the report numerous technical and historical observations derived from reviews of historic engineering drawings, JPL photographic records, site visits to the solid propellant line, and telephone and taped interviews with JPL test engineers. Photocopied engineering drawings from the JPL Edwards Facility engineering office, and copies of test stand schematics used in preparing the HAER report and drawings have been filed with the HAER project field records, along with several dozen 35mm field photographs taken by Mr. Hudlow in 1994-1995.

Neither time nor funding was available to study the impact of individual engineers and personalities on either the design and evolution of the JPL Edwards Facility or its individual solid propellant facilities, nor could these individuals' contributions to the design and success of spacecraft series be evaluated. The financial aspects of JPL Edwards operations, such as the costs and schedules of any or all specific series of tests (equipment, propellants, etc.) were outside the scope of this report. Neither time nor opportunity to review the design and results of individual projects for what they might reveal about the evolution of the solid propellant line was available. The history of specific rocket engine designs tested at JPL Edwards Facility was beyond the scope of this report. These topics each deserve further research given the uniqueness of the site and its historic mission.

In addition to the HAER report, Mr. Anderson prepared two HAER measured drawings, and collaborated with Mr. Hudlow in selecting sites for HAER photographic documentation as well as photographic copies of historical photographs and drawings for inclusion in the HAER record. Brian Grogan and Philipp S. Rittermann, Photography & Preservation Associates, Inc., Yosemite, California made contemporary (1995) large format photographs. Historical JPL negatives were photographically copied by Bob Schlosser of the Huntington Library, San Marino, California, with the invaluable help of David Deats at the JPL Photographic Laboratory in Pasadena, California. The HAER report, measured drawings and large format photography were prepared under Computer Sciences Corporation purchase order No. CS5-00020, 7 July 1995, Richard K. Anderson, Jr., vendor.

Mssrs. Hudlow and Anderson appreciate the numerous hours of assistance given by JPL employees William C. Tibbitts (JPL Edwards Facility Manager), Bob Ray (JPL Facility Test Engineer), John Bluth (JPL Archivist, Pasadena) and others in pointing out files, investigating facilities, answering questions and reviewing the HAER documentation at various stages of its preparation.

Primary and Secondary Research

Primary and secondary research for the Phase III HAER report on the solid-propellant processing line was conducted between August and December 1995.

Primary records, including historic photographs and as-built and schematic drawings, were reviewed at the JPL Edwards Facility. Due to the facility's closure, the records were transferred to the custody of the JPL Archives, Pasadena, California during review. The JPL Edwards Facility records were placed in long-term storage at the Dryden Flight Research Center at Edwards AFB, California in August 1995. These records were made available to Scott M. Hudlow under special arrangements in November 1995, thanks to John Bluth of the JPL Archives. Batch records, mixing records, safety information, floor plans, memos, and project information were made available at that time. The JPL Edwards Facility real estate files recorded information concerning the construction of each of the standing buildings, and the JPL Edwards Facility "as-built" drawings documented the standing structures and their cultural landscape. Selected files were consulted for test stand process schematics and relevant operator's manuals.

Finally, the JPL Archive in Pasadena, California was consulted. The JPL Archive contains historic photographs, articles, historic reports, and JPL's newspaper. The JPL archive housed the most quintessential historic information germane to the JPL Edwards Facility.

The Air Force Flight Test Center History Office (AFFTC/HO) preserved sparse documentation pertaining to the JPL Edwards Facility. Because JPL was a non-Air Force tenant organization, AFFTC/HO did not retain JPL's historic records. The AFFTC/HO did, however, contain some useful historic Army reports which discussed JPL. The base library proved useful for locating secondary sources on JPL and the space program.

Off-base libraries and repositories were contacted and/or visited to complete the project. Beale Memorial Library (the main branch of the Kern County Library) in Bakersfield, California, was contacted and visited and the Walter W. Stiern Library at California State University, Bakersfield was visited. Secondary sources on JPL and the space program were located at both libraries.

FIGURE SOURCES

Notes: Building plans illustrated in this report are heavily edited copies of JPL engineering drawings. Most construction symbology and annotations have been removed in order to present each structure's plan more clearly. The copies of the engineering drawings used in this process are included in the project field notes for reference. Since the copies used for the illustrations are products of several "generations" of reproductions, they should not be regarded as scale drawings; inevitably, distortions have been introduced. Line quality had also deteriorated significantly on some drawings. In the interest of clarity, these were "touched up" for the HAER illustrations, but not redrawn due to time limitations.

Fig. 21 Left: Collection pit for Buildings 4232/E-33 through 4248/E-49 taken from: Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex-Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Typical Structural Sections & Details -- Bldgs E33 to E49,** Sheet S-2, 26 June 1962; JPL Drg. No. E33/8-0.

Right: Collection pit for Building 4236/E-37 taken from: California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Addition to Bldg E-37, Utilities Plan,** 25 June 1979 change to drawing dated 25 Feb 1977; JPL Drg. No. E37/9-1.

Fig. 22 Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California. **Electrical - Typical Bldg. Service Panel.** Sheet E-18, 26 June 1962; JPL Drg. No. E33/18-0. Warning Light Detail.

Fig. 23 Diagram by BHM [Bruce H. Morrison] 14 June 1982

Fig. 24 California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Building No. E-70, Site Plan, Floor Plan, Elevations and Details,** 2 June 1962; JPL Drg. No. E70/3-2.

Fig. 25 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Bldg. E-36, Grinder Bldg. Plans, Elevations, Sections & Details,** Sheet A-37 (6 of 35), 26 June 1962; JPL Drg. No. E36/1-0

Fig. 26 California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Propellant Processing Building E-84: Flr. Plan, Elevations & Sections.** Sheet A1, 3 June 1980; JPL Drg. No. E84/3-0.

Fig. 27 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Dryer Building: Plans, Elevations, Section, Details, Door and Finish Schedules,** Sheet A-39, 26 June 1962; JPL Drg. No. E38/1-0.

Fig. 28 California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Addition to Weigh & Control Bldg. E-35, Demolition, Floor & Roof Plans,** Sheet A-2, 3 Oct. 1983; JPL Drg. No. E35/3-0.

Fig. 29 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex-Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Liner Laboratory: Floor Plan and Schedules,** Sheet A-31, 26 June 1962; JPL Drg. No. E33/4-2.

Fig. 30 J. A. Barry. Standard Operating Procedure No. 2055, Revision 3. Manufacturing and Testing of Physical Property Samples. 16 January 1992; Figure 8, p. 13 of 33.

Fig. 31 J. A. Barry. Standard Operating Procedure No. 2018, Revision 4. Preparation of Cured Propellant Burn Rate Strands. 8 March 1990; Figure 1, p. 13 of 17.

Fig. 32 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex-Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Casting Building Plans, Elevations, Section, Details, Finish and Door Schedule,** Sheet A-34A, 26 Oct. 1962; JPL Drg. No. E34/3-0.

Fig. 33 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Mixer Building: Plan, Elevations, Section, Details, Finish and Door Schedule,** Sheet A-38, 26 June 1962; JPL Drg. No. E37/1-0.

Fig. 34 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Remote Prep. Bldg: Plans, Elevations, Section, Details, Finish and Door Schedule,** Sheet A-43, 26 June 1962; JPL Drg. No. E44/1-0. (Original building)

Ben Beckler & Associates Architects & Engineers 4227 Lankershim Blvd. North Hollywood, California 91602. California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Addition to Building E-44, Floor Plan, Elevations & Section** Sheet A-16, no date; JPL Drg. No. E-44/6-0.

Fig. 35 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Cure Building: Plans, Elevations, Section, Details, Finish and Door Schedules,** Sheet A-40, 26 June 1962; JPL Drg. No. E39/1-0. *General arrangement of E-39, -40 and -41.*

Fig. 36 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Preparation Building: Plans, Elevations, Section, Details, Finish and Door Schedule,** Sheet A-41, 26 June 1962; JPL Drg. No. E42/1-0.

Fig. 37 J. A. Barry. Standard Operating Procedure No. 2018, Revision 4. Preparation of Cured Propellant Burn Rate Strands. 8 March 1990; Figure 2, p. 14 of 17.

Fig. 38 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Control Building: Plans, Elevations, Section, Details, Finish and Door Schedule,** Sheet A-42, 26 June 1962; JPL Drg. No. E43/1-0.

Fig. 39 California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Propellant Storage Magazine, Floor Plan Sect's & Elev's** no date; JPL Drg. No. E45/1-0.

Fig. 40 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Magazine: Plans, Elevations, Section, Details, Finish and Door Schedule,** Sheet A-44, 26 June 1962; JPL Drg. No. E46/1-0.

Fig. 41 Austin Field & Fry, Architects Engineers 2311 West Third Street, Los Angeles 57, California. "Edwards Test Station Complex--Phase II, Jet Propulsion Laboratory, California Institute of Technology, Edwards Air Force Base, Edwards, California: **Magazine: Floor Plan, Elevations, Section & Schedules,** Sht. A-46, 26 June 1962; JPL Drg. No. E47/1-0.

Fig. 42 California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Sterilization Facility Bldg E-73, Mechanical Site Plan, Piping & A/C Plans, Sections & Details,** Sheet M1, 5 Jan. 1965; JPL Drg. No. E73/7-0.

Fig. 43 California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Addition to Technical Services Facility E-83, E.T.S. Floor Plan, Schedules and Details,** Sheet A-2, 19 June 1981; JPL Drg. No. E83/15.

Fig. 44 L. R. Shiraishi. Standard Operating Procedure No. 2082. Manufacture and Peel Testing of Propellant/Liner/ Insulation (PLI) Interface Test Samples. 7 February 1990; Figure 4, p. 10 of 18.

Fig. 45 California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Building No. E-68, Site Plan, Floor Plan, Elevations and Details,** 2 June 1962; JPL Drg. No. E68/4-1.

Fig. 46 Ben Beckler & Associates Architects & Engineers 4227 Lankershim Blvd. North Hollywood, California 91602. California Institute of Technology, Jet Propulsion Laboratory, Facilities Engineering and Construction Office, **Radiographic Inspection Facility, Floor Plan, Sections & Elevations** Sheet A, 25 June 1979; JPL Drg. No. E87/4-0.

Fig. 47 California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Assembly Bldg E-61 Floor Plan Foundation,** no date; JPL Drg. No. E61/2-0.

Fig. 48 Kistner Wright & Wright, Architect & Engineers, Los Angeles California. **Bldg E-69, Site Plan, FLoor Plan, Elevations and Details; Design and Construction of Oxidizer Bldg, Remote Process Bldg & Igniter Bldg, Edwards Test Station, Edwards, California.** Sheet A-3, 12 Dec. 1963; JPL Drg. No. E69/3-0.

Fig. 49 California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Addition to Building E-62,** 12 Dec. 1964; JPL Drg. No. E62/4-1.

Fig. 50 California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Vibration Test Facility Bldg E-72, Floor and Roof Plans, Sections, Details & Door Schedule,** Sheet A1, 21 May 1964; JPL Drg. No. E72/2-5.

Fig. 51 California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering, **Administration & Communications Wing, Building E-32, Floor Plan, Schedules, Abbreviations & Symbols,** Sheet A, 1 November 1962; JPL Drg. No. E32/4-3.

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B. Maps and Drawings

California Institute of Technology, Jet Propulsion Laboratory, Plant Engineering: engineering drawings of structures at JPL Edwards Facility. Drawings on file at JPL Plant Engineering, Pasadena, California.

C. Historical Photographs

A large collection estimated at 2000 images was reviewed at JPL Edwards Facility in 1994-1995. Original negatives are retained by JPL at its Pasadena, California headquarters as series 381, 344, and JPL. Of these images, ones used for this report or photographically copied for the HAER record are cited by negative number.

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