The Fermilab Tevatron Cryogenic Cooling System

An International Historic Mechanical Engineering Landmark
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Fermi National Accelerator Laboratory
United States Department of Energy
Batavia, Illinois

The American Society of Mechanical Engineers

INTERNATIONAL HISTORIC MECHANICAL ENGINEERING LANDMARK

CRYOGENIC COOLING SYSTEM
OF THE
FERMILAB TEVATRON ACCELERATOR
UNITED STATES DEPARTMENT OF ENERGY
1983

When placed in service, this was the largest very-low-temperature (cryogenic) cooling system ever built, with a capacity of 23.2 kW at 5 K (-268°C, -450°F) plus 1,000 liters (264 gallons) per hour of liquid helium. It maintains the coils of the magnets, which bend and focus the particle beam, in a superconducting state (zero electrical resistance). Power consumption is one-third what it would be at normal temperatures. Many innovations are included in the system, which has been a model for similar systems worldwide.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS — 1993

An Engineering Landmark

Over almost three decades, teams of scientists and engineers at the United States Department of Energy's Fermilab have developed and integrated very powerful magnets, computers and control systems into a unique instrument — the Tevatron particle accelerator. The Tevatron has opened new vistas into the fundamental subatomic structure of our physical world and provided the first large-scale application of important new technologies, including high-speed computing, superconductivity and cryogenic engineering — the practical utilization of phenomena below 123K (-150° C).

The 6.3-km circumference Tevatron is the world's first superconducting synchrotron. Foremost among the many engineering achievements that made this unique scientific instrument possible are its superconducting magnets and their impressive cryogenic cooling system. At its startup, the Tevatron's refrigeration system was seven times larger than any other in existence, and its liquefaction capability increased the world's capacity for producing liquid helium by more than 50 percent. These accomplishments won numerous awards, including the 1983 IR-100 Award for the Tevatron Transfer Line and the 1984 Outstanding Engineering Achievement Award from the National Society of Professional Engineers for the Tevatron Accelerator. It is for the technical achievement of the Tevatron's refrigeration system that the American Society of Mechanical Engineers (ASME) has designated the Tevatron's Cryogenic Cooling System an International Historic Mechanical Engineering Landmark.

The sections that follow describe Fermilab's research mission and the principles and operating characteristics of the Tevatron to place in context the subsequent discussion of the unique aspects of the accelerator's cryogenic cooling system.

The Nature of Matter

Fermilab supports the mission of the Department of Energy by conducting research in high-energy physics, the science that seeks to understand the fundamental particles and forces of the universe.

Greeks in the 5th century B.C. imagined that everything in the universe was made of *atomos,* indivisible pieces of matter that could not be reduced to a simpler state. By the turn of the 20th century, though, scientists had theorized that atoms were actually made of smaller particles. In this century, accelerators of increasingly higher energies have taken apart the atom, probing deeper inside it in search of the most basic form of matter. Early research into the atom

	ELECTRIC CHARGE (PROTON IS + 1)	*M = MASS IN ENERGY UNITS*		
The Quarks	**+2/3**	M = 5 MeV **u** **up**	M = 1500 MeV **c** **charm**	M > 91,000 MeV **t** **top** *NOT YET DISCOVERED*
	-1/3	M = 10 MeV **d** **down**	M = 150 MeV **s** **strange**	M > 5000 MeV **b** **bottom** *DISCOVERED at FERMILAB*
The Leptons	**0 (neutral)**	M = 0 or almost ∅ ν_e **electron neutrino**	M = 0 or almost ∅ ν_μ **muon neutrino**	M = 0 or almost ∅ ν_τ **tau neutrino** *NOT YET OBSERVED DIRECTLY*
	-1	M = 0.511 MeV **e** **electron**	M = 105 MeV **μ** **muon**	M = 1784 MeV **τ** **tau**

The Standard Model of particles and forces revealed its central nucleus (comprising neutrons and protons) and orbiting electrons. Today, using the Tevatron accelerator, high-energy-physics experiments can focus on the particles inside the nucleus.

These elementary particles are the building blocks of nature, and they act on the universe through simple physical laws. They are ordered in the Standard Model, a theoretical framework developed over 30 years of experimental high-energy-physics research. Fermilab physicists use accelerators to study the known fundamental particles that constitute the Standard Model of particles and forces and to search for new particles that may answer questions about the physical world. Matter, in its most basic forms, exists as quarks and leptons. The particles are progressively heavier from one generation to the next and, accordingly, accelerators of increasingly higher energies have been required to create them.

The single undiscovered element in the Standard Model is the top quark, a particle so massive that the only accelerator in the world capable of producing it is the Tevatron — the world's highest-energy accelerator. At Fermilab, an intensive search is underway to observe the top quark and to determine its mass.

The Tevatron System

Fermilab's Tevatron comprises five accelerators working in sequence to accelerate protons to nearly the speed of light. Protons are accelerated by an electric field and guided and focused by the magnetic field of an electromagnet. The Tevatron's superconducting magnets make possible the world's most energetic particle beams, making the Laboratory an international center for high-energy-physics research.

A ring of 1,000 superconducting magnets forms the Tevatron, a proton synchrotron so named because of its ability to accelerate protons to nearly one trillion electron volts around a circular path. The Tevatron ring lies immediately below the Main Ring accelerator in a 2.1-m diameter concrete tunnel buried 6.0 m below ground. Proton beams circulating in the Tevatron are either extracted and brought to collide with a stationary target or left in the ring and made to collide with countercirculating beams of antiprotons, the antimatter equivalent of protons. Out of these collisions emerge the exotic quarks and leptons that the Standard Model describes.

History

Finished in 1971, the Main Ring was designed to be Fermilab's premier accelerator and was built to reach an energy of 200 GeV — a level it eventually more than doubled. Fermilab's first director, Robert Wilson, began the drive to build the Tevatron in 1971, when he described to the Joint Committee on Atomic Energy how the Main Ring accelerator could be used as an injector to a second, higher-energy machine. In 1972, with the Main Ring recently completed, Fermilab physicists William Fowler and Paul Reardon drafted the proposal to DOE that ultimately would take the Tevatron from Wilson's concept to reality. To support the project, between 1973 and 1979 the Laboratory's superconductor research and development gave birth to the new magnet technology — coils of superconducting niobium-titanium wire cooled to the temperature of liquid helium — necessary for the Tevatron.

In parallel with the magnet effort, the Laboratory began a variety of projects to design and build prototypes of the refrigeration system. The concept of a hybrid system, which included local refrigeration supplemented by a Central

Helium Liquefier (CHL), was chosen to assure high reliability. In 1975 Fermilab, together with a group headed by Peter Vander Arend of Cryogenic Consultants, Inc., produced a conceptual design of the satellite refrigerators. Research and development focused on problems with reliable gas compression, filtering of process gas, reciprocating expansion devices and large-scale system integrity issues. Several prototype refrigerators and test stations were operated on site, providing data on the most appropriate equipment for the final system.

Construction

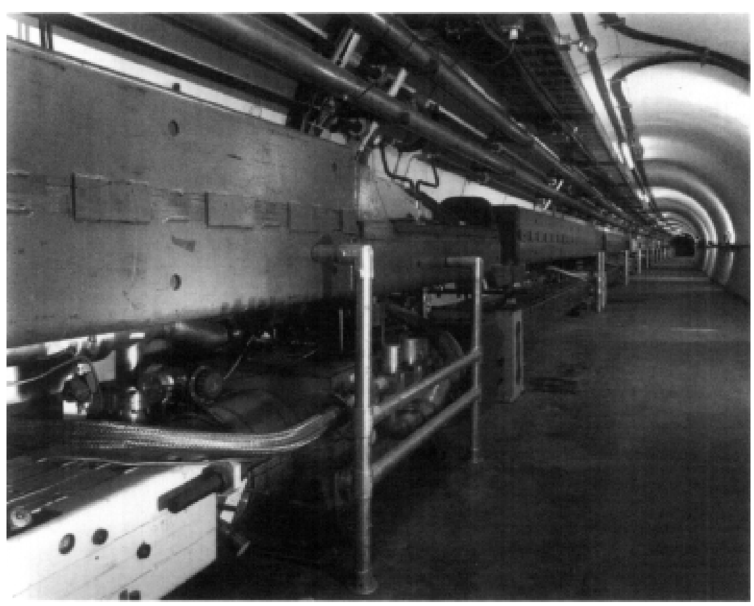
Construction of the Tevatron Cryogenic Cooling System (CCS) began in earnest in 1978. Satellite refrigerator construction and feed transfer line fabrication went forward in parallel. In early 1982, one-sixth of the cooling system was successfully tested. Construction work continued, and a half-ring test was performed in late 1982. Finally, in May 1983, the entire Tevatron system was cooled down and operated for the first time.

The Tevatron project drew on the resources of many talented personnel from around the Laboratory — engineers and physicists, technicians and laborers. J. Richie Orr headed the Tevatron project, and Helen Edwards served as Orr's deputy. Thomas Collins was the principal designer of the accelerator system, and Richard Lundy, Alvin Tollestrup and Robert Wilson managed the magnets' production and testing. William Fowler, Ron Walker and engineer Claus Rode were in charge of constructing the CCS for the superconducting magnets. Given the magnitude of the project, the Laboratory mounted a sitewide effort involving individuals from every department to meet the schedule for fabricating the cooling system. In 1989, President Bush bestowed the National Medal of Technology on Edwards, Lundy, Orr and Tollestrup for their achievements in the design, construction and operation of the Tevatron.

Refrigeration

Cooling the magnets is essential for the Tevatron to accelerate protons and antiprotons to nearly one trillion electron volts. Only at a near-absolute zero temperature can the magnets' coils become superconducting and carry the 5,000-ampere current that produces the strong magnetic field needed to control high-energy-particle beams.

In order to cool the magnets to approximately 5K (-268° C), they are encased in vacuum-tight stainless steel tubes called cryostats through which flow liquid helium and liquid nitrogen. Liquid helium is the coolant media for the magnets. Liquid nitrogen is used to shield the liquid-helium-temperature surfaces and to intercept the heat load from the room-temperature environment. The CHL delivers both helium and nitrogen to the satellite refrigerators and eventually to the magnets through an above-ground, vacuum-jacketed pipeline atop the Tevatron's earthen berm.

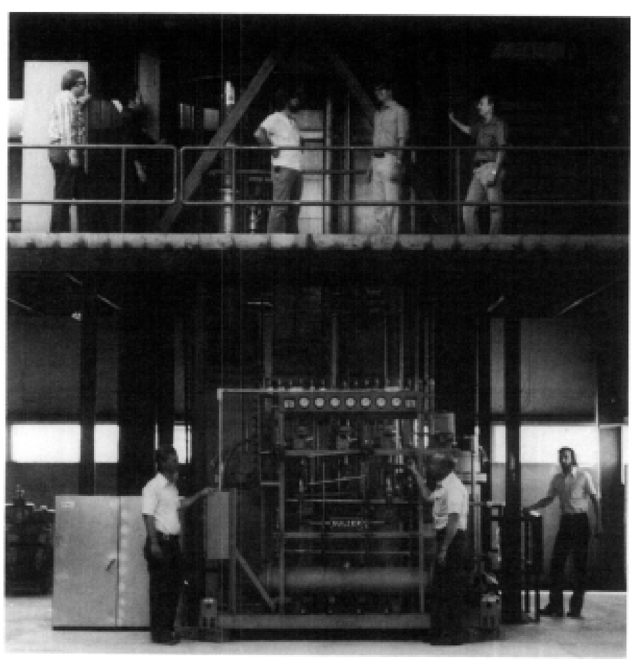


The tunnel of the main accelerator at Fermilab. The conventional magnets of the Main Ring are located above the superconducting magnets of the Tevatron.

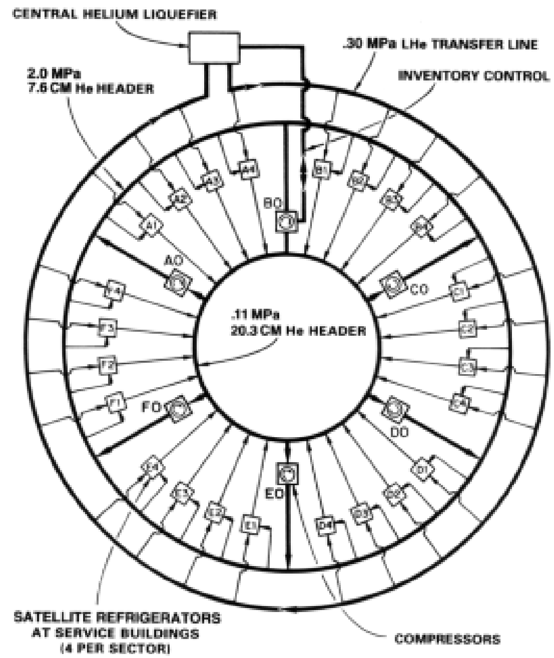
Engineering Significance of the Cryogenic Cooling System

A typical cryogenic refrigeration thermodynamic cycle differs slightly from a conventional refrigeration process. The compression system in a cryogenic process is quite standard; however, emphasis is placed on keeping the process stream free of contaminants. The higher-pressure compressed helium enters the heat exchanger where it is cooled to 80K by a combination of liquid nitrogen and the helium return flow. In the heat exchanger, some of the high-pressure gas is split off and undergoes an expansion process, lowering its pressure and temperature. This colder, lower-pressure gas is reintroduced to the return side of the heat exchanger to cool the remainder of the high-pressure flow.

Eventually, the remaining high-pressure helium gas is expanded, producing a change of state from gas to liquid. The liquid helium flows through the magnets, absorbing heat by vaporizing some of the fluid. A mixture consisting mostly of helium gas returns to the low-pressure side of the heat exchanger at approximately 4.5K, warming as it passes through the heat exchanger while it simultaneously cools the incoming flow. The gas exits the warm end of the cold box and returns to the suction of the compression system.



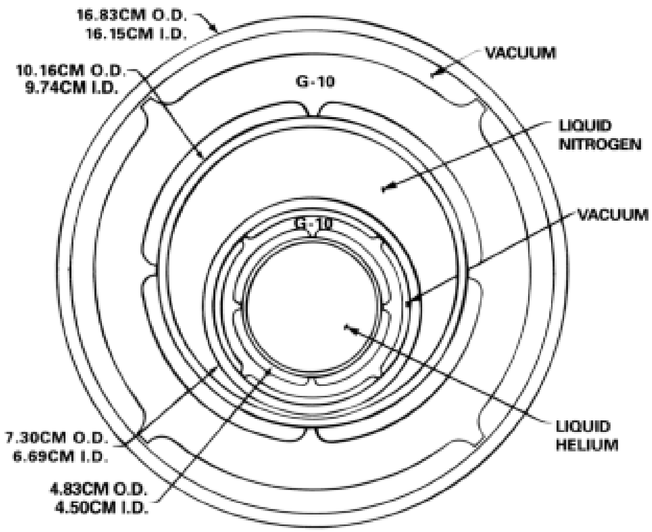
The CHL Helium Cold Box



Layout of the Refrigeration System

The CCS has a total capacity of 23.2 kW at 5 K (-268°C) plus 1,000 liters (264 gallons) per hour of liquid helium. The refrigeration capacity (23.2 kW) represents the maximum heat input accepted at the operating temperature (5K). The liquefaction rate (1,000 liters per hour) corresponds to the amount of liquid helium used to cool the magnet power leads. This flow, equivalent to approximately 35 g/sec, returns to the compression system as warm gas. All of its heat of vaporization and sensible heat is utilized in cooling the power leads. At the time of its commissioning, the Tevatron Cryogenic Cooling System was the largest helium-temperature system in the world.

The major components of the system are the CHL, the above-ground feed transfer line and the satellite refrigerators. The CHL supplements the cooling of the Tevatron magnets by delivering liquid helium via the feed transfer line to each of the 24 satellite refrigerators. Liquid helium is added to the process stream after the last stage of expansion in the satellite refrigera-



Transfer Line Cross Section

tors, increasing the flow to the magnets and to the return side of the heat exchangers. Adding the CHL liquid helium flow to the process boosts the refrigeration capacity of each of the satellite refrigerators by over 50 percent. The combination of a central facility and distributed refrigerators takes advantage of the higher efficiencies possible with large-scale equipment and provides continued operation in the event of an equipment failure.

CHL Components

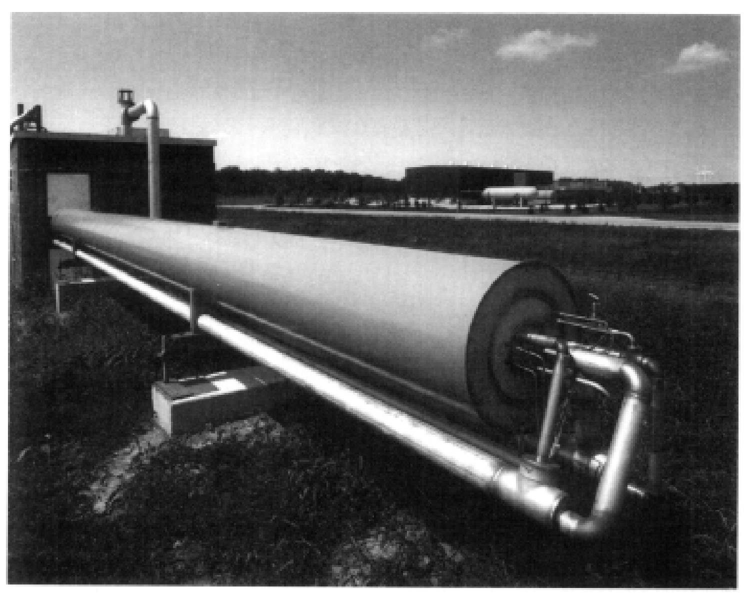
Three large helium compressors, a helium purification system, helium cold box, helium storage tanks and liquid nitrogen system all make up the CHL. Each helium compressor has a flow rate of 539 g/sec at a discharge pressure of 1.3 MPa (175 psig). Originally used for air service, the compressors were reconditioned and converted to helium service. The gas purification system purifies both the process- and seal-gas flow. Thirteen gas storage tanks located inside the Tevatron ring hold approximately 30,000 liquid liters equivalent of helium.

The cold box accepts helium gas at 300K (27°C) and produces liquid helium at approximately 5K (-268°C). Liquid nitrogen counter-flowing with high-pressure helium provides the first stage of cooling. The nitrogen system comprises two 76,000-liter (20,000-gal) storage dewars, numerous sections of piping associated with the shields and transfer line systems, and a nitrogen reliquefier that creates a semi-closed loop flow path. Final stages of cooling are achieved through the use of three high-speed turbine expanders. The helium system uses two on-line storage dewars and liquid helium pumps to provide a few hours of stable operation in case the main CHL refrigerator must be shut down.

Feed Transfer Line

The CCS owes a large part of its success to the system that transports its cryogens. The feed transfer line is fabricated from four stainless steel pipes held in position by spacers made of a glass fiber-reinforced composite. Twenty-six 250-m sections interconnected with vacuum jacketed U-tubes form the loop that constitutes the transfer line system.

The line consists of four nested pipes. The inner stainless steel pipe, which has an interior diameter of 4.50 cm, contains super-critical



Satellite Refrigerator Building

helium at 4.6 to 5.3K at 0.33 MPa (33 psig). This inner pipe is wrapped with 15 layers of aluminized Mylar and Dexter paper superinsulation. The 7.30-cm outer diameter second pipe and the 9.74-cm inner diameter third pipe form the subcooled liquid nitrogen passage used to shield the transfer line and magnets as well as to precool the refrigerated helium. The 16.83-cm outer diameter fourth pipe acts as the outer vacuum jacket.

A specially designed, off site facility produced the transfer line in 24.4-m lengths. A helicopter lifted the transfer line sections and expansion boxes into place, positioning 203 assemblies around the ring in 16 hours. Transfer line interconnect components were anchored to the floor of the refrigerator buildings, making alignment of the transfer line critical since the system is rigid without bellows. In May of 1980, a single section of transfer line was first cooled down, followed by a cooldown of the entire line in November 1982.

Satellite Refrigerators

The 24 satellite refrigerators consist of a compression system, warm distribution piping, a cold box, a liquid reciprocating expander, two flow-splitting subcoolers, two Joule-Thomson valves and a standby gas reciprocating expander. Six compressor buildings feed 2.1-MPa (290-psig) helium to the refrigerators through a 9.0-cm diameter discharge header located atop the Tevatron berm. A 22.0-cm diameter suction header located in the tunnel doubles as the cooldown line and quench relief header. The satellite refrigerators act as amplifiers by using the enthalpy of the helium supplied by the CHL as liquid, converting it to 4.5-K refrigeration and returning it to the compression system as 300-K gas. In normal operation, each refrigerator is supplied 4.48 g/sec of liquid helium from the CHL. In this mode, cooldown takes less than two days. The system can also be operated without the CHL supplying liquid helium. Cooldown in this mode requires twice as much time.

On May 29, 1983, after years of design and field testing, the entire Tevatron ring had been commissioned and was fully operational. Triumph for the developers of the CCS came on July 3, 1983 when the Tevatron accelerated a proton beam to 512 GeV. The world's highest-energy particle beam had been created in the Tevatron, doubling the energy of the Main Ring while reducing power consumption by a factor of three.

Performance

The CCS's performance over its lifetime has been impressive, as improvements to the system between experimental runs have continued to strengthen its overall design. During the 1984 experimental run, the CHL recorded an average weekly downtime of 2.5 hours while the satellite refrigerators experienced a downtime of about 12 hours. The 1985 experimental run saw the CHL's average weekly downtime drop to 2.0 hours, and average weekly downtime for the satellite refrigerators decreased to 3.5 hours. The 1987 experimental run had no downtime associated with the CHL, and downtime for the satellite refrigerators decreased to an average of 2.5 hours per week.

The performance gain from the 1984 and 1985 runs to the 1987 run is credited to three major improvements at the CHL: the addition of a third redundant compressor, improvement in helium purity and the addition of a liquid helium pump. During the five experimental runs that took place in the period between 1984 and 1989, the expanders logged a total of over one million hours. Improved alignment and material selection for use in the expanders have significantly improved satellite refrigerator downtime, resulting in a mean time between failures of over 8,300 hours during the 1989 run. Continued successful operation of the CCS can be attributed to improvements in equipment as well as to many contributions made by the dedicated Laboratory staff associated with this project.

Acknowledgments

Special thanks are owed to Claus H. Rode, formerly of the Fermilab Accelerator Division Cryogenic Department, for documenting the construction and testing of the Tevatron's Cryogenic Cooling System. Most of the technical information contained in this brochure comes from his 1983 talk on the subject given at the 12th International Conference on High-Energy Accelerators held at Fermilab. Much credit also goes to Richard P. Stanek who spearheaded the landmark designation effort and assisted with this brochure.

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The History and Heritage Program of the ASME

The ASME History and Heritage Recognition Program began in September 1971. To implement and achieve its goal, ASME formed a History and Heritage Committee, composed of mechanical engineers, historians of technology and the Curator Emeritus of Mechanical and Civil Engineering at the Smithsonian Institution. The Committee provides a public service by examining, noting, recording and acknowledging mechanical engineering achievements of particular significance. The History and Heritage Committee is part of the ASME Council on Public Affairs and Board on Public Information. For further information, please contact Public Information, the American Society of Mechanical Engineers, 345 East 47th Street, New York, NY 10017-2392, (212) 705-7740; telefax (212) 705-7141.

Designation

The Cryogenic Cooling System of the Fermilab Tevatron is the 39th International Historic Mechanical Engineering Landmark to be designated. Since the ASME History and Heritage Program began, 157 Historic Mechanical Engineering Landmarks, six Mechanical Engineering Heritage Sites and four Mechanical Engineering Heritage Collections have been recognized. Each reflects its influence on society either in its immediate locale, nationwide or throughout the world.

An ASME international mechanical engineering landmark represents a progressive step in the evolution of mechanical engineering. Site designations note an event or development of clear historical importance to mechanical engineers. Collections mark the contributions of a number of objects with special significance to the historical development of mechanical engineering.

The ASME Historic Mechanical Engineering Recognition Program illuminates our technological heritage and serves to encourage the preservation of the physical remains of historically important works. It provides an annotated roster for engineers, students, educators, historians and travelers and helps establish persistent reminders of where we have been and where we are going along the divergent paths of discovery.

References

Focus on Fermilab. Fermi National Accelerator Laboratory, June 1991.

Lederman, Leon M. "The Tevatron," *Scientific American,* March 1991.

Rode, Claus H. *Proceedings of the 12th International Conference on High-Energy Accelerators.* Fermi National Accelerator Laboratory, August 1983.

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