FREDERICK S. BILLIG

CHINA— AS VIEWED BY AN AEROSPACE ENGINEER

From November 5 through 18, 1979, a group of eight U.S. scientists and engineers (Fig. 1) visited ramjet and turbojet engine facilities in the People's Republic of China.

We took the train from Hong Kong to Canton on November 5, stayed overnight in Canton, and flew to Beijing (Peking) the next morning (Fig. 2). The next five days were spent in Beijing at the Institute of Aeronautics and Astronautics, the Institute of Mechanics of the Chinese Academy of Sciences, and the Power Plant Research Laboratory of the China Precision Machinery Corporation. On November 9, the delegation boarded the night train to Shenyang (Mukden), visited the Shenyang Aeroengine Factory and its Development Center on November 10 and 11, and returned by night train. Mr. Wilson of the Marquardt Co. and I left the delegation in Beijing to revisit the aforementioned facilities, while the remainder of the delegation went to the Sian Aeroengine Factory and the North Western Engineering University, and then to Chiang-Yu via Cheng Tu to visit the Aeronautical Research Establishment. The delegation was reunited in Beijing on November 18, flew to Canton, and left for Hong Kong the following day.

BEIJING INSTITUTE OF AERONAUTICS AND ASTRONAUTICS

Our first visit was to the Beijing Institute of Aeronautics and Astronautics, which is the principal educational institution in aeronautical engineering in China. Currently there are 3000 undergraduate and 200 graduate students. Its principal areas of study are aerodynamics, propulsion, structures, radio (electrical) engineering, and instrumentation.

After a warm greeting and a terse overview of the Institute, we were taken on a tour of the facilities. The first of two air supply systems that we saw consists of 3500 hp compressors that can pump 14 kg/s of air to 25 atm. The air storage system comprises 220 tanks with a total volume of 224 m^3. The maximum operating pressure of the facility is 8 atm. Air is heated in a combustion heater, without oxygen makeup, to a maximum temperature of 600°C and is available for compressor, combustor, and nozzle test rigs and a blowdown cold-flow wind tunnel with run times of about 2 min. The facility exhauster consists of two air-to-air ejectors that provide altitude simulation to 9 km. The wind tunnel has cross-section dimensions of 540 × 470 mm. Five contoured nozzles range in Mach from 1.5 to 2.75 and in Reynolds numbers to as high as 2×10^6. Models are mounted in a 3.8 mm diameter, six-component strain gauge balance that can provide continuously varying angles of attack of −6 to +8°. A minicomputer built in China (2 μs, 16K 16-bit words) is used in conjunction with a 200 sample/s data acquisition system.

Fig. 1—Delegation members and hosts in front of the Institute of Mechanics, Chinese Academy of Sciences. Left to right, first row: L. O'Brien, United Technologies Research Center; D. Wilson, The Marquardt Co.; C. Swan, Boeing Aerospace Co.; Wu Chung Hua, of the Institute; J. G. Mitchell, Arnold Air Force Station; Yao Peng, Avco Lycoming; Zhu Shouxin (the interpreter), Chinese aeronautical establishment. Staggered second/third row: Mr. Wu and Chen Nai Xing of the Institute; Dr. J. E. Bubb (delegation head), F. M. Fox and Assoc.; Tsien Shou Hua and Huang Chao Hsia of the Institute; the writer; Ko Shau Yen and S. Yue of the Institute. (E. Woll, General Electric Co., joined the delegation later.)

Beijing: Institute of Aeronautics and Astronautics
Institute of Mechanics, Chinese Academy of Sciences
Power Plant Research Laboratory, China Precision Machinery Corp.

Shenyang: Aeroengine Factory and Development Center

Sian: Sian Aeroengine Factory
North Western Engineering University

Chiang-Yu: Aeronautical Research Establishment

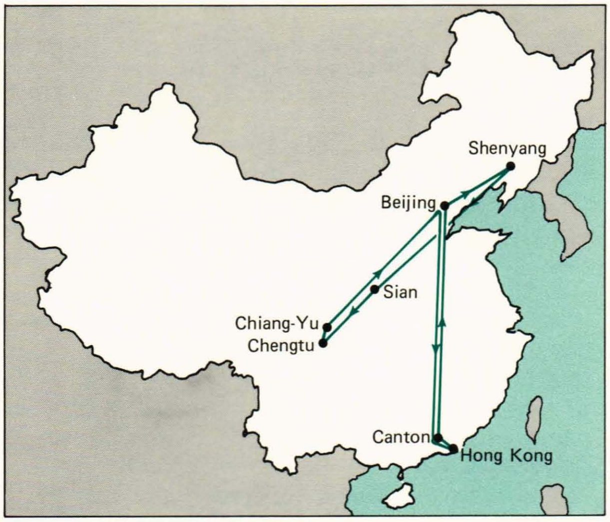

Fig. 2—Itinerary of the U.S. delegation to the People's Republic of China.

Another test rig is used to study supersonic mixing. Here we saw a 16-channel oscillograph recorder, a precisely machined spherical pressure probe about 0.8 mm in diameter containing eight separate tops, and Schlieren/shadowgraph systems, all made in China.

The second air storage system has a volume of 24 m^3 at 150 atm, 500 m^3 at 55 atm, and 1000 m^3 at 8 atm. A silica gel dryer is used in this system, and again air-to-air ejectors are used for the exhauster. Connected to the air supply is a manually controlled variable Mach number (1.5 to 3.5) wind tunnel with a 100 × 100 mm test section. Maximum total pressure in this tunnel is 8 atm and maximum run time is 5 to 8 min. A normal shock inlet about 50 mm in diameter was being tested.

Next we saw a connected pipe test setup of a ducted rocket. A rubber-based propellant with 20% aluminum and 3% magnesium was used on the gas generator. Air was brought to the secondary combustion chamber in four ducts about 50 mm in diameter each. The entrance angle was 90° and the flow rate was about 5 kg/s. The secondary combustor was about 150 mm in diameter and 760 mm in length, and the nozzle throat area was about 50% of the duct area. On our second visit, we were shown a video tape of a motor firing and were told that the air/rocket flow ratio was 3:1, the rocket pressure 70 atm, the burn time 20 s, and the average specific impulse (I_{sp}) 389 s.

We were then shown a modern large-scale computer facility that featured a 256K 32-bit word, 200,000 computations-per-second computer "Felix" built in Romania under French license. Peripherals included eight disk drives, five tape drives, two high speed card readers, and a high speed printer.

We saw a Continental jet engine with a maximum thrust of 870 kg that was used by students to measure thrust, specific fuel consumption, pressures, temperatures, etc. Quarter segments of several other engines, including the Rolls Royce HS 125, the GE J47, and engines for the MiG 15 and 17, were also in use as teaching aids.

Following our tour, each member of the delegation met with a particular group of 20 to 30 professors, graduate students, and staff for technical discussions. As it turned out, this format of "one on many" was to be typical of many subsequent sessions at this Institute and elsewhere. In some cases, an interpreter was needed, but generally the host scientist filled that role. The discussion usually focused on reports on the technical activities in the U.S., but a notable exception was a discussion by Professor J. S. Chin, a graduate of the University of Cranfield, England, on the enhancement of ignition in afterburners with the addition of small amounts of oxygen (see, e.g., Ref. 1).

Undergraduate students at the Institute are selected on the basis of nationwide examinations, which result in tuition-free university level education for only about 10% of the relevant age group in the population. A disproportionate 50% of those admitted are from urban secondary schools, whereas these students represent only 20% of the total population. The undergraduate curriculum has been extended from three years[2] to four years. Neither undergraduate nor graduate degrees are granted (graduate students spend either two or six additional years in the Institute), but the recognition that titles are important in dealing with the outside world may cause the issuance of degrees within one to two years.

INSTITUTE OF MECHANICS, CHINESE ACADEMY OF SCIENCES

On November 6, the delegation visited the Institute of Mechanics, Chinese Academy of Sciences in Beijing. I made a second visit to the Institute on November 15 to discuss catalytic combustion with Huang Chao Hsiang and his colleagues.

The Chinese Academy of Sciences, formed in 1949, is the national academic organization for research in science and technology in China. It contains four science and engineering universities, the Ministry of Education, and 112 research institutes, 36 of which are located in Beijing. The staff has grown from 300 in 1949 to 36,000 at present and includes 23,000 research scientists and engineers, 1600 research professors or associate professors, plus supporting personnel.

In 1960 the Power Laboratory was merged with several research institutes in gas dynamics that had been formed during 1956-60 into the Institute of Mechanics. At present there are 400 research scientists and engineers and 56 professors and associate professors.

The Institute has two major departments: Mechanics and Engineering Thermophysics. The Mechanics Department has five divisions: (a) High Speed Aerodynamics, (b) Solid Mechanics, (c) Explosion Mechanics, (d) Plasma Dynamics and Magnetohydrodynamics, and (e) Physical Mechanics. The Engineering Thermophysics Department also has five divisions: (a) Conversion and Transmission of Energy, (b) the 1st Research Division (Engine Thermodynamics and Aerothermodynamics of Turbomachinery), (c) the 2nd Research Division (Aerothermodynamics of Heat Engines), (d) the 3rd Research Division (Heat and Mass Transfer), and (e) the 4th Research Division (Combustion).

Professor Wu Chung Hua, Deputy Director, gave a brief description of the Institute and introduced the division heads, each of whom described his technical activities and showed us the test facilities.

The Mechanics Department

High Speed Aerodynamics — The division is involved in experimental and theoretical studies of supersonic, hypersonic, and viscous flows. Its facilities include:

1. Two supersonic blow-down wind tunnels with 200 × 200 × 300 mm test sections and Mach 1.6, 2.0, 2.5, 3.0, and 4.0 nozzles. The air supply system comprises a 7 kg/s compressor system with a maximum pressure of 9 atm and two 600 m^3 storage tanks with an 8 atm capability. The tunnels were built in 1958. Future plans call for a 30 atm, 7 kg/s air capability. The exhauster system is a single 600 m^3 vacuum tank. The run durations are 3 min at Mach 4 and continuous at Mach 1.6.
2. A Mach 6.6 to 18 shock tunnel with a test section diameter of 1.2 m (Fig. 3). The driver gas is a mixture of 6.5% oxygen and 93.5% hydrogen ignited by a 10 kV spark discharge. The driven gas is a mixture of hydrogen and nitrogen. Maximum pressure is 800 atm and the run time is 5 to 11 ms.
3. A Mach 8 to 12 shock tunnel with a test section diameter of 0.5 m. Driver and driven gas characteristics are similar to the larger tunnel.
4. A gun tunnel with a 200 × 200 mm test section and Mach 1.6 to 4 nozzles. An aluminum piston is used, and the maximum pressure is 1000 atm with run times of 20 to 30 ms.
5. An 800 kW arc-heated tunnel for ablation testing of reentry bodies.

Solid Mechanics — This division studies lightweight structures, computational methods of stress analysis, vibration fatigue, fracture mechanics, crack growth, and modeling of elastic and plastic deformations. Its laboratories are well equipped for measuring strain, crack propagation, etc., under constant and cyclical loading at ambient and elevated temperatures.

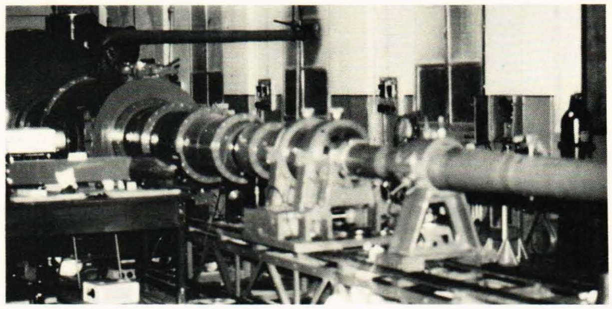

Fig. 3—Mach 6.6 to 18 shock tunnel at the Institute of Mechanics.

Explosion Mechanics — Programs include theoretical and experimental studies of the effects of explosions and high velocity.

Plasma Dynamics and Magnetohydrodynamics. — Investigations are conducted of the stability of magnetically confined high temperature plasmas and the industrial applications of low temperature plasma torches.

Physical Mechanics — Divisional studies comprise fluid mechanics, biomechanics, mechanical properties of matter, and cosmic gas dynamics.

The Engineering Thermophysics Department

Conversion and Transmission of Energy — This division studies basic academic education with particular emphasis on engineering thermodynamics, aerothermodynamics of heat engines, heat and mass transfer, and combustion.

1st Research Division (*Engine Thermodynamics and Aerothermodynamics of Turbomachinery*) — The division has 7 senior scientists, 18 junior scientists, and 23 engineers. Professor Chen, who speaks excellent English with a Russian accent reflecting his academic training in the Soviet Union, gave a rather detailed description of analytical work concerning an extension of Professor Wu's renowned work on turbomachinery flow theory. His work uses nonorthogonal curvilinear coordinates and nonorthogonal velocity components to provide a design procedure for axial flow turbomachine blades. Streamline extension techniques, matrix direct solution, and line relaxation methods are employed in the computer routines. By use of fictitious grid points, the storage requirement ($\approx$32K) in the matrix direct solution is reduced by about one-half.

Figure 4 shows a M $\geq$1.3 transonic cascade tunnel that has a 220 × 290 mm 5-blade cascade test section. The cylindrical tube running transverse to the tunnel axis houses the Schlieren/shadowgraph optics and provides an optical path that is free from room disturbances. Maximum airflow is 21 kg/s; maximum Reynolds number is 3 × 10^6; and

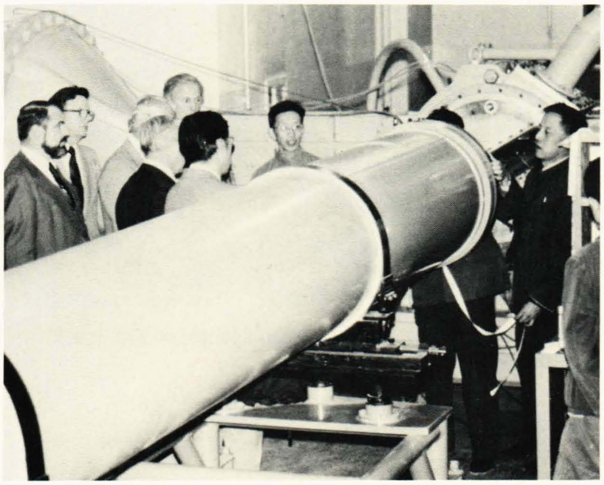

Fig. 4—Mach 1.3 cascade tunnel at the Institute of Mechanics.

maximum run time is 200 s. We were also shown a 500 kW rotating cascade driven by a 3000 kW motor at 750 rpm.

2nd Research Division (*Aerothermodynamics of Heat Engines*) — The division has three senior scientists, seven junior scientists, and seven engineers. The facilities include two centrifugal compressor test rigs, an axial turbine test rig, and a pressure wave supercharger engine. The compressor rigs are 250 kW and 850 kW with maximum speeds of 37,000 rpm. Under construction is a 3000 kW axial compressor test rig. The pressure wave supercharger is attached to a 150 hp rotary combustion engine.

3rd Research Division (*Heat and Mass Transfer*) — The division has three senior scientists, nine junior scientists, and ten engineers. Work includes experimental and theoretical studies of film cooling of turbine blades, analysis of flowfields in turbojet and ramjet combustors, tests and analysis of sodium heat pipes to 800°C for cooling electrical equipment, techniques for harnessing solar energy, and heat transfer to improve the cooling of air-and water-cooled engines. In the tour of the heat transfer laboratory, we saw film cooling tests on flat plates and blade cascades, low and high temperature heat pipes, and a rotary combustion engine. This 450 cc, 49 hp air-cooled engine had been run the equivalent of traveling 17,000 km without repair at an average specific fuel consumption of 25 gal hp-h.

4th Research Division (*Combustion*) — Five senior scientists, fifteen junior scientists, and four engineers comprise the division. Tasks include tests and analysis of annular gas turbine combustors and afterburners with emphasis on durability, oscillatory mixing and flow stabilization, the use of catalysts, the ignition of lean mixtures, combustion of hydrogen and air in supersonic flow, and mixing of parallel flows in a ramjet combustor. During the early 1960's, Professor Wu and his colleagues were quite interested in supersonic combustion, but at present the work in this area is minimal. Nonetheless, many of the Chinese scientists were interested in my lectures on the subject and asked many questions regarding details from the contemporary U.S. literature.

POWER PLANT RESEARCH LABORATORY, CHINA PRECISION MACHINERY CORP.

On November 7, the entire delegation visited the Power Plant Research Laboratory located at Yungang, southwest of Beijing in the Fengtai District. (En route we crossed the Yongding River on a new bridge adjacent to the old Marco Polo bridge, passing into an area of restricted access to foreigners.) The Laboratory is responsible for the development of propulsion systems, primarily ramjets, some testing of turbojets, and some research for the China Precision Machinery Corp. The Laboratory is 35 to 40 years old and the airbreathing test facilities were built in the late 1950's and early 1960's. Its activity during the Cultural Revolution (1966-69) was limited, but it is currently very busy. Most of the staff of 600 are engineers.

Mr. Shu Shen Wang, the Director, described the activities of the Laboratory and led the tour of the test facilities (shown schematically in Fig. 5). Two 3500 kW centrifugal first stage compressors and two 1500 kW second stage superchargers comprise the pumping system. The air is stored in a large number of cylindrical tanks having a total volume of 6840 m^3. Of this volume, 6600 m^3 is stored at 22 atm, the remainder at 220 atm. Air is piped to both the five test cells and two-stage air-air ejectors (Fig. 5) that are used to exhaust cells 2 through 4. In contrast to most U.S. airbreathing test facilities, which use common exhausters, each cell has its own ejector system. The maximum flow to the test cells is 230 kg/s, which can be heated directly in one of two vitiation heaters (cells 2 and 3) or indirectly in a tube-and-shell heat exchanger. For direct heating, the air is subdivided, with half of it passing into 16 kerosene-fueled turbojet can combustors and the other half bypassed for subsequent mixing. No provision is made for oxygen makeup. The vitiation heater is used for temperatures up to 350°C. The tube-and-shell heat exchanger is used for the range of 350 to 700°C, so it is possible to simulate flight Mach numbers up to 4.2 in the tropopause with unvitiated air.

Five test cells are in operation: a sea level cell, two direct-connect high altitude cells, a supersonic high altitude free-jet cell, and a ram-air-turbine test cell. A sixth cell for testing solid ducted rockets is currently under design. Test Cell 1 is approximately 2.6 m in diameter and 12 m in length, with a hydraulically actuated cell closure similar to Cell 8 at the Marquardt Co. Both ramjet and turbojet engines, with inlet diameters up to 800 mm and 1000

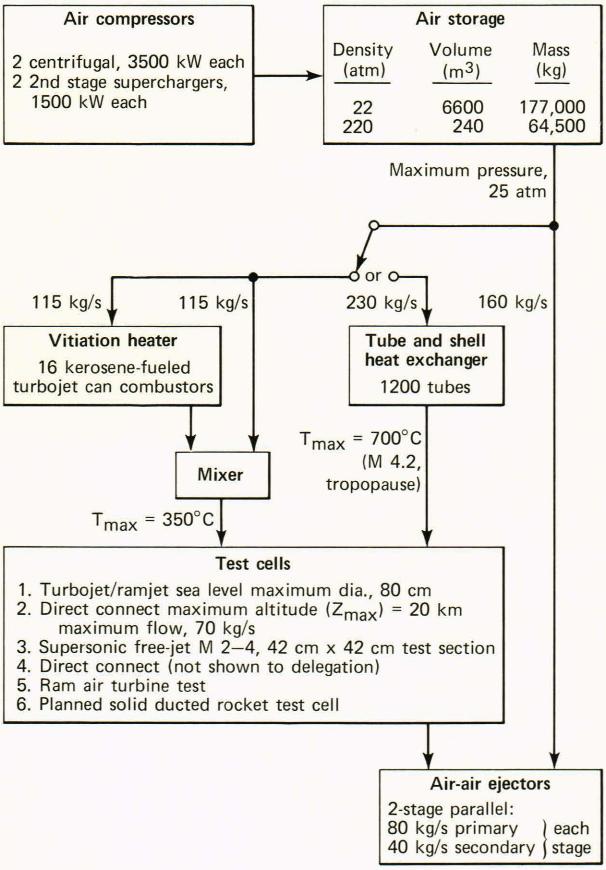

Fig. 5—Schematic diagram of the ramjet test facility at the Power Plant Research Laboratory.

mm, respectively, can be installed on a load cell balance for testing, with a maximum static thrust limit of 5700 kg.

Test Cell 2, completed in 1965, is a high altitude direct-connect facility with a maximum simulated altitude of 20 km and a maximum flow of 70 kg/s. This cell is about 1.8 m in diameter and 4.6 m in length; cell closure is accomplished by hoisting a half cylinder cap in place. Cell 3, completed in 1969, is a Mach 2 to 4 free-jet facility. Five nozzles with nominal Mach numbers of 2.0, 2.5, 3.0, 3.5, and 4.0 are used. Minor adjustments can be made in the nozzle throat blocks (not during a run) to obtain ±0.25 M change from the nominal design Mach number in the test section. The nozzle exits are square, 420 mm on a side, and the major fraction of the air not captured by a test engine inlet, generally circular in cross section, passes through a bypass diffuser to the ejector system. The cowl of the engine inlet is then centered in a cut-out of the downstream end of the test cabin, which is sized to provide a small gap that permits clearance at angles of attack. The maximum engine diameter tested to date is 300 mm, which corresponds to 40% of the nozzle discharge area. Engines are mounted on a 1000 kg maximum thrust stand that can be rotated in the horizontal plane from −2 to +10°. A long-focal-length Schlieren/shadowgraph optical system located in the vertical plane is used to view the flowfield via camera and TV coverage. Maximum flow rate to this cell was stated to be 115 kg/s, which would permit sea level testing at Mach 2 and altitude simulation of 1.3 and 2.1 km at Mach 3 and 4, respectively. Run times are typically 3 min. Instrumentation consists primarily of strain gauge pressure transducers and thermocouples connected to a 300-channel data acquisition system.

Cell 4 was not shown to the delegation. Cell 5 is a smaller test cell used for the development of ram-air turbines and pumps. Maximum airflow to this cell is 4 kg/s at pressures of 10 atm and temperatures of 600°C. We were shown a turbine/pump that produces 180 hp at 4000 rpm with a pump outlet pressure of 100 atm at a flow rate of 10 l/s. The cell is also used for testing seals and bearings.

Under development at the facility were a Mach 3.5 to 4.0 ramjet, similar in design to the Typhon that was developed in the U.S. in the early 1960's, and a solid ducted rocket. We were also shown a wind tunnel test model of an aft-inlet ramjet installed on a variable flow throttle support. The 1/4-scale model was about 88 mm in diameter, had been designed by method of characteristics, and was very precisely machined and assembled. It had been tested in a 1 × 1 m wind tunnel at the Institute of Mechanics in Beijing at angles of attack up to 6°.

Mr. Wang also described briefly other research efforts at the Laboratory, including: analysis of bridging on spike and cone inlets; evaporation of droplets; injection, mixing, and atomization; studies of atomization from centrifugal injectors by the "wax" method; low temperature ignition of kerosene and high density fuels; and catalytic ignition and combustion.

SHENYANG AEROENGINE FACTORY AND DEVELOPMENT CENTER

The U.S. delegation took the overnight train on November 9 that arrived in Shenyang the following morning. Shenyang, an industrial center of 4 million people located in Manchuria, was occupied by the Japanese from 1931 until VJ Day. Interesting was the widespread use of Pinyin (the Chinese phonetic alphabet) on street signs and buildings. The State Council has decreed that the Roman alphabet will be used to spell out Chinese names and places according to standard Beijing pronunciation beginning January 1, 1979.

On the morning of November 10, we visited the Aeroengine Factory where J6 and J7 engines for the MiG fighters are manufactured. The factory was built in the 1950's with the help of the Soviets. There are about 10,000 employees, 10% of whom are technical (500 engineers, 500 graduates — a graduate must have 6 to 7 years experience before he is designated an engineer). The factory has 2000 "precision" machine tools and turns out 1000 engines per year on a two-shift, six-day (the standard work week in China) operation. The equipment varied from 1930-vintage drop forges to computer-driven lathes for finish machining of compressor blades.

Following a visit to the manufacturing plant, we witnessed a "green run-in" of a J7 engine. With the afterburner operating, the exhaust nozzle was bright yellow and the three actuators and supports were a dull red, a most impressive sight. Normal procedure is to operate the engine for two hours at sea level conditions at various throttle settings, shut it down, disassemble and check all parts, and reassemble it for three hours of additional testing before shipment to the aircraft assembly plant. We also saw an advanced 9070 kg bypass engine about 1.15 m in diameter that was under development at the Development Center, which we visited in the afternoon.

The Development Center is a large facility used for engine development, including component testing of the compressor, combustor, turbine, afterburner, and exhaust nozzle. Power is supplied to the facility by two 18,000 kVA transformers that step down the voltage to the 6300 V compressor motors. The air supply consists of six centrifugal compressors driven by 1050 kW synchronous motors that pump 5 kg/s each to a pressure of 8 atm. This machinery was built in the Soviet Union and installed in Shenyang in the 1950's. In addition to the aforementioned bypass engine, we saw a 20,000 rpm spool test rig, several combustor test rigs emphasizing reignition capability, a set-up for bypass duct burning that was instrumented with an IR spectrometer, and a complete structural testing laboratory.

CONCLUSIONS, COMMENTS, AND TRIVIA

There is no doubt that the delegation members were truly "guests of the People's Republic of China," which is how we were treated and greeted on every occasion. The food was superb, the beer excellent, the wine sweet, and the mao tai (a liquor distilled from sorghum) strong. We entered and left China without clearing customs. We were met at each city by two or more interpreters, escorted to VIP waiting rooms, and chauffeured in vans or automobiles to guest houses or hotels, and were the guests at a banquet in each city. Our hosts could not have been more gracious.

There is no question that the principal objective of the delegation's visit was met, *viz.*, "to promote cooperation through the exchange of scientific information." The discussions were free and open. Questions in areas that would be regarded as sensitive were avoided for the most part, but when they arose, the disinclination to answer was unhesitatingly accepted. The Chinese were appreciative of the technical advice they were given and want further exchanges. We were impressed by both their technical capability and their strong commitment to the training of aerospace engineers and to the development of facilities for testing and manufacturing advanced jet engines. Our hosts were very familiar with U.S. technical literature; it was not uncommon to be asked very detailed questions regarding derivations of one's equations or methods of solution, or explanations of a particular figure where the questioner had a photostatic copy of the material in hand. On many occasions, the Chinese described their own equipment as inferior and their technology as primitive. The delegation felt quite differently. We were impressed by both their technical capability and their ability to manufacture complex equipment. Obviously, although their resources at present are limited, they are focused on specific goals. There is little doubt that their national commitment to "The Great Goal of Four Modernizations," *viz.*, achieving modernization of agriculture, industry, national defense, and science and technology by the end of this century, will result in world prominence in aerospace sciences and technology.[3]

We were quite impressed by the apparent adequacy, if not abundance, of food. The fields of South China were lush, interwoven with myriad irrigation channels. In North China it was harvest time for bok toi, the white cabbage, which was stacked like cordwood on many of the sidewalks of Beijing and Shenyang. It sells for about four cents a kilogram and can be used during the entire winter. Wages range from $40 to $70 per month. All able-bodied adults work a six-day, 48-hour week, with five public holidays and one week vacation each year. Housing is very modest, being assigned by the state and consisting of one to two rooms per family at a cost of $2 to $5 per month. Most people live within walking or bicycling distance of their work. Private ownership of automobiles is nonexistent, but higher officials are assigned vehicles with drivers. Most of the automobiles are made in China and are eastern European in appearance. Both city and rural roads are crowded with buses (many imported), automobiles, trucks, vans, mechanized or animal-drawn farm vehicles, bicycles, and pedestrians.

Primary and secondary education for all is provided by the government but university admission is limited and very competitive. Nationwide entrance examinations are the basis for admittance. University life has returned to normal following the acute disruptions of the Cultural Revolution, which created a large void in the population of those with advanced education. Many people with technical inclinations had to be trained on the job during that period; they represent a significant part of the technical staff at the Power Plant Research Laboratory and similar facilities. Such people, who are anxious for opportunities to study abroad, inundated the writer with résumés and requests for the names of people to contact in the U.S. Similarly, there were many expressions by university people for establishing programs to exchange graduate students.

Manufactured goods of all types were available in stores with prices comparable to the United States, e.g., good quality bicycles selling for $120 and color television sets for $500. However, not only does such a purchase represent many months of saving, but for many goods a ration coupon issued by the state is a prerequisite for purchase. The state-run television system broadcasts only a few hours a day, with heavy emphasis on education. In Beijing there is a daily program teaching English and one on computer programming (in English). We were also told that English is taught by radio throughout the nation.

Finally, although our sightseeing was limited, the places we visited — the Forbidden City, the Great Wall, the Ming Tombs, the Summer Palace, Beihai Park, and others — were magnificent.

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