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A RADIANT HEATING TEST FACILITY FOR SPACE SHUTTLE ORBITER THERMAL PROTECTION SYSTEM CERTIFICATION

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ABSTRACT

A large-scale Radiant Heating Test Facility has been constructed at the NASA Lyndon B. Johnson Space Center so that thermal certification tests can be performed on the new generation of thermal protection systems developed for the Space Shuttle Orbiter. This facility simulates surface thermal gradients, onorbit cold-soak temperatures down to 200 K (-100° F), entry heating temperatures to 1710 K (2620° F) in an oxidizing environment, and the dynamic entry pressure environment. The capabilities of the facility and the development of new test equipment are presented.

INTRODUCTION

The Space Shuttle Orbiter has a lightweight reusable thermal protection system (TPS) that was developed to withstand the dynamic acoustic, thermal, and load environments associated with launch, orbit, and atmospheric entry. Although several thermal protection systems are used on the Orbiter, the most demanding requirements apply to the leading edge structural subsystems (LESS), where maximum heating and the most severe thermal gradients occur in the stagnation regions of the leading edges. A test program is in progress at the NASA Lyndon B. Johnson Space Center (JSC) to certify the LESS by subjecting full-scale test articles of the nose cap and the wing leading edge (WLE), which make up the LESS, to sequential tests that simulate launch acoustics, air loads, and entry heating. The entry heating simulations, scheduled to begin in July 1980, are being performed to verify thermal analyses used to design the LESS, to demonstrate the LESS structural integrity under thermally induced stress, and to evaluate the effects of oxidation on the LESS performance.

Because a new facility was required to accept items as large as the LESS test articles, a large-scale Radiant Heating Test Facility (RHTF) was constructed at JSC. The entry environments simulated in the RHTF include peak temperatures to 1710 K (2620° F) in an oxidizing environment, severe surface thermal gradients, cold-soak temperatures to 200 K (-100° F), and dynamic pressure. The concurrent simulation of temperature and pressure in an oxidizing environment is important because the LESS have reinforced carbon-carbon (RCC) components whose oxidation characteristics, and therefore mission life, are sensitive to these factors. The RCC forms the exterior surface of the LESS; simulation of severe surface thermal gradients on RCC is important to the structural behavior of the RCC and to the indepth temperature response of the test article, which is dependent on

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cross radiation from the RCC. Simulation of cold-soak conditions that result from the orbital attitude of the vehicle relative to the Sun are required to demonstrate that the attach fittings have adequate allowance for thermal contraction and to precondition the test articles before heating because the thermal stresses are increased by this effect.

To accomplish the test objectives associated with simulation of oxidation effects and surface thermal gradients, the RHTF incorporates two unusual technical features: a new type of multizone large-scale heater that operates at high temperatures in an oxidizing environment over a wide pressure range, and a multichannel fiber optic pyrometer system that, in combination with a digital computer, controls the power to the heater.

Because the LESS test requirements dictated the design of the RHTF, these requirements are described in detail and used throughout the paper to illustrate the functions of the facility systems. However, the RHTF test capabilities are not restricted to the LESS tests because another objective was to construct a facility that could, with little or no modification, test other areas of the Orbiter TPS. The design and development of the RHTF to perform complex large-scale entry simulation tests on the Orbiter LESS is the subject of this paper.

TEST ARTICLES

The nose cap and WLE test articles (fig. 1) were fabricated from a variety of specialized components to form a strong lightweight assembly capable of withstanding the severe entry heating conditions in the Orbiter stagnation regions while limiting aluminum structure temperatures to less than 450 K (350° F). The higher temperature regions of the LESS are fabricated from RCC, a laminate of carbon cloth that is molded to the required shape and coated with silicon carbide to inhibit oxidation. The RCC is attached to the Orbiter primary structure with a complex set of high-temperature linkages that performs three important functions: (1) attaches the RCC to the structure, (2) allows differential expansion of the RCC components over a wide temperature range, and (3) thermally isolates the RCC from the primary structure. The attachment fittings are covered with flexible insulation to shield the structure from radiant heating at the attachment points. The area aft of the RCC is covered with high-temperature reusable surface insulation (HRSI), a lightweight silica insulation with a silicon tetraboride thermal emissivity coating that is bonded to the vehicle with a flexible strain isolation pad (SIP) and silicon rubber adhesive. A large section of the Orbiter primary structure (the forward fuselage area and bulkhead or the nose cap) and a portion of the wing spar and wing box (the WLE) are incorporated in both test articles to mount the RCC and HRSI and to ensure proper test boundary conditions.

TEST ENVIRONMENTS

To meet the objectives for LESS certification, the nose cap and WLE test articles must be subjected to environments that simulate critical flight conditions. These environments are as follows.

1. Temperatures ranging from 240 to 200 K (-30° to -100° F) to simulate onorbit thermal conditions and the thermal gradients resulting from entry heating of the cold-soaked TPS.

2. Heating at specified rates from 200 to 1730 K (-100° to 2650° F) and cooling to near-ambient conditions over a period of 2000 seconds to simulate entry heating conditions from a 61-kilometer (200 000-foot) altitude to touchdown. Typical entry heating profiles are shown in figure 2.

3. Surface temperature gradients representative of the entry environments to evaluate the effects of thermally induced stresses within the nose cap and WLE systems. Gradients are produced by dividing the radiant heaters into a number of zones, then independently controlling each zone to a specified temperature profile. Several of these profiles for the nose cap are shown in figure 2 and the corresponding isotherms are shown in figure 3.

4. Control of the test article ambient pressure over a dynamic range from 0.013 to 101.3 kilopascals (0.1 to 760 torr) to simulate the entry altitude pressure environment. Degradation of RCC strength is expected to result from subsurface oxidation that occurs when microcracks in the protective silicon carbide coating of the RCC admit air. Because RCC oxidation effects and the thermal conductivity of LESS insulation depend on temperature and pressure, control of the pressure profile to within ±267 pascals (±2 torr) over the entire dynamic range and synchronization of the temperature and pressure profiles are essential.

TEST SEQUENCE

A typical test sequence begins by evacuating the chamber and repressurizing it to about 50 kilopascals (380 torr) to prevent condensation from forming during the cold soak of the test article. The test article is radiantly cooled in front of a cold shroud that is cooled by chilled methanol. When the cold-soak conditions have been achieved, the test article is moved to a position in front of the radiant heater, the nitrogen is pumped out of the chamber, and coordinated repressurization and heating profiles are begun. After peak temperature is achieved, progressively less power is applied to the heaters until they are no longer active. The test article is then returned to the cooling shroud so that heat stored in the heater elements will not delay the prescribed test article cool down. Before the test article is moved from the heater position, the cooling fluid circulating through the cold shroud is switched over to the cooling water circuit. The operation of these systems is described in more detail later.

RHTF SYSTEMS

The RHTF (fig. 4) is composed of several primary and support systems that provide the desired environments. The altitude simulation system consists of an altitude chamber, vacuum pumps, and a vacuum/repressurization control system. This system is central to the facility since all tests are conducted within the chamber. Figure 5 shows the altitude chamber with the WLE test article, the heater, and the cooling shroud installed. Because the altitude chamber can accommodate only one heater and one test article at a time, individual heaters for the nose cap and the WLE are assembled on carriages that roll on rails inside the chamber to facilitate rapid installation and removal. The heaters are controlled by a computerized feedback control system.

The coolant system is subdivided into several subsystems. The test coolant subsystem provides closed-loop water cooling for the heater reflectors and auxiliary shrouds to prevent overheating of the altitude chamber walls and instrumentation wiring. The refrigerated coolant subsystem circulates refrigerated methanol through the cold shrouds to simulate onorbit cold soak. A test article positioning subsystem with rails and an air-motor-powered chain drive is used to move the test article from the cold shroud to the heater position. A cryogenic subsystem supplies dry gaseous nitrogen to the altitude chamber to prevent condensation of atmospheric moisture on the surface of the test article and the cooling shroud during cold soak. The instrumentation and computer systems are used for test data acquisition and control and for critical measurement limit checks and automatic aborts. The computer provides real-time data output through cathode ray tube (CRT) terminals and a plotter for monitoring and quick-look evaluation of test data.

Heater System

The heaters have the most stringent requirements of any system in the RHTF; consequently, they received the most extensive design and development effort. These heaters must operate repeatedly at temperatures up to 1810 K (2800° F) in a low-pressure oxidizing environment without arcing while providing thermal gradients on the surface of the test articles.

Several heater concepts were considered, but the most promising used a resistance-heated graphite bar or plate as a heater element. Graphite heater elements can operate at high temperatures and can be readily machined to complex heater element geometries, thereby simplifying the assembly of compound curved arrays. The operating voltage of graphite heater elements can be limited to prevent arcing at low pressures by adjusting the cross-sectional area and selecting a graphite with the appropriate electrical resistivity.

WLE heater.- The WLE heater (fig. 6) is composed of 19 heater modules, 11.4 centimeters (4.5 inches) wide by 185 centimeters (73 inches) long, configured in a WLE array by a support structure that also serves as a manifold for supply and return of coolant to the heater modules. Each module (fig. 7) contains two "hairpin" graphite elements supported by power electrodes at one end and a pivoted graphite support post at the other. This pivoted post allows the 1 centimeter (0.4 inch) of thermal expansion that the element experiences between 295 and 2035 K (70° and 3200° F) without overstressing the elements. The electrodes are water cooled and are supported by two rectangular tubes that also serve as the coolant manifolds for the module. Gold-plated base, side, and end reflectors are installed for maximum thermal efficiency and to limit the view factor of each module.

The modular construction serves two functions: each module can be independently controlled and the heater modules can be mounted on an alternate support to test flat articles up to 1.8 by 2.4 meters (6 by 8 feet) with 22 heater zones. If required, the center section of each module can be removed to make an array 1.2 meters (4 feet) wide for testing smaller articles.

The WLE heater was originally fabricated with bare graphite elements capable of reliable long-term operation at temperatures of 2035 K (3200° F) in a nitrogen atmosphere. However, because of the need to determine the effects of subsurface oxidation on the RCC, oxidation-inhibiting coatings were developed for the heater elements so that the heater could also be operated in an air environment. These coated heater elements were fabricated from graphites compatible with the coating but with relatively high electrical resistance. The increase in electrical resistance was compensated for by redesigning the heater element from a two-pass hairpin configuration to a shorter single-pass configuration. Four single-pass coated elements are installed in each heater module on new water-cooled electrodes. The electrodes at one end of the heater are fixed; those at the other end are mounted on electrically isolated ball bearing slides to accommodate the thermal expansion of the elements. The single-pass configuration offers another operational advantage by eliminating the high electrical potentials across the narrow gap at the electrode end of the double-pass elements, thereby reducing the probability of electrical arcing.

<u>Nose cap heater</u>.- The nose cap heater (fig. 8) forms a paraboloid of revolution that approximates the exterior surface contour of the nose cap test article. The heater is composed of 96 triangular and trapezoidal graphite elements arranged in 22 independent heating zones (fig. 9). The zones are arranged and sized to provide the desired gradients on the test article surface and to match the power capabilities of the heater control system as closely as possible.

The nose cap heater elements have serpentine current paths (fig. 10) to provide the proper resistance and evenly distribute the power over the surfaces of the elements. Element thickness is sized to provide the proper resistance and a wide current path so that a high ratio of heated-to-unheated surface area (approximately 70 percent) is maintained. This high ratio allows the heaters to operate only 83 K (150° F) hotter than the test article under peak temperature steady-state conditions. Also shown in figure 10 are the large-diameter electrodes that are capable of conducting high currents without encountering electrical contact problems resulting from excessive resistive heating.

A water-cooled stainless steel reflector is located approximately 15 centimeters (6 inches) behind the element surface to improve the efficiency of the heater and to shield the associated electrical connections and coolant hoses from excessive heat. The reflector and heater electrodes are mounted on a large stainless steel structure suspended from a carriage installed on rails in the chamber. The electrodes for the nose cap heater are rigidly mounted and thermal expansion is accommodated by element flexing.

Coated heater elements.- Concern over the effects of RCC subsurface oxidation led to the requirement to perform 100 mission simulations in an oxidizing environment. Studies conducted at JSC showed that bare graphite elements were capable of surviving a number of test cycles before becoming severely degraded but that they would compromise test results by depleting the oxygen available to the test article. An effort was therefore undertaken to develop an oxidation-inhibiting coating for graphite heater elements. Initial attempts at coating graphite centered around a silicon carbide pack cementation process used to coat the nose cap and the WLE. The results of these attempts were not encouraging because this coating was extremely rough and porous and the graphite substrate appeared to be eroded. The next attempt used a chemical vapor deposition (CVD) process that produced a silicon carbide coating rather than converting the surface of the graphite to silicon carbide as in the pack cementation process. The CVD coating produced a smooth dense uniform layer of silicon carbide.

Preproduction samples of CVD-coated heater elements have been evaluated during development tests. Entry simulation profiles for zones that have peak element temperatures below 1730 K (2650° F) can be repeated more than 40 times before elements in that zone exhibit coating loss. A transition to a higher coating loss rate occurs above 1785 K (2750° F) and temperatures approaching 1865 K (2900° F) reduce coating life to about four entry simulations. Although the oxidation of CVD-coated heater elements is fairly low (approximately equivalent to that of the test articles) for the LESS tests, it was believed that oxygen-depleted air could be produced within the region between the heater and the test article and ingested into the test article through gaps around the RCC components during repressurization of the chamber. This possible source of oxygen depletion is counteracted by the injection of a small amount of makeup air between the heater and the test article.

Heater Control System

The RHTF heater control system consists of (1) a set of temperature sensors to measure the surface temperature of the test article, (2) a computerized control subsystem that generates error signals proportional to the difference between the measured and the desired temperatures, (3) a set of 22 ignitron power controllers that control the voltage level at each heater zone in proportion to the error signal, (4) one 4:1 stepdown transformer for each power controller to reduce peak voltage from 480 to 120 V ac to prevent heater arcing at low-altitude chamber pressure, and (5) a set of water-cooled conductors that transmit power to the heaters. This system, when properly tuned and calibrated, is capable of controlling within

±5.6 K (±10° F) of a specified temperature under steady-state conditions and within ±27.8 K (±50° F) during transient conditions.

Infrared Pyrometers

Unique problems associated with the LESS test articles precluded the use of thermocouples as control sensors. Basically, the problems were threefold: (1) the silicon released from the RCC tended to form a eutectic with platinum/platinum-rhodium thermocouples, degrading them in a short time; (2) alternate thermocouple materials did not survive exposure in the high-temperature zones; and (3) attempts to use thermocouples with high-temperature inert sheaths resulted in a wide variability of measured data due to variations in thermal contact resistance where the thermocouples were bonded to the RCC. In addition, all thermocouples displayed extremely poor reliability after repeated cyclic tests and replacement/refurbishment was time consuming and costly. Because of these problems, alternate temperature sensors were researched.

The control sensors ultimately selected to replace the thermocouples are fiber optic infrared pyrometers (fig. 11). These pyrometers are used to monitor the temperatures of the control points on the test article opposite each heater zone and the temperatures of the heater elements to keep the elements below the operational temperature limit of the CVD coating. Each pyrometer is equipped with a lens assembly that gathers infrared energy over a very narrow view angle of 0.75° and focuses it on the end of a flexible fiber bundle, 1.83 meters (6 feet) long. The fibers transmit energy to a lead sulfide (PbS) detector cell located in a detector head assembly with signal conditioning electronics that amplify the signal before it is sent to the control room, where it is linearized and output to the computer control system. The transmission characteristics of the fibers and the spectral response of the lead sulfide cell make the pyrometer sensitive to a narrow wavelength band center around 2.2 micrometers. The narrow view angle permits the lens head to be mounted behind the heater reflector where it views the test article through slots in the heater elements. Use of the flexible fiber bundle allows the lens head to be mounted near heater electrodes, wiring buses, or the coolant line while the physically larger detector head can be positioned in a more protected location away from high-current fields that could induce electrical noise into the sensitive electronic amplifiers.

These pyrometers provide a useful output from 645 to 1920 K (700° to 3000° F). The lower output threshold is limited by the detector sensitivity and the small amount of energy that can be gathered by the narrow view angle. This threshold is acceptable for control purposes because the heaters are normally operating near full power level to achieve initial element warmup during the time the profile temperature rises from starting temperature to 645 K (700° F).

Initial trials of the pyrometers with RCC test articles produced poor results. The problem was traced to a defect in the lens head that caused the pyrometer to accept infrared radiation from a target area larger than desired. The manufacturer corrected the problem by adding additional light stops to the lens assemblies to block out light from outside the design view angle. Other inaccuracies were traced to small nonlinearities in the linearization circuitry, which were corrected by performing a multipoint blackbody calibration.

Computer Control Subsystem

The output of the fiber optic pyrometers is fed into the RHTF computer control subsystem where it is processed by a control algorithm in the computer to provide an output error signal to the power controllers. The infrared pyrometer output is first converted to a temperature using blackbody calibration data and the first derivative of the response temperature. The response temperature is then algebraically summed with a temperature profile point generated by the computer using linear interpolation of a table of critical profile points. The resultant error signal is integrated and the response derivative, basic error signal, and integrated error signal are multiplied by their respective gain factors, which have been specified in a configuration card deck. The products of these three signals and their gain factors are then summed to provide a composite error signal.

Adding the response derivative to the basic error signal permits greater dynamic control accuracy by anticipating test article response, and adding the error signal integral results in an error signal to keep the heaters energized even when the basic error is zero. This composite error signal permits better steady-state control by compensating for test article thermal losses. The composite error signal is then processed to compensate for input nonlinearities in the ignitron power controllers, which results in linear input-to-output characteristics for the system.

Computer control offers several advantages over equivalent analog controllers. The gains can be input or changed to a precise level with the input of a computer card, whereas, with analog control, numerous potentiometers must be adjusted and input/output gains confirmed by physical measurements. Also, the computer system does not require the frequent realinement common to analog systems. The only potential disadvantages of computer control are that the gains must be determined empirically and the relatively short update interval can result in instabilities under rapidly changing conditions. Control checkout tests indicate that neither of these shortcomings is signficant.

Another advantage of computer control is the capability to select alternate control sensors rapidly if a primary sensor fails. The control algorithm automatically monitors control response and compares it to preset temperature and control rate-of-change limits. If either limit is exceeded for more than one computer cycle (1 second), the computer automatically selects a backup sensor for control. This sensor can be another infrared pyrometer, a thermocouple, or the heater input electrical power. Each backup sensor can be programed with its own profiles and gain factors to ensure optimum control. If the secondary sensor fails, the computer can be programed to select tertiary and then quaternary control sensors or to abort at a predetermined point in the backup selection.

The RHTF computer control subsystem provides control of up to 5 megawatts of power in 22 control zones with minimum operator input. It also detects out-of-limit conditions rapidly and immediately follows predetermined corrective actions or automatically aborts the test.

Altitude Simulation System

The altitude simulation system provides a controlled entry pressure environment and consists of an altitude chamber, a vacuum pumping unit, an altitude control subsystem, and an air replenishment subsystem. The stainless steel altitude chamber has penetrations for instrumentation and heater power lines and has an internal diameter and length of 3 and 6.1 meters (10 and 20 feet), respectively. An end bell can be removed from the chamber for installation and removal of test equipment, and four personnel doors provide entry for test article inspection and checkout. The vacuum pumping unit (a Stokes-type roughing vacuum pump in series with a Rootes blower) evacuates the altitude chamber at a rate of 0.47 m^3/sec (1000 ft^3/min) to an operational chamber pressure of 13.3 pascals (0.1 torr).

Altitude chamber pressure is controlled by modulating a ball valve in the vacuum line between the Rootes blower and the chamber and a valve in the repressurization line with a closed-loop feedback control system. Pressure profiles are generated by a microprocessor-based programer, and chamber pressure is measured with a capacitance manometer over a three-decade range from 1.3 to 133.3 kilopascals (10 to 1000 torr). Signals from the programer and the manometer are scaled, algebraically summed, and amplified to generate an error signal that drives the vacuum and repressurization control valves. Overshoot at points of inflection in the pressure profile is minimized by simultaneously operating these valves in opposition (as one valve opens, the other closes). Vacuum and repressurization amplifier gains are adjusted to optimize system response for different altitude pressure profiles. Dynamic entry pressure environments from 0.013 to 101.3 kilopascals (0.1 to 760 torr) are controlled to an accuracy ±267 pascals (±2 torr).

Cooling System

A closed-loop coolant system provides 0.06 m^3/sec (1000 gal/min) of cooling water for distribution to heater reflectors, heater electrodes, water-cooled conductors, auxiliary cooling shrouds used to protect instrumentation wiring and chamber wells, and other components that experience significant heating. The coolant transfers heat to a water-to-air exchanger that lowers inlet water temperature by 12.8 K (23° F) with a 4.2-megawatt heat load.

An emergency coolant subsystem is also installed to meet minimum cooling requirements in the event of a main pump failure. This subsystem provides a waterflow of about 0.03 m^3/sec (400 gal/min) from a potable waterline and is automatically activated by a drop in coolant supply pressure. A control panel and logic board permit manual activation and prevent inadvertent triggering during noncritical operations.

Refrigerated Coolant Subsystem

For selected tests, the test article must first be cooled to temperatures between 240 and 220 K (-30° and -100° F) to simulate orbital cold-soak conditions before entry heating simulation begins. The test article is positioned in front of a cooling shroud contoured to the approximate shape of the test article (for maximum cooling efficiency) and located at the opposite end of the chamber from the heater. The shroud is cooled by recirculating methanol coolant chilled to temperatures as low as 195 K (-105° F) by an 82-megajoule (78 000-Btu) refrigeration unit.

After orbital cold-soak and peak entry heating conditions have been simulated, the test article is repositioned in front of the cooling shroud to simulate cool-down rates between temperatures of 1030 and 295 K (1400° and 70° F). To prevent a potential fire hazard resulting from a methanol coolant leak in the vicinity of a hot test article, the shroud coolant is switched to circulating water from the test coolant subsystem by air-operated diverter valves before repositioning the test article in front of the cooling shroud.

Test Article Positioning Subsystem

The test article is transported between the heater and the cold shroud by a carriage drawn along a rail by an air-motor-driven chain. The nose cap test article is rotated 180° at a point midway between the two test positions by an air-motor-driven rotational drive incorporated in the test article carriage. The air motor drives are operated by a control system that senses the position of the test article within the altitude chamber and uses solid-state logic to automatically start, stop, and change speeds, thereby providing rapid precise positioning of the test article.

Data Acquisition System

The RHTF data acquisition system acquires, conditions, processes, records, and outputs in both tabular and plot formats data from 200 test article sensors and 56 facility sensors for engineering review and analysis. This system consists of an analog instrumentation and signal conditioning subsystem for acquiring raw data and a digital computer subsystem for processing and recording the data on magnetic tape.

The instrumentation subsystem acquires data from the sensors and performs preliminary signal conditioning before sending the data to the computer system for further processing. The system is prewired to accept inputs from the following sensors: (1) type K (chromel/alumel), type R (platinum/platinum-13-percent rhodium), and type T (copper/constantan) thermocouples; (2) bridge balance sensors, such as strain gages, strain-gage-based transducers, and resistance temperature devices; (3) fiber optic pyrometers; (4) heater voltage; (5) heater current; (6) altitude chamber pressure; and (7) other voltage output sensors, such as calorimeters. The data cables are routed through environmental feedthroughs in the altitude chamber to a programmable patch panel that allows rapid instrumentation configuration changes between tests and facilitates frequent system calibration.

The channels selected for processing are routed to the analog input subsystem, which scans each channel 10 times per second, amplifies and digitizes the signal, and outputs the coded data to the central processing unit (CPU). The CPU performs all linearizations, zero offsets, and engineering unit conversions on the basis of previously input data and pretest calibration and displays the data on two CRT terminals in the RHTF control room.

Post-test data processing of the test data tapes is also accomplished with the computer subsystem. Tabular data can be retrieved in either sampled or averaged form for any timespan and interval specified, and data plots can be made with up to 6 measurements per page for any time interval specified.

CONCLUDING REMARKS

A large-scale Radiant Heating Test Facility has been constructed at JSC to perform certification tests on the Space Shuttle Orbiter TPS. Simulation of entry heating on full-scale test articles required development of innovative test techniques. One of these innovations was the development of silicon-carbide-coated graphite heater elements that make it possible to operate radiant heaters at temperatures up to about 1765 K (2750° F) in an oxidizing environment. Another innovation was combining a multichannel fiber optic pyrometer system with a digital computer system to control the power to each heater zone. Although the principal certification tests for which the facility was designed (the nose cap and wing leading edge structural subsystems) have not been completed, extensive tests to demonstrate the functional status of the facility systems have been performed. Nose cap and wing leading edge tests supporting the first flight are scheduled to be completed by the fall of 1980.

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Suppanz, Murray J.; and Grimaud, John E.: Space Shuttle Orbiter Nose Cap and Wing Leading Edge Certification Test Program. Paper presented at Eleventh Space Simulation Conference, Sept. 23-25, 1980.

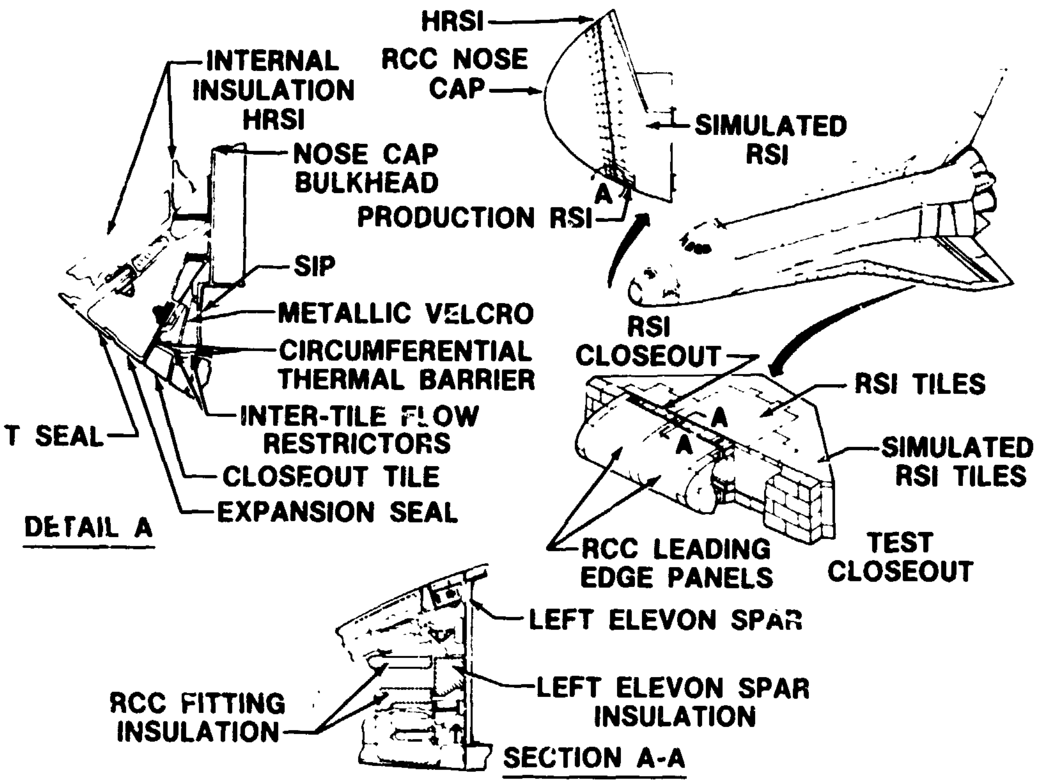

Figure 1.- Leading edge structural subsystem test articles.

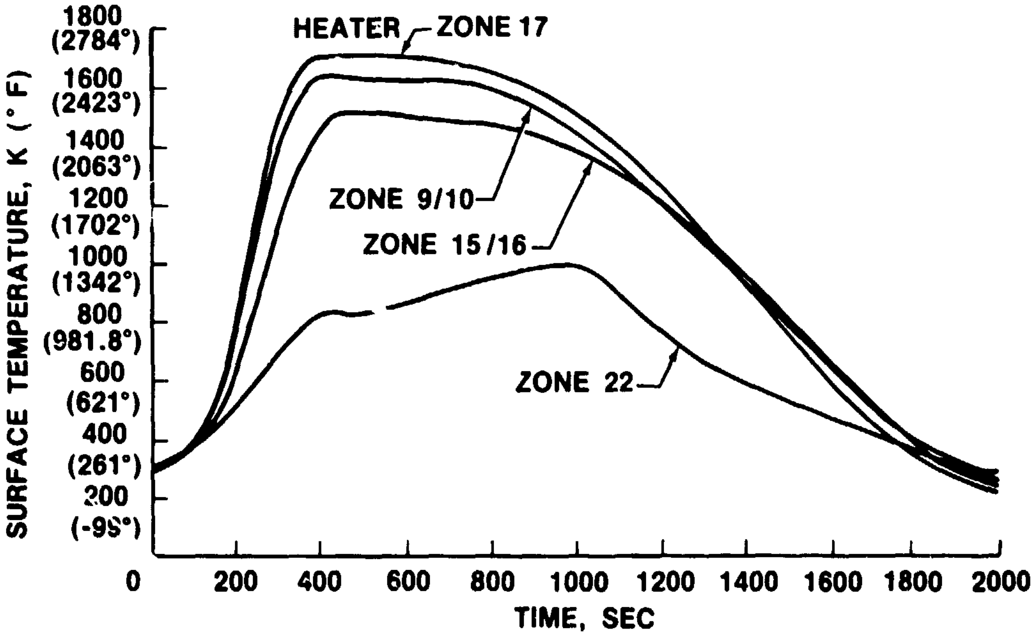

Figure 2.- Typical nose cap isotherms.

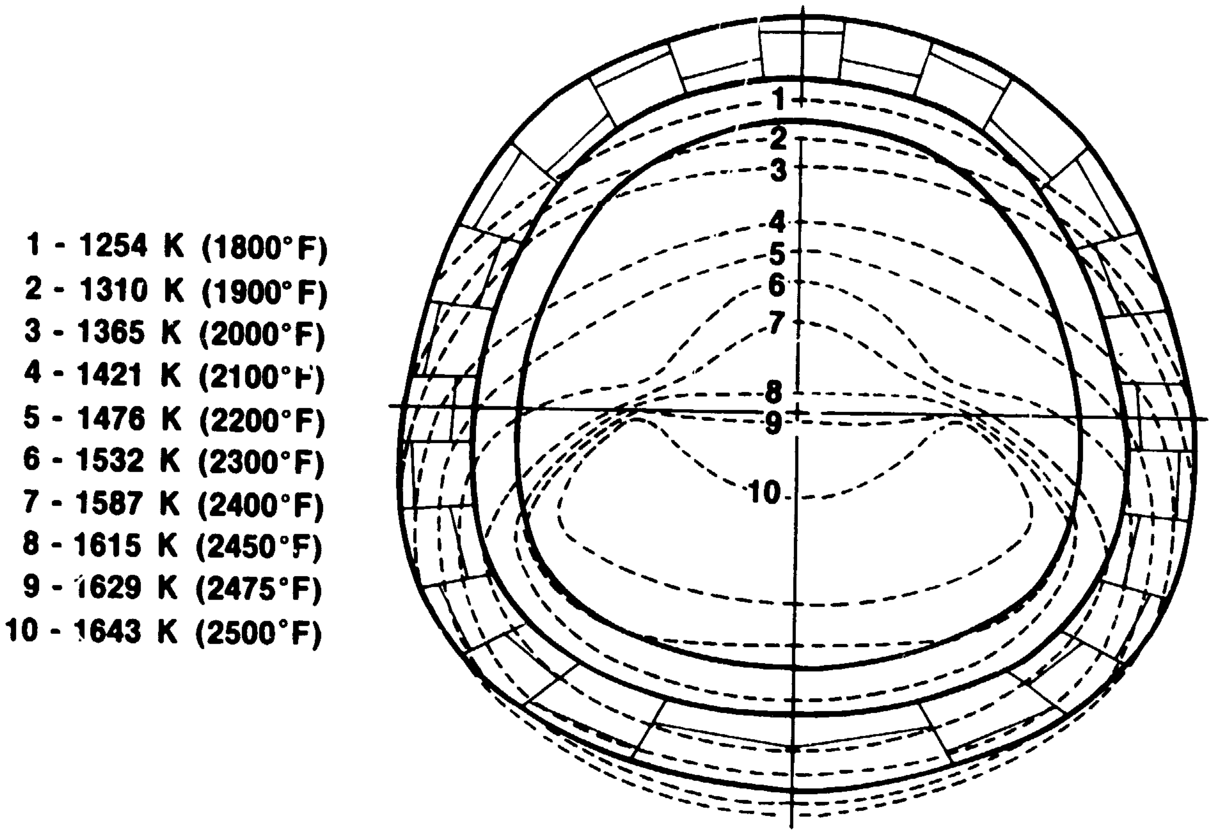

Figure 3.- Typical nose cap entry temperature profiles.

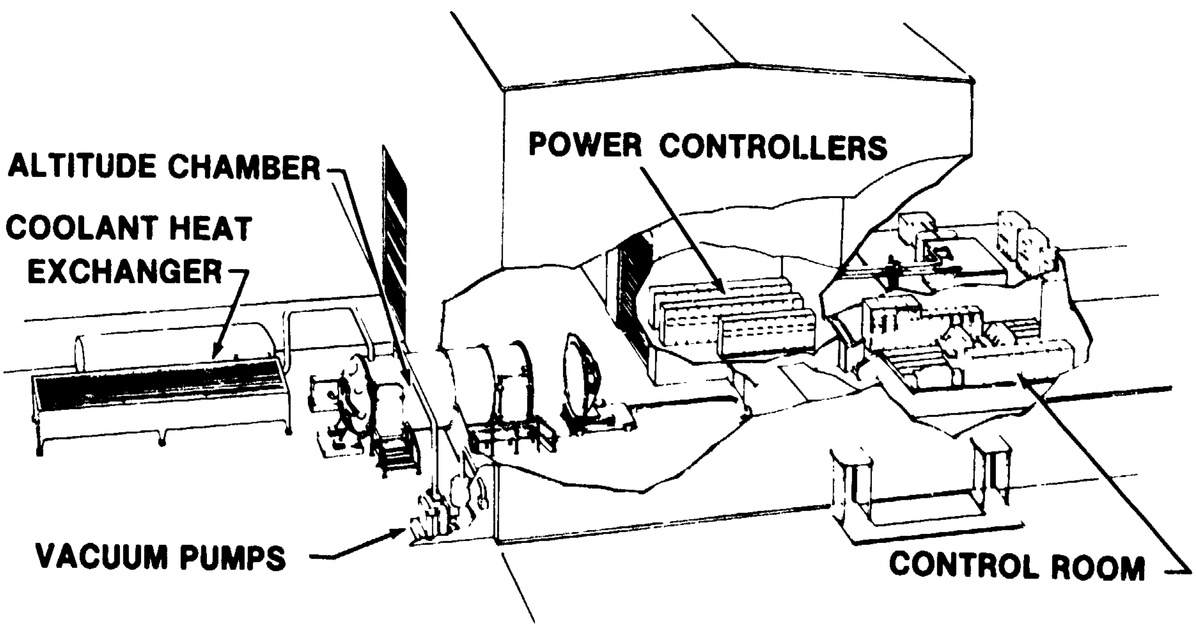

Figure 4.- Radiant heating test facility.

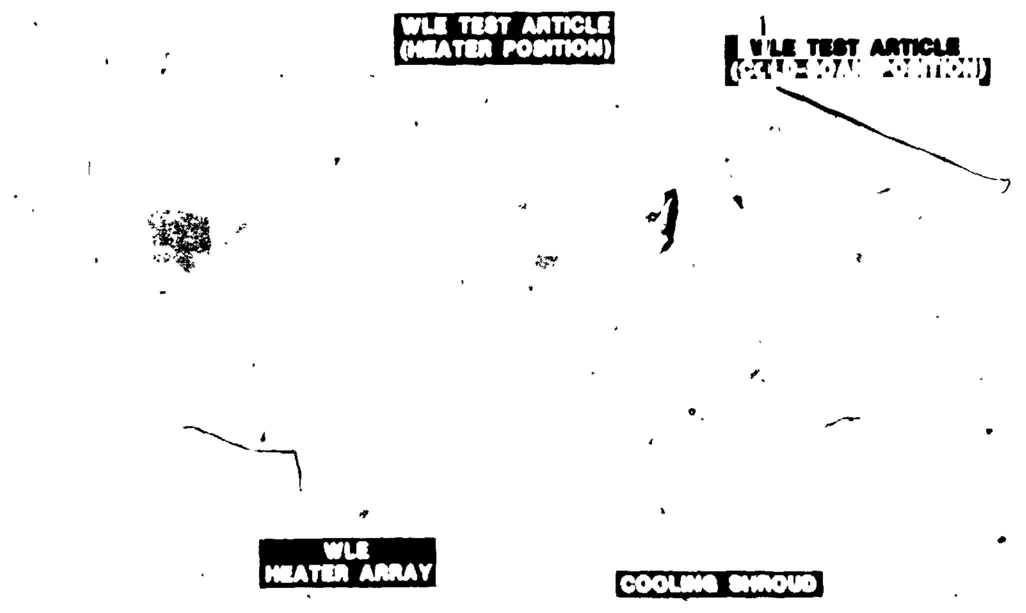

Figure 5.- Wing leading edge test configuration. The test article is shown in both the heater and the shroud positions for illustrative purposes only.

Figure 6.- View of wing leading edge heater during test article fit check.

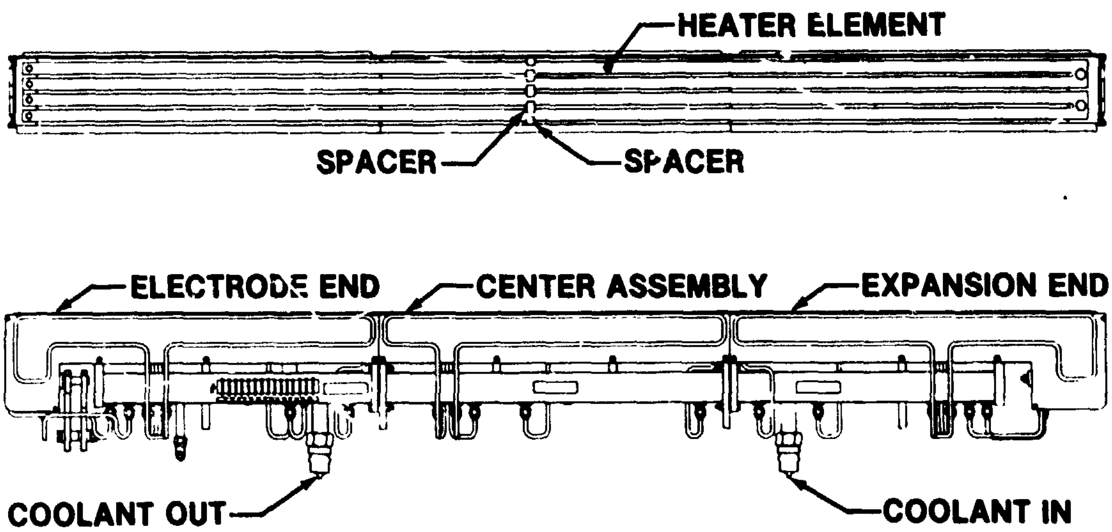

Figure 7.- Wing leading edge heater module.

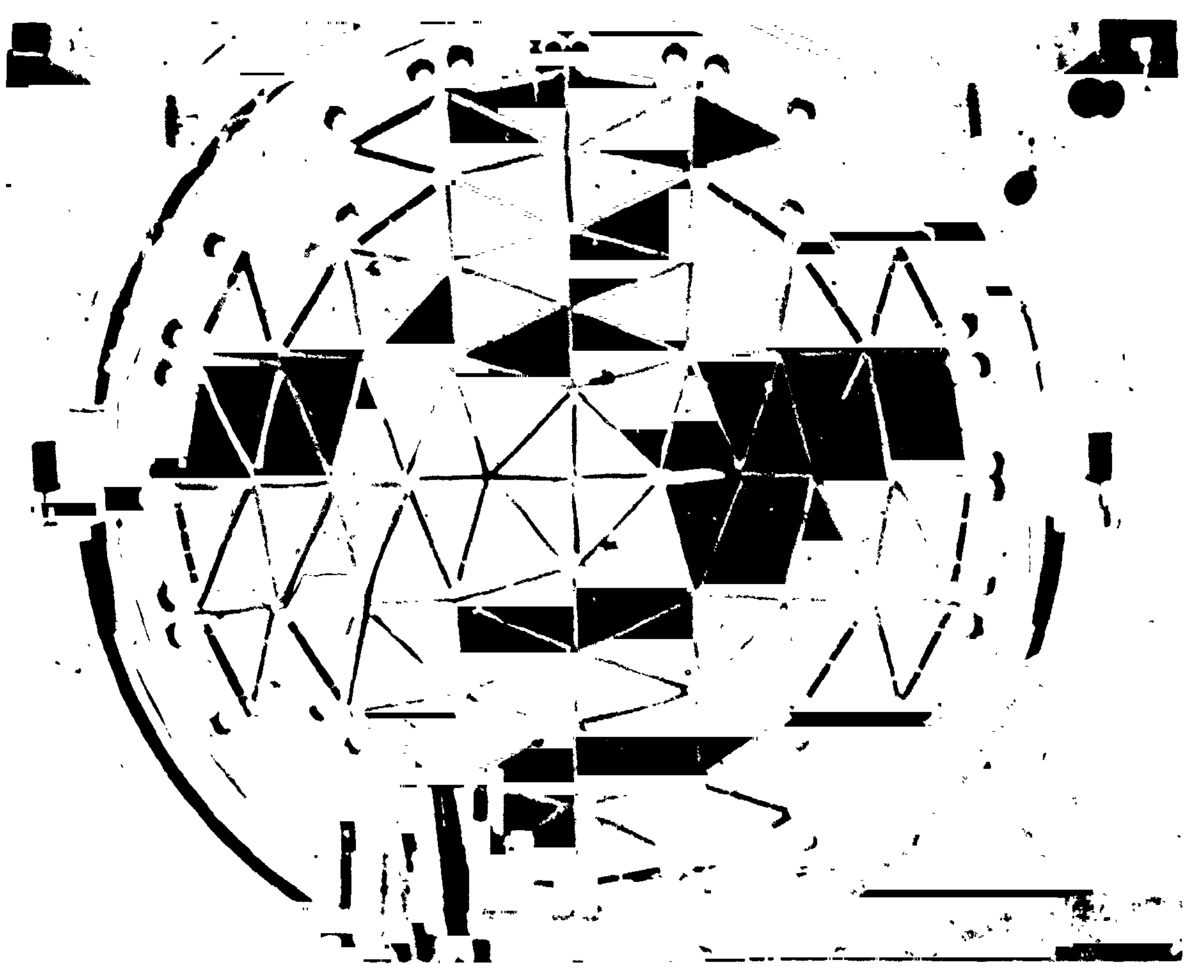

Figure 8.- Nose cap heater.

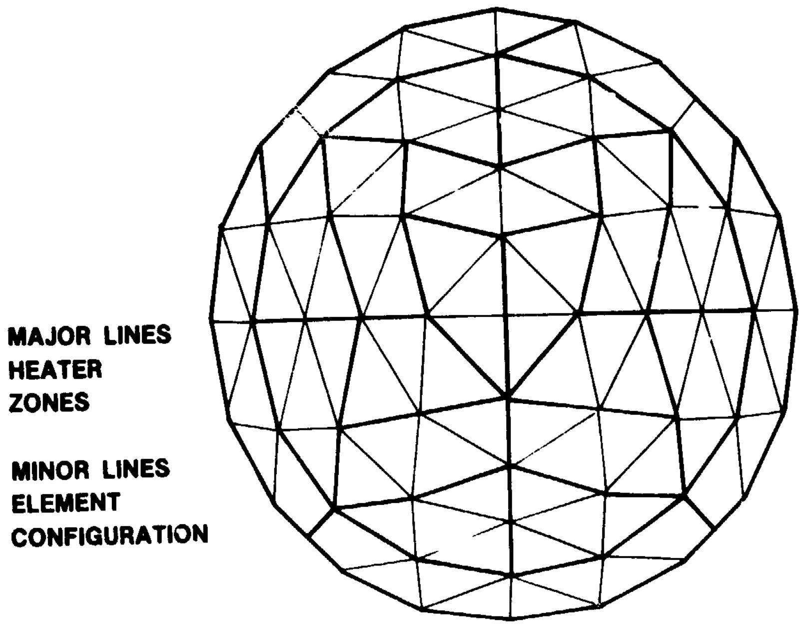

Figure 9.- Control zones and element configurations for nose cap heater.

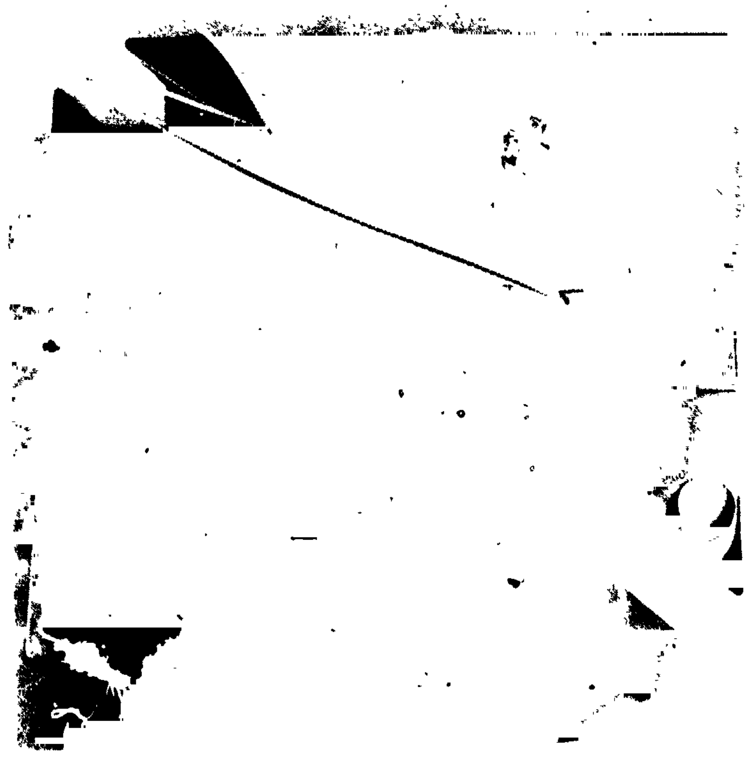

Figure 10.- Typical nose cap heater elements.

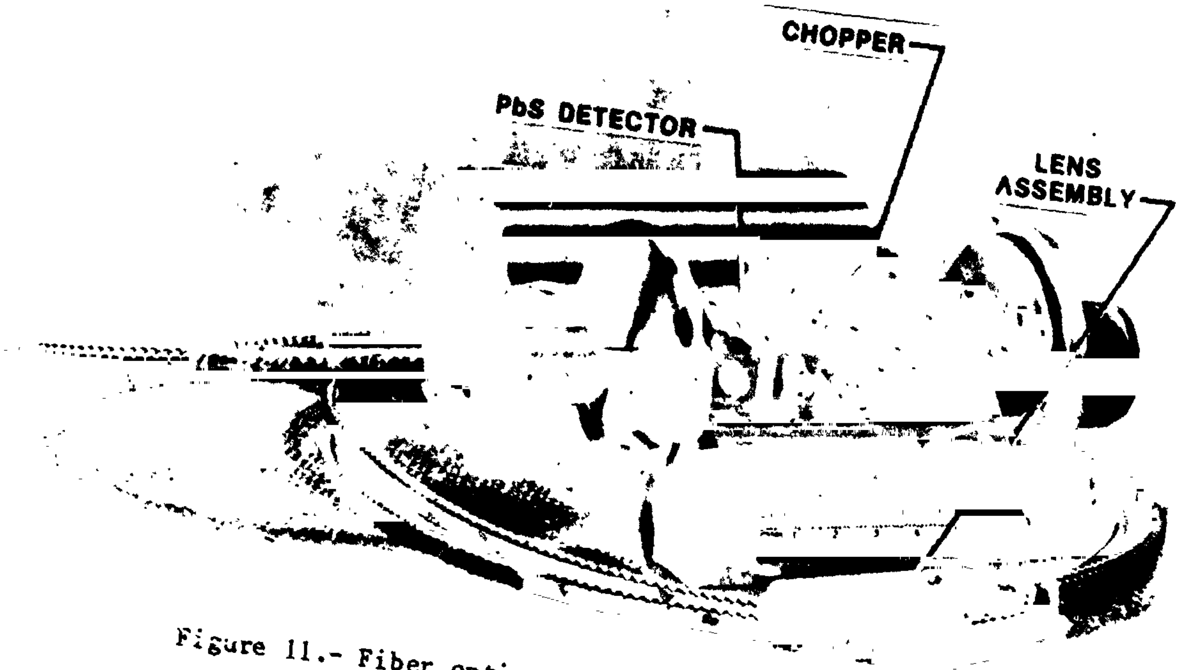

Figure 11.- Fiber optic pyrometer detector head.