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THERMOELECTRIC TEMPERATURE CONTROL SYSTEM FOR THE PUSHBROOM MICROWAVE RADIOMETER (PBMR)

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SUMMARY

This report describes a closed-loop thermoelectric temperature control system for the Pushbroom Microwave Radiometer (PBMR) which has been designed, assembled, and successfully flight tested onboard the NASA Skyvan aircraft. In flight, the instrument is exposed to the airstream and may experience temperature extremes from -20°C to +45°C, airstream velocities to approximately 300 knots, and altitudes to 3000 feet.

Development of the thermal control system was accomplished through four phases. First, the system was conceptually designed; the concept was then analytically modeled using the Martin Marietta Interactive Thermal Analyzer System (MITAS); next a full scale mock-up was assembled and tested; and finally, flight hardware was assembled and flight tested.

The system features an unusual three-level control concept which provides precise temperature control for the sensitive radiometer front ends (RF units). These units are partially isolated (thermally) from a reference sink; the instrument deck. This sink is temperature controlled and is totally isolated from the ambient environment by an insulated container.

The analytical, laboratory, and flight test efforts used to verify the temperature control system demonstrated that the sensitive RF units are effectively controlled about a set-point with an accuracy of ±0.1°C.

INTRODUCTION

NASA Langley Research Center has undertaken a program to demonstrate the technology of broadband microwave systems to permit radiometric measurements of the Earth and its environment with significantly improved spatial resolution, sensitivity, and coverage. One approach involves the development of a multiple beam radiometer system named the Pushbroom Microwave Radiometer (PBMR). The radiometer system detects the electromagnetic radiation being emitted from the Earth with three beams which sweep the surface. These measurements at 1.4 GHz (L-Band) can be used to infer geophysical parameters such as soil moisture, sea surface temperature, and salinity.[1, 4]

The PBMR under development at NASA-Langley utilizes sensitive, microwave, integrated circuit front ends (RF units) which require precise thermal control to maintain the desired instrument sensitivity. An earlier study indicated that it is necessary to regulate the radiometer front-end temperature within ±0.1°C to attain a 0.5K radiometric temperature sensitivity and ± 2.0K radiometric temperature accuracy in soil moisture measurements.[2]

The PBMR will be utilized in an aircraft flight test program over a wide range of environmental conditions from warm tropical day (+45°C) to cold winter day (-20°C). The temperature control system must regulate the temperature of the instrument over an altitude range from sea level to approximately 3000 feet and at air speeds up to 300 knots.

The purpose of this paper is to present the design of a closed loop thermoelectric temperature control system which was designed, assembled, and tested to achieve the ±0.1°C stability of the RF units. The system features redundant air-cooled thermoelectric coolers which provide either cooling or heating, as required. The function of the coolers is to provide temperature control of an internal heat sink; the instrument deck. The RF units are partially isolated (thermally) from the heat sink and their temperature is sensed by an integral thermistor and controlled by computerized heater controllers. Thin film resistance temperature detectors (RTD's) are used to precisely monitor temperature.

This paper will first, explain the temperature control system both descriptively and analytically; and second, describe the test apparatus, procedure and results which demonstrated the performance of the system. The thermoelectric temperature control system concept is considered to be of such accuracy and versatility that it could be useful for other control applications.

INSTRUMENT DESCRIPTION

Radiometer System

The PBMR instrument is an electronic package comprised of five assemblies as shown in Figure 1:

1. Antenna and Feed Network Assembly.
2. Signal Conditioning Assembly.
3. Digital Signal Processor Assembly.
4. Data Acquisition Assembly.
5. Power Supply Assembly.

The first two assemblies are enclosed in a modular, insulated enclosure--the "radiometer container," which is 90.0 cm x 90.0 cm x 50.0 cm (36.0 in. x 36.0 in. x 20.0 in.). This container is composed of three modules to facilitate assembly and disassembly. Thermal isolation is provided by the walls of the container consisting of three 0.25 cm (0.1 in.) fiberglass layers separated by two 2.5 cm (1.0 in.) styrofoam insulation layers. The Digital Signal Processor Assembly (DSPA), Data Acquisition Assembly (DAA), and Power Supply Assembly (PSA) are external to the radiometer container.

Antenna and Feed Network Assembly. - This assembly contains an array of sixty-four (64) aluminum dipole antennas mounted on the antenna deck. These antennas are connected to three levels of strip-line printed circuit (PC) boards to form the feed network. The circuit boards are 77.5 cm x 10.0 cm x 0.155 cm (31.0 in. x 4.0 in. x 0.062 in.).

Energy radiated from the surface, received by the individual antennas, is combined in the feed network to form three beam patterns. These signals are the input for the Signal Conditioning Assembly.

Signal Conditioning Assembly.- This assembly includes the radiometer front-ends (RF units) and the mixer-preamplifiers (IF units). The front-ends provide filtering, gain, and RF signal conditioning. Because the front-ends are extremely sensitive to temperature changes, they are enclosed in an insulated enclosure--the RF container. This aluminum container is 55.1 cm x 45.0 cm x 12.5 cm (22.0 in. x 18.0 in. x 5.0 in.) and has 2.5 cm (1.0 in) of internal styrofoam insulation.

The mixer-preamplifiers provide additional gain and signal conditioning needed before signal processing. These units are less sensitive to temperature changes and do not require an additional thermal enclosure.

Digital Signal Processor Assembly.- The Digital Signal Processor is a microprocessor system which performs radiometer calculations, monitors and controls system temperatures, and formats and transmits data to the Data Acquisition Assembly. This assembly is located external to the radiometer container.

Data Acquisition Assembly. - The fourth assembly is located inside the aircraft equipment rack. Its function is to record the radiometer data on tape and to provide operator interface with the system. The components of this assembly are:

a. A nine (9) track tape recorder for complete data storage.

b. A four (4) channel stripchart recorder for temperature monitoring.

c. A monitor (CRT) and keyboard for data display and communication with the radiometer system.

d. A thermoelectric cooler (TEC) temperature controller.

e. A TEC mode switch and power supply.

f. A computer for data management.

Power Supply Assembly.- The Power Supply Assembly provides the DC power for the entire radiometer system. This assembly is also located external to the radiometer container.

Temperature Control System

Three levels of temperature control within the radiometer container make up the temperature control system necessary to obtain accurate radiometric data. The first level of control is in the Antenna and Feed Network Assembly (Figure 2). The antenna deck of this assembly is instrumented with three, centrally located, bead type thermistors for temperature sensing and control. The deck is also equipped with thin film heaters, proportionally controlled by the Digital Signal Processor Assembly, to provide temperature stability for the deck and the antennas. These heaters also provide ambient air temperature stability for the feed network within the assembly.

The second level of control is in the Signal Conditioning Assembly. The focal point of control at this level is the instrument deck. The deck is instrumented with seven thermistors; several thin film heaters; and two, high convective, dual mode, thermoelectric coolers. The proportionally controlled heaters provide ambient air stability for the assembly and uniform instrument deck temperature for a cold condition. The thermoelectric coolers, proportionally controlled by a dedicated controller, serve two purposes: (1) they provide a thermal path, from the instrument deck to the external environment for excess heat removal; (2) they stabilize the instrument deck to a uniform temperature for a hot condition.

The third level of temperature control is also in the Signal Conditioning assembly. The focal point of control is the front-end units (Figure 3). Each front-end is constructed of electronic components mounted on a 6061-T6 aluminum plate. These plates are isolated from the instrument deck with bakelite thermal resistive material. Each front-end is instrumented with a thermistor and two RTD's. Two proportionally controlled heaters, also controlled by the Digital Signal Processor Assembly, stabilize the temperature of the mounting plate. One RTD accurately senses the temperature of a referenced location on the plate and the other RTD serves as a survival spare temperature sensor. The bakelite insulation creates a temperature differential between the front-ends and the instrument deck so that they can be independently and precisely controlled.

A typical operational scheme for the temperature control system would begin by first selecting a reference temperature for the front-ends. The instrument deck can then be set at a lower temperature--approximately five degrees lower than the front ends. The Antenna and Feed Network Assembly is thermally stabilized at the same temperature as the instrument deck. Therefore, through the three levels of temperature control the front-end units can be held stable within ± 0.1°C of the selected reference.

TEMPERATURE CONTROL SYSTEM ANALYSIS

Systems Description

A schematic for a single beam of the radiometer depicting the typical components and boundaries of the system is shown in Figure 4. The local oscillator (LO), video processor (VP), IF and RF units are the thermally active components within the radiometer container whose dissipated heat must be managed. The specific thermal requirements for the entire radiometer are listed in Table I and the thermal characteristics of each component are shown in Table II. From Table II, the total power generated by the active components within the radiometer is 31.4 watts and the total weight of the system is 111.7 Kg (246.5 lbs.)

With the physical boundaries, thermal requirements, and thermal characteristics of the system defined, an initial thermal analysis was done.

TABLE I. - PUSHBROOM RADIOMETER THERMAL REQUIREMENTS

OBJECTIVE: To Provide Temperature Control for the RF units of the Pushbroom Radiometer

DESIGN REQUIREMENTS:

I. External Environment of Radiometer Container

  A. Temperature
    1. Hot: +45°C
    2. Cold: -20°C
  B. Altitude: $0 \leq ALT \leq 10{,}000$ FT.
  C. Velocity: $0 \leq VEL \leq 300$ Knots
  D. Flight Duration: 4 to 6 Hours

II. Temperature Limitations of the Internal Components of the Radiometer Container are: MAX: +55°C
MIN: -20°C

III. The RF receivers are to be controlled to ± 0.1°C of the set temperature, +50°C.

TABLE II. - PBMR COMPONENT THERMAL CHARACTERISTICS

Element	Quantity	Power Generated Watts	Weight Kg (lbs.)	Material
o Radiometer Container	1	--	40.8 (90)	Fiberglass/Styrofoam
- Instrument Deck	1	--	10.9 (24)	6061-T6 Aluminum
- Antenna Deck	1	--	10.4 (23)	6061-T6 Aluminum
- Antennas	64	--	2.3 (5)	Cast Aluminum
- IF Unit	4	16.0(4.0 EA)	6.8 (15)	6061-T6 Aluminum
- LO	1	1.8	.4 (1.0)	6061-T6 Aluminum
- VP	1	5.0	.9 (2.0)	6061-T6 Aluminum
- PCBoard	3	0.0	6.8 (15)	Cu-Clad Fiberglass
o RF Container	1	0.0	4.5 (10)	Aluminum Sheet
- RF Unit	4	8.6(2.15 EA)	4.5 (10)	6061-T6 Aluminum
- Isolator	5	0.0	.7 (1.5)	Bakelite
o Mounting Hardware	--		22.7 (50)	Aluminum and Steel
Totals		31.4	111.7 (246.5)	

Initial Analysis

A steady-state heat balance (hand calculation) was initially done for the hot environment to estimate the quantity of heat to be managed by a thermal control system. A comparable calculation was done to determine the amount of heat needed in the cold environment. Using the data information presented in Table I and Table II, a control volume was defined in Figure 5. The control volume was assumed to be in an environment of +45°C (hot case) and allowed to soak for 12 hours. For this initial estimate all internally generated heat was considered as a lump source; all electronic components were considered as a lumped mass; and convection and radiation modes of heat transfer were omitted. It was found from this hand calculation that after 12 hours, in the 45°C hot environment, 46.5 watts of heat would have to be removed from the radiometer container for thermal balance. After a 12-hour soak in an assumed worst-case -40°C cold environment, 30.0 watts of heat would have to be added to the radiometer container.

This calculation demonstrated the need for an adequate thermal flow path for the transfer of heat in and out of the radiometer container. Therefore, a control philosophy was needed to provide both a heating mode and a cooling mode.

Temperature Control Philosophy

In developing the control philosophy, the design objectives and requirements, the geometric boundaries, and the thermal design limitations were considered. The thermal system design limitations were: (1) compactness, (2) no fluid cooling loops, (3) low power consumption, (4) ability to heat or cool dependent on the external environment, (5) inexpensive, (6) simple to operate, and (7) stabilize the RF units within 2 hours.

The primary concern in developing the thermal control system was to maintain the critical RF units to ± 0.1°C about a reference temperature. In the design concept (Figure 6), the RF units were mounted on the instrument deck and enclosed in an insulated container (RF container).

Designating the environment as the source, the RF units as the mass to be controlled, and the instrument deck as the thermal sink, a control philosophy was developed[3]:

1. Control the heat dissipation at the controlled mass.
2. Control the temperature or heat absorption capacity of the sink.

To control the heat dissipation of the controlled mass, a variable but precisely controlled heat load is applied to the RF units. In addition, a known thermal resistance is placed between the RF units and the instrument deck. This thermal resistance establishes a temperature differential, thus making the mass thermally controllable and distinct from the sink.

To control the heat absorption capacity of the sink, heating and cooling must be employed depending on the environmental temperatures. In the cold environment, thin film heaters, proportionally controlled, are used to maintain a stable sink temperature. In the hot environment, the instrument deck is held at a stable temperature by thermoelectric coolers. In both hot and cold environments a constant temperature differential is maintained between the RF units and the sink. This control philosophy was used to develop the thermal control schematic, shown in Figure 7, which was used for computer analysis.

Computer Analysis

With the thermal control system concept as described, and a preliminary design configuration defined, a detailed analysis of the radiometer system was done. Four items would be determined from the computer analysis: (1) the validity of the proposed control concept for the hot and cold environments, (2) the quantity of heater power required, (3) the cooling capacity required, and (4) thermal characteristics of the sink and thermal resistances in the control system.

A thermal model of the radiometer container, its components, and its thermal control system was developed. This model, shown in Figure 8, was used in the thermal analyzer program, MITAS (Martin-Marietta Interactive Thermal Analysis System, Version 2.0).

The model consists of 37 nodes and 61 conductors. All the radiometer walls, sinks, and components were represented by conduction elements. Radiation and convection exchange between the walls and components, and between components were also represented. A convection element was also used to simulate in-flight heat transfer between the radiometer container and the circulating air. In addition, a node was designated to simulate the thermoelectric coolers needed in the hot environment. Heater nodes were designated at the appropriate components locations. A FORTRAN logic sequence was integrated into the program to simulate the previously described control philosophy.

A typical computer run would subject the radiometer model to an environment (+45°C or -40°C) for 12 hours; simulating an overnight soak. After this period of exposure, the instruments and control system would be activated. The instrument deck would be stabilized at +45°C via heaters or coolers and the RF units would maintain a temperature of +50°C at all times with the use of thin film heaters. Once the RF units and deck reached the selected temperatures, the control system was exercised for a simulated six hour period to test its long-term stability.

From this computerized study of the radiometer thermal control system, the following was observed:

1. In the worst case cold environment (-40°C) the instrument deck required 300 watts of heater power to reach the +45°C set point within the required time period of 2 hours (See Figure 9).
2. In the cold environment, 25 watts of heater power were required to maintain each RF unit at the +50°C set point. The antenna deck required only 12 watts per unit to maintain the +50°C set point.
3. In the hot environment (+45°C) 32 watts of cooling were required to maintain the instrument deck at the +45°C set point (See Figure 10). The RF units required only 12 watts per unit to maintain the +50°C set point.
4. The resistive material between the RF units and the instrument deck was selected to be bakelite, 1.3 cm (0.5 in.) thick.
5. The convection heat transfer from the Radiometer container to the environment was small.
6. Approximately 2 hours was required for the sinks (instrument deck and antenna deck) to reach the desired set point temperature.
7. The RF container which encased the RF units provided excellent isolation from temperature fluctuations.
8. The RF units are stabilized to the 50°C set point within a half hour of activation.

From these analytical results, it was concluded that the control concept would work for both hot and cold environments. A thermal mock-up of the radiometer and the control concept was the next step in the design process.

EXPERIMENTAL EVALUATION

Test Apparatus

To obtain laboratory verification of the PBMR thermal concept, a simple, full-scale mockup of the radiometer container, antenna deck, instrument deck and thermal control system was assembled. The complete thermal mockup with external instrumentation is shown in Figure 11. The simulated radiometer container was a tightly-sealed plywood box which supported all of the internal components and isolated them from the ambient environment. The thermal analysis had established that the convective coupling to the atmosphere was minimal.

As shown in Figure 11a, all instrumentation was external to the radiometer container including the thermoelectric cooler controller and power supply, heater controllers, and the precision bridge network used to monitor the temperature sensors through a selector switch. Also shown mounted on the radiometer container are dial temperature gauges used to monitor average internal air temperatures.

Since the components mounted on the instrument deck were of primary interest, this section of the radiometer was simulated in detail, as shown in Figure 11b. Each thermally active component (RF units, IF units, LO unit, and VP) was simulated by a typical heat sink base with precision wirewound resistive heaters located at each internal thermal source. Thus, both the total and distributed heat loads for each component were simulated. The four assemblies in the center of the deck, surrounded by rigid foam insulation are the RF units which were to be controlled to $\pm$ 0.1°C During testing these units were covered by an enclosure (RF container), as previously described.

The PBMR thermal mockup was configured for a four channel radiometer but is also applicable for either a 3-channel or 5-channel configuration depending on the experiment objectives.

The air-cooled thermoelectric coolers can be seen in the upper right and left hand corners of the instrument deck. In operation, external air is ducted into the side of these units and blown-out the top of the radiometer container by integral fans. There is no forced air movement within the radiometer container.

The PBMR thermal concept depends on accurately controlling the temperature of the RF units at a reference differential temperature above the instrument deck, which is itself thermally controlled. An important purpose of the experimental evaluation was to determine the temperature stability of the instrument deck. To determine the deck temperature profile, an array of thin-film Nickel resistance temperature detectors (Ni-RTD) were attached to the deck at 12 symmetrical locations.

The use of thin-film Ni-RTD's in this application was itself experimental in nature. The sensors were considered desirable for this application because of their linearity, sensitivity, and potential for high accuracy (± 0.01°C). Due to their inherent strain sensitivity, the sensors require calibration after they have been permanently mounted. It was impractical to calibrate the sensors after installation on the instrument deck, therefore, a procedure was developed for bonding the sensors to an aluminum shim prior to calibration--the shim and sensor were subsequently bonded to the instrument deck. While this method was successful, it did not completely eliminate strain induced errors in temperature measurement. The bonding strain introduced a systematic error in temperature indication with a standard deviation estimated at 0.10°C.

While this error exceeded the desired accuracy, the temperature sensors did retain their sensitivity and were very useful in measuring small variations in temperature at each location.

The same type of thin-film sensors were attached to each RF component to measure the individual component temperatures, as can be seen in Figure 11b. Not shown are the heater strips attached to the bottom of each RF unit and their associated thermistor temperature sensors imbedded in the base. Deck instrumentation locations are shown on Figure 12.

Experimental Procedure

The primary objective of the PBMR thermal mockup was to demonstrate the operation of the thermal control system over a simulated range of ambient temperatures (-20°C to +45°C) that might be encountered in actual system operation. The secondary objectives were, first, to determine the range of operating modes where cooling or heating would be required; and second, to perform a transient "warmup" from a cold soak condition to determine the time required to temperature stabilize the system.

It was desired to do as many of these simulations as possible at ambient laboratory conditions. The analysis had indicated that the thermal mockup was essentially isolated from the ambient environment with regard to convective heat transfer. However, the thermoelectric coolers performance is very significantly linked to the ambient temperature. When the desired cooler temperature is the same as ambient temperature, the thermoelectric coolers will transfer approximately 66 watts of heat; when the cooler temperature exceeds the ambient temperature by approximately 15°C, up to 90 watts of heat can be transferred. However, when the desired cooler temperature is 45°C less than ambient temperature, 0 watts of heat can be transferred.

To demonstrate the performance of the PBMR thermal control system, it was necessary to account for this ambient temperature effect on cooler performance. This could be done, at ambient temperature, by changing the internal deck and component reference temperatures to obtain the desired variation in temperature simulations. By using this method during initial testing, the PBMR thermal mockup was able to simulate a wide variation of environmental conditions.

The mockup was tested in a cold ambient environment by mounting it on an enclosed cold target base into which liquid nitrogen (LN_2) was periodically injected (see Figure 13). The mockup was also tested in a hot ambient environment by means of heat lamps within the same enclosure. Thus, the thermal mockup was exposed to the complete operating range expected during the life time of the instrument.

Experimental Results

This section describes the experimental results which were obtained with the full-scale thermal mockup of the PBMR instrument. Data are shown for three cases: nominal ambient, cold ambient, and hot ambient cases.

Nominal Ambient.- The objectives of this test at nominal ambient temperature were, first, to establish a baseline temperature (nominal) profile for the instrument deck; second, to determine the time required to raise the instrument deck to a set point temperature; third, to determine the time required to increase the RF units from baseline to a set temperature; and fourth, to measure the amount of power required to maintain the RF units at the set point. Test conditions are shown in Table III.

TABLE III. - Nominal Ambient Test Conditions

Test Conditions

Ambient Temperature	21.1°C
RF Units set-point (nominal)	50°C
Instrument Deck set-point (nominal)	45°C
Thermoelectric Coolers	OFF

Baseline Conditions

The initial temperature conditions within the thermal mockup were very stable. The average instrument deck temperature was 23.89 ± .22°C; average IF unit temperature was 23.88 ± .08°C; and the average RF unit temperature was 24.24 ± .08°C.

Instrument Deck Warm-up

All heaters and dummy component thermal loads were turned on at time t=0. Temperature readings were taken at times t=0, 30, 60, 90, 210, and 330 minutes. The instrument deck warm-up temperature profile is shown on Figure 14. It can be seen that the average deck temperature rose from approximately 24°C to 40°C within the first 30 minutes and had essentially stabilized by time t=60 minutes. The deck temperature gradually drifted upward until a temperature of 45°C was achieved after 330 minutes. This gradual temperature change can be attributed to set-point drift of the prototype temperature controllers.

Instrument deck temperature distributions during warm-up are plotted on Figure 15. The uniform temperature distribution at the baseline condition for all the deck locations is apparent from the lower curve. The temperature distribution becomes less uniform during the system warm-up. As shown on Figure 16, the instrument deck temperature distribution variance is a maximum at time t=60 minutes, reaching a value of ±1.38°C across the plate. By time t=90 minutes, the variance is reduced to ± 1.20°C which is a reasonable value for a deck of this size with discrete thermal sources. Deck temperature contours, including temperature sensor locations, were also plotted for the instrument deck. These are shown in Figures 17, 18, 19, 20, 21, and 22. The nominal condition at time t=0 minutes is plotted with a contour interval of 0.07°C. The highest temperature is located near the middle of the deck but there is no uniform gradient since there are no thermal sources. At time t=30 minutes, a uniform temperature gradient is being established from the center of the deck where the RF units are located. The development of the temperature gradients continue at t=60, 90, 210, and 330 minutes. The thermal gradient is fully developed by this time and is uniform in all directions. This is typical for a plate with a concentrated heat source and with no localized cooling. Such a stable temperature distribution provides a very good baseline heat sink for the thermally isolated RF units,

RF Units Warm-Up

The primary goal of the PBMR thermal control system was to precisely maintain the temperature of the RF units. The RF units warm-up temperature profile is shown on Figure 23. It can be seen that the average RF unit temperature rises quickly in the first 30 minutes and essentially remains constant from time t=30 minutes to time t=90 minutes. Subsequently, the average temperature gradually drifts upward as was also seen with the instrument deck. The RF units temperature distribution for the four (4) RF unit locations is shown on Figure 24. The temperature at each location is seen to be very stable after 30 minutes, which is the goal for RF unit temperature control. Although the temperatures are not identical for each unit, due to difficulty in setting the prototype temperature controllers, their stability is within the requirements.

The RF units average temperature variance is shown on Figure 25. As indicated, the average variance between units is initially quite large, being ± 0.37°C after 90 minutes. This temperature variance does decrease to less than ± 0.1°C after 210 minutes, by which time the RF units have stabilized at 50°C. The performance on this run clearly indicated the need for more rapid, stable and precisely adjustable temperature controllers.

One significant consideration for obtaining a stable RF temperature is establishing a temperature differential between the RF units and the instrument deck as shown on Figure 26. It can be seen that the temperature differential is fully established by time t=30 minutes; by time t=90 minutes, the temperature differential is 6.80°C. At time t=210 minutes, the system is more stable and a differential of 5.86°C is established.

The temperature differential between the RF units and the instrument deck is related to the total power input to the RF units. This parameter is plotted on Figure 27. This curve shows that the total power input is reduced almost to a steady state value by time t=90 minutes. Thus the basic performance of the PBMR thermal concept was acceptable.

Cold Ambient.- The objectives of this test in a cold ambient environment were first, to determine the time required to raise the instrument deck to a set temperature; second, to establish a stable deck temperature profile; third, to determine the time required to stabilize the RF units; and fourth, to measure the power required to maintain the RF units at the set point. As mentioned previously, the entire radiometer mockup was located within an enclosure and the cold ambient environment was maintained by injecting controlled amounts of LN_2 into the enclosure (see Figure 13). It was possible to maintain a temperature of 0°C within this set up. Test conditions are listed in Table IV.

Table IV. - Cold Ambient Test Conditions

	Test Conditions
Ambient Temperature (within enclosure)	0°C
RF Units Set-point (nominal)	50°C
Instrument Deck Set-Point (nominal)	45°C
Thermoelectric Coolers	OFF

Baseline Conditions

An ambient baseline reading was taken prior to start of the test to verify temperature sensor calibration. The average instrument deck temperature was 23.13 ± 0.21°C. The unit was then chilled for approximately 4 hours to assure thermal equilibrium and a cold baseline reading was taken. The average instrument deck temperature at that time was relatively stable at -13.75 ± 1.89°C; the average RF Unit temperature was -11.08 ± 0.39°C.

Instrument Deck Warm-Up

All heaters and dummy thermal loads were turned on at time t=0. Temperature readings were taken at times t=0, 60, 90, 120, and 220 minutes. The instrument deck warm-up temperature profile is shown in Figure 28. The average deck temperature rose from approximately -13°C to 39°C in the first 120 minutes of operation, where it remained essentially stable. The controllers continued to cycle on and off at this level, indicating that the controllers had reached a stable control point. The average deck temperature of 39°C was less than the desired deck temperature of 45°C since the deck temperature controllers were regulated by a discrete temperature sensor in the center of the deck rather than by averaging the entire deck temperature. The effect is apparent, and is shown in Figure 29 on the instrument deck temperature distribution plots. It can be seen that the critical control points in the center of the deck (locations 5 and 8) have reached the desired set point after 90 minutes. The uneven appearance of the temperature distribution is due to the lower temperatures which exist along the edge of the deck during this cold ambient condition.

The instrument deck temperature variances, shown on Figure 30, are a maximum at time t=60 minutes and are in the range of ± 5°C across the plate at the end of the test. Deck temperature contours were also plotted and are shown in Figures 31, 32, 33, 34, 35, and 36. The ambient condition prior to cool-down (Figure 31) is plotted with a contour interval of 0.05°C and shows a very uniform temperature profile. The cold condition, prior to warm-up is plotted on Figure 32 with a contour interval of 0.3°C and, again, is quite uniform. At time t=60 minutes, shown on Figure 33, the deck temperature has risen to an average value of 22°C and the contours (on

$1^{o}C$ increments) are seen to form a relatively warm ridge down the center of the deck. By time t=90 minutes, Figure 34, the warm area under the RF units is apparent, but the edges of the deck have also become warmer. At time t=120 minutes, Figure 35 the instrument deck temperature profile has become very symmetrical and the contours ($1^{o}C$ interval) form a ridge centered under the RF units. The final figure (Figure 36) shows a stable well centered temperature profile which permits the RF units to operate in a stable environment. It is apparent that the deck temperature is being maintained by power from the RF units; the deck heaters are essentially inoperative at this time.

R.F. Units Warm-up

The RF units warm-up time is shown on Figure 37. The temperature rose very rapidly from the $-11^{o}C$ starting point and reached a stable plateau after 90 minutes. The RF units temperature distribution, plotted on Figure 38, is seen to be very stable after 90 minutes. The variance between units is plotted on Figure 39 and is seen to be about $\pm 0.25^{o}C$ after 90 minutes, slightly higher than the desired variance of $\pm 0.1^{o}C$. Again, this appears to be a result of the prototype temperature controllers used. The temperature differential between the RF units and the instrument deck is shown on Figure 40. The desired temperature differential is fully established after 90 minutes and remains relatively constant at about $10^{o}C$. This temperature differential is dependent on the amount of thermal dissipation of the RF units, which is plotted on Figure 41. The power input is relatively constant at 200 watts after 90 minutes into the test, much higher than the power required during the ambient test, and illustrates the adaptability of the thermal control system to operate over a wide range of conditions.

Hot Ambient Condition. - This environmental condition was achieved by using heat lamps within the enclosure shown in Figure 13. The test was basically an evaluation of thermoelectric cooler performance as the coolers must remove all of the radiometer thermal load and the thermal load entering through the radiometer housing. The objectives of this test were similar to those for nominal and cold conditions; test conditions are shown in Table V.

Table V. - Hot Ambient Test Conditions.

Test Conditions

Ambient Temperature	45°C
RF Units Set-point (nominal)	50°C
Instrument Deck Set-Point	--
Thermoelectric Coolers (nominal)	40°C

Baseline Conditions

Initial temperature conditions, prior to warm-up, were very stable within the thermal mockup. The average instrument deck temperature was 23.83 ± 0.13°C; average RF unit temperature was 23.51 ± 1.10°C. Following the baseline readings, all heaters and heat lamps were turned on. The thermoelectric coolers were also operated in the heat mode to raise the instrument deck temperature, and the unit was allowed about 1 hour to stabilize in temperature. The temperature within the thermal enclosure was maintained in the range of 45-50°C throughout the test.

Instrument Deck Stabilization

After the unit was warmed up, a series of temperature readings were taken, showing the instrument deck average temperature to be 42.61 ± 0.48°C. Then the thermoelectric coolers and the RF unit temperature controllers were turned on to stabilize the deck. The average instrument deck temperatures are plotted on Figure 42. It can be seen that the average deck temperature first decreased slightly and then gradually increased while the temperature was stabilizing. Figure 43 provides a indication of what is happening during this period. As mentioned previously, the primary method of thermal control under these conditions is the thermal rejection of the coolers. The thermoelectric coolers were set at approximately 40°C and are located at locations 1 and 3. It can be seen that they control the deck temperature very well at those locations. The reason for the average deck temperature to continue to rise is that a temperature gradient is being established across the deck to permit heat flow to the coolers. A gradual rise in the average deck temperature occurs, because a temperature gradient is being established across the deck.

RF Units Stabilization

The RF units average temperature performance is shown in Figure 44. The temperature came up very quickly, and reached the desired 50°C. The RF unit temperatures were relatively stable after 150 minutes.

The RF temperature distributions are shown on Figure 45 and the temperature variances are shown on Figure 46. After 270 minutes, the temperature variances were approximately ± 0.2°C.

The temperature differential between the RF units and the instrument deck are shown on Figure 47 and is relatively constant.

The total power required by the RF units during this test is plotted on Figure 48, and is shown to be less than 10 watts throughout the test.

Deck temperature contours for the hot ambient condition are shown on Figures 49, 50, 51, 52, and 53. The ambient condition is shown on Figure 49. Initially deck temperatures are seen to be relatively uniform with no well-defined temperature gradient. By time t=60 minutes (Figure 50), the deck has a uniform temperature distribution, being stabilized by the two thermoelectric coolers in the forward corners. The stable gradient continues at time t=150 minutes (Figure 51) as the deck temperature reaches the set point, and continues to remain stable at times t=270 minutes and t=360 minutes (Figures 52 and 53).

In the hot ambient test, the system required a longer period of time to stabilize than in the nominal and cold ambient tests. However, the performance demonstrated in these tests verified the PBMR thermal control concept, and it was decided to proceed with the assembly and testing of flight hardware.

FLIGHT EVALUATION

At this point of the instrument development, all flight hardware (i.e., insulated containers, thermal system, and all associated control systems) was assembled. Before flight testing of the instrument, a brief laboratory examination of the thermal control system was conducted. A selected RF unit was examined for temperature stabilization. The instrument deck and the antenna deck temperatures were visually monitored. Figure 54 shows a strip chart recording of the RF unit stabilization temperature profile. (The 35.5°C stabilized temperature was an arbitrary selection for system checkout and was stable within ± 0.05°C.)

Next, a flight test was conducted at Wallops Flight Center with the instrument installed aboard the Skyvan aircraft. For this flight, the ambient temperature was 18°C, and the RF units were set for 38°C. The thermal system was activated for an hour during the preflight checkout of the aircraft. The aircraft's mission was to obtain an altitude of 500 ft. and a velocity of 80-90 knots and operate all PBMR systems.

Figures 55, 56, 57, and 58 depict the stability of the RF units. It can be seen that each RF unit does not have an exact 38.0°C temperature reading; however, the stability about its normal temperature is 0.1° in three units (RF #1, #3, and #4) and ± 0.15°C in the other unit (RF #2) This one case deviation could be corrected by resetting the fine control on the temperature controller.

In summary, the flight evaluation of the thermal system was very successful and the entire radiometer system was made available for use in several agricultural programs to sense soil moisture.

CONCLUSION

A closed-loop thermoelectric temperature control system has been designed, fabricated, and tested for the purpose of stabilizing sensitive integrated circuits within a microwave radiometer. The temperature control system features a dual mode (heating and cooling) control concept based on accurately controlling the temperature of the RF units within ± 0.1°C. These units are thermally isolated (partially) from their support, the instrument deck, and the deck is thermally controlled by thermoelectric coolers and thin film heaters.

The radiometer boundaries and the temperature control concept was simulated with a thermal analyzer program (MITAS) which consisted of 37 nodes and 61 conductors. Typical computer runs subjected the simulated model to environmental temperatures of -40°C and +45°C

A full scale thermal mockup was developed and tested in the laboratory at ambient temperatures of 0°C, +21°C and +45°C. The mockup testing indicated that temperature stability of the RF units and radiometer components could be achieved within 90 minutes and confirmed the validity of the control concept.

A flight radiometer and temperature control system with precision temperature controllers was fabricated and flight tested. Conditions for the flight test were an ambient temperature of 18°C, an airspeed of 80-90 knots, and an altitude of 400 feet. The following data summary shows that the flight control system essentially performed as well as the analysis prediction.

RF Unit No.	Analysis	Flight
1	± 0.10	± 0.10
2	± 0.10	± 0.15
3	± 0.10	± 0.10
4	± 0.10	± 0.10

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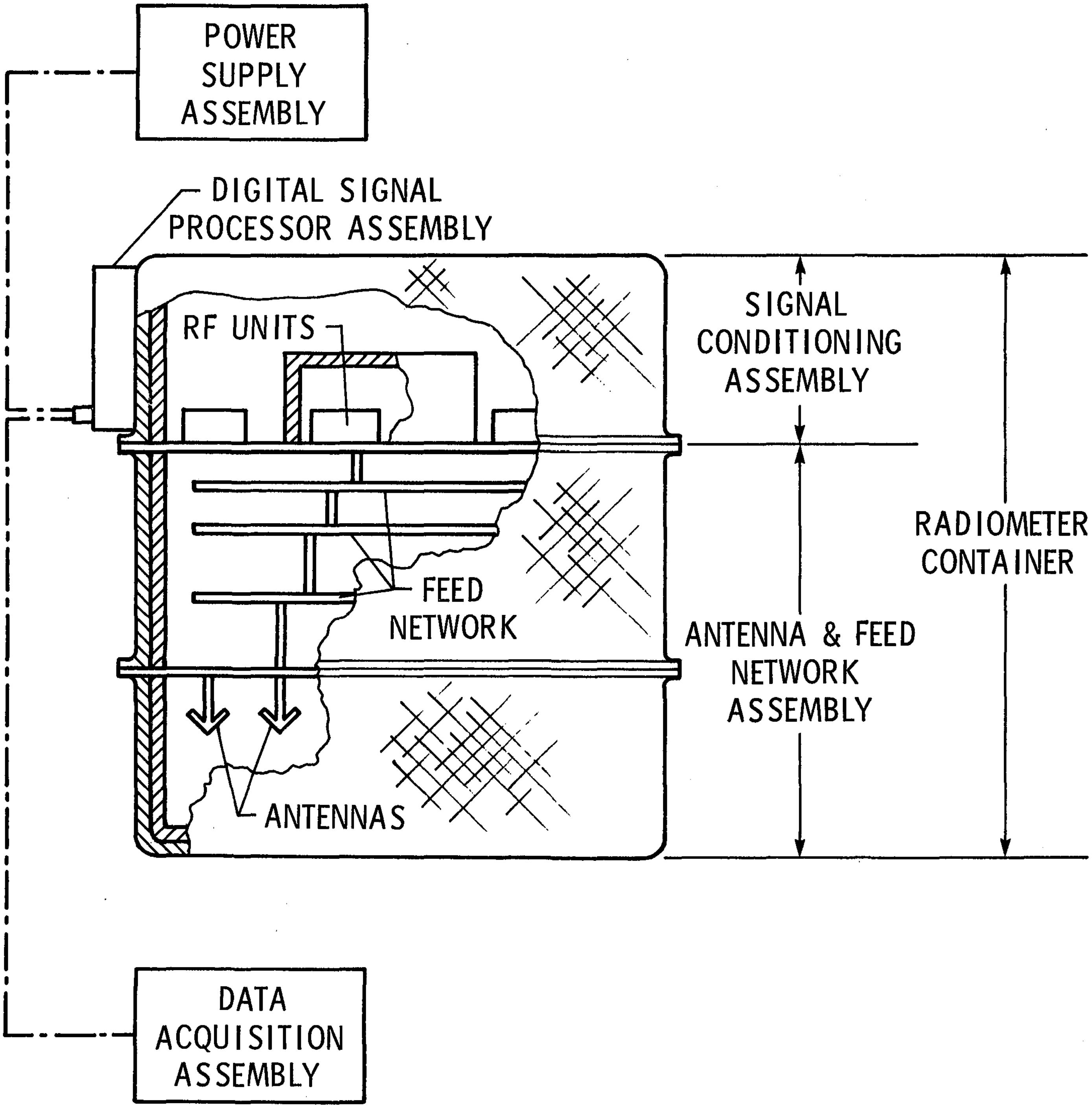


Figure 1. - PBMR instrument.

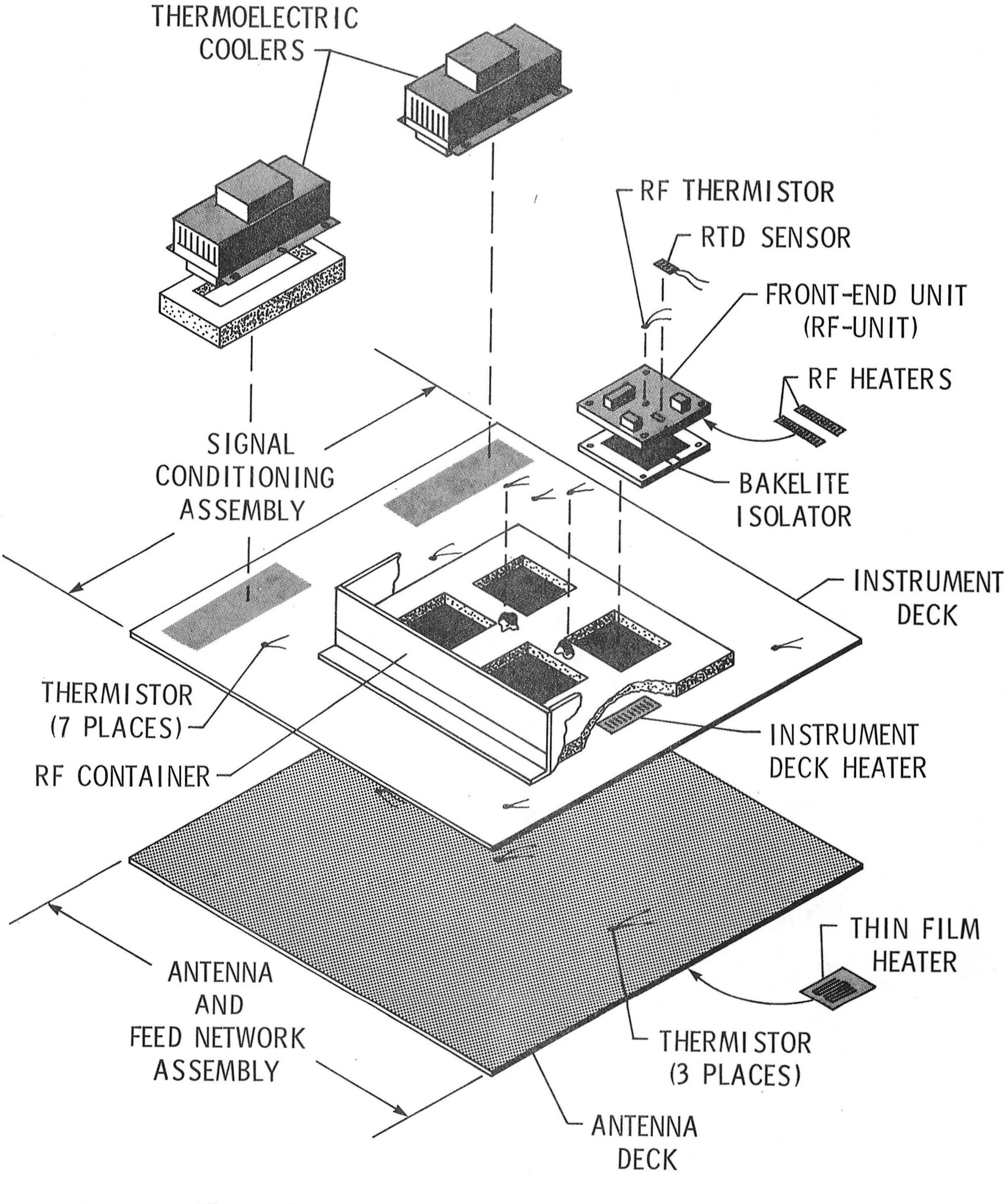


Figure 2. - Temperature control system hardware.

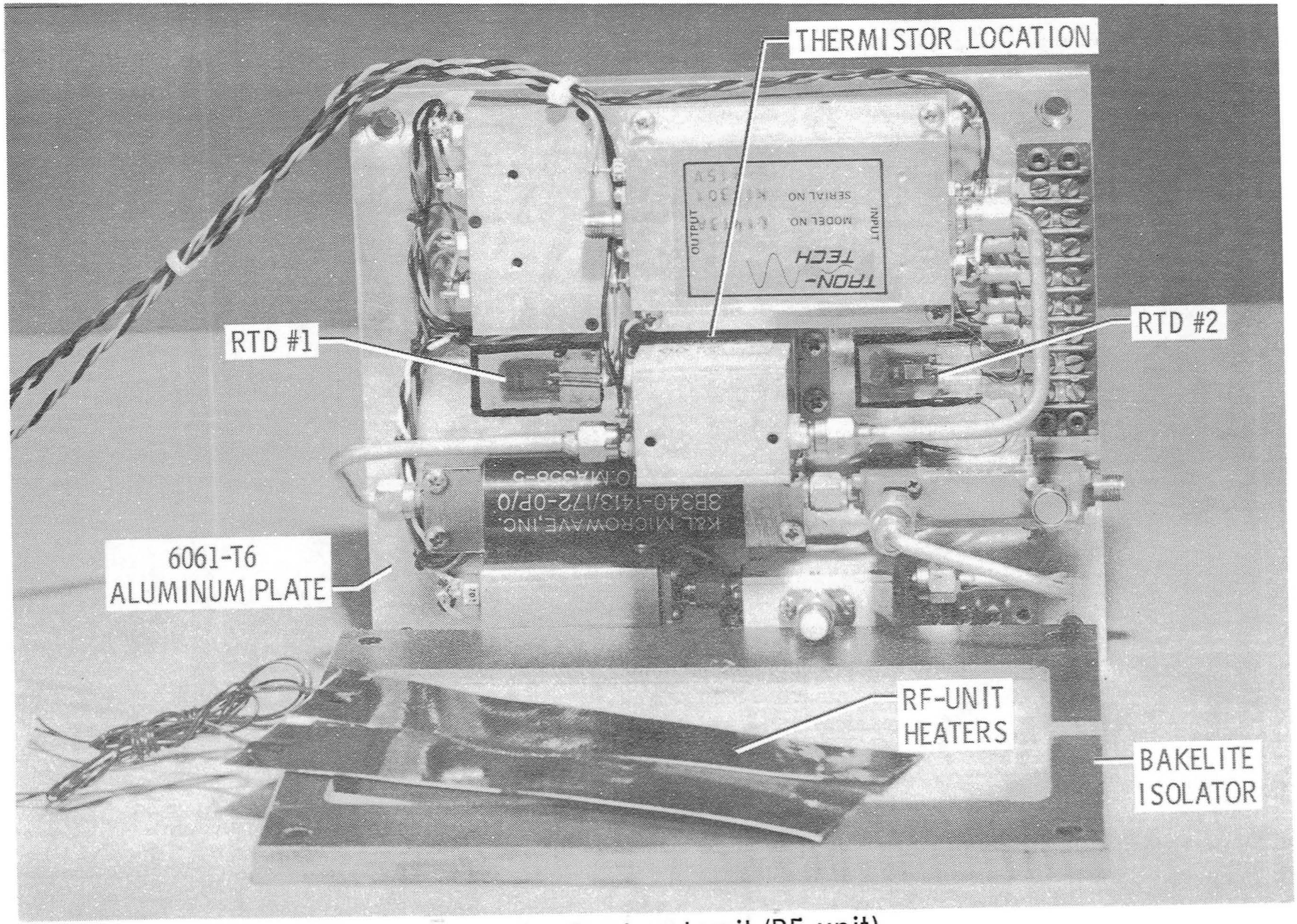
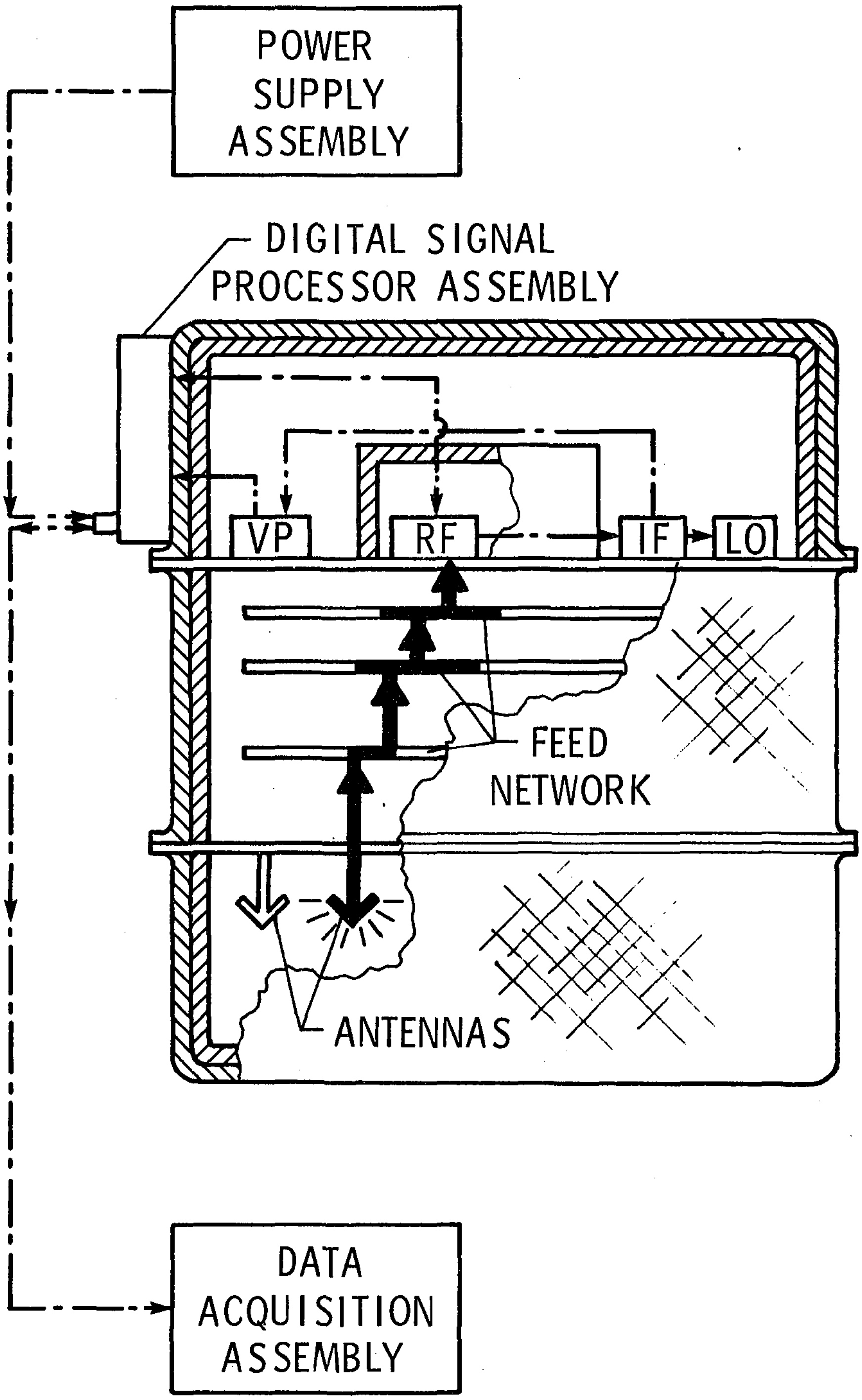


Figure 3. - Front-end unit (RF-unit).



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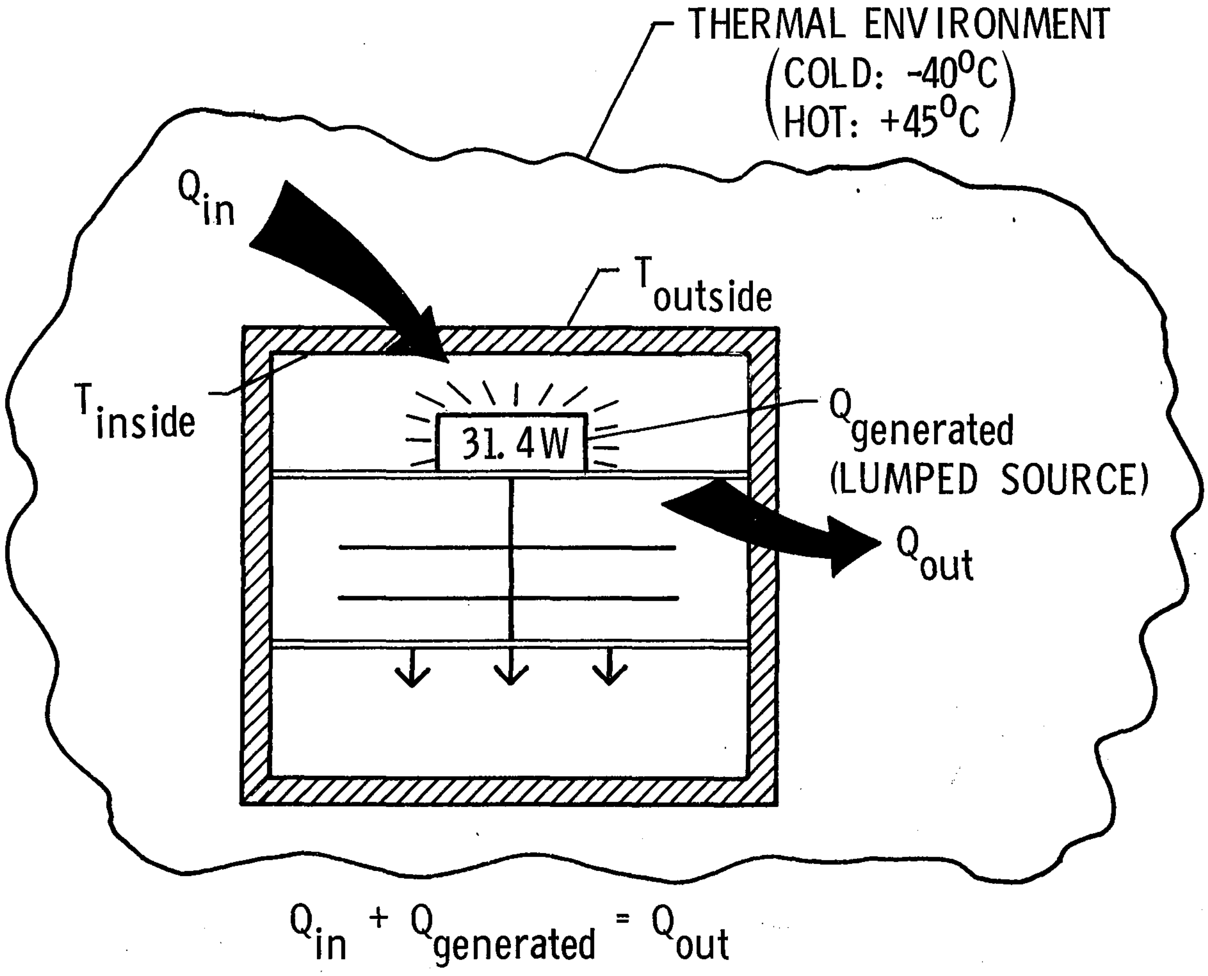

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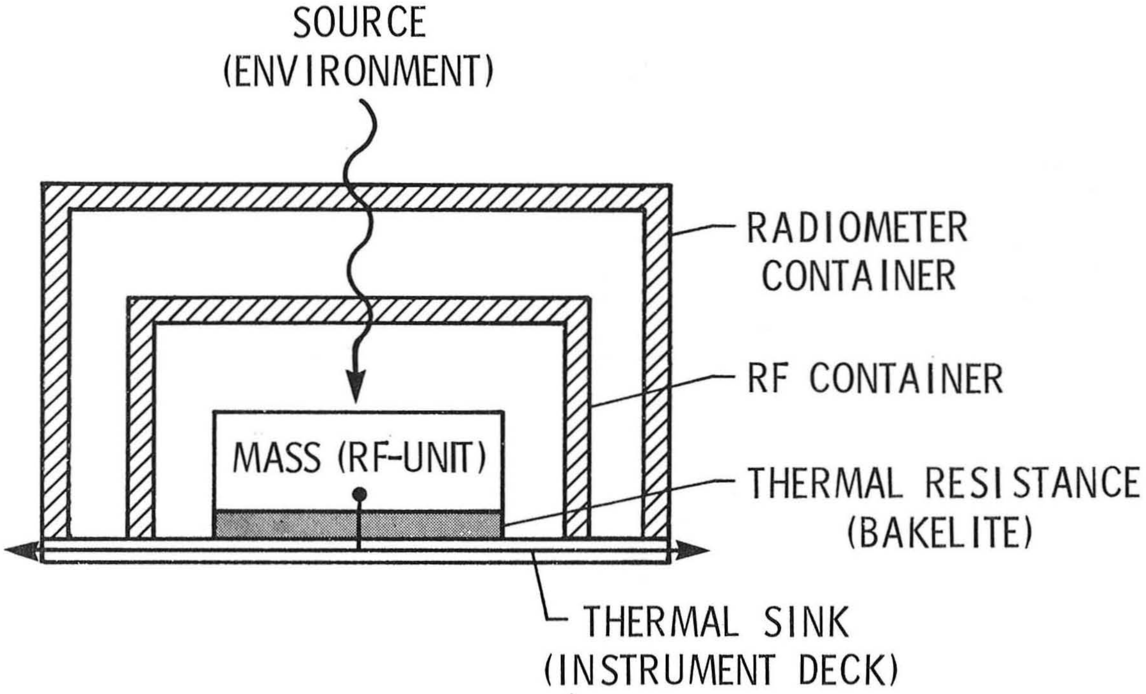

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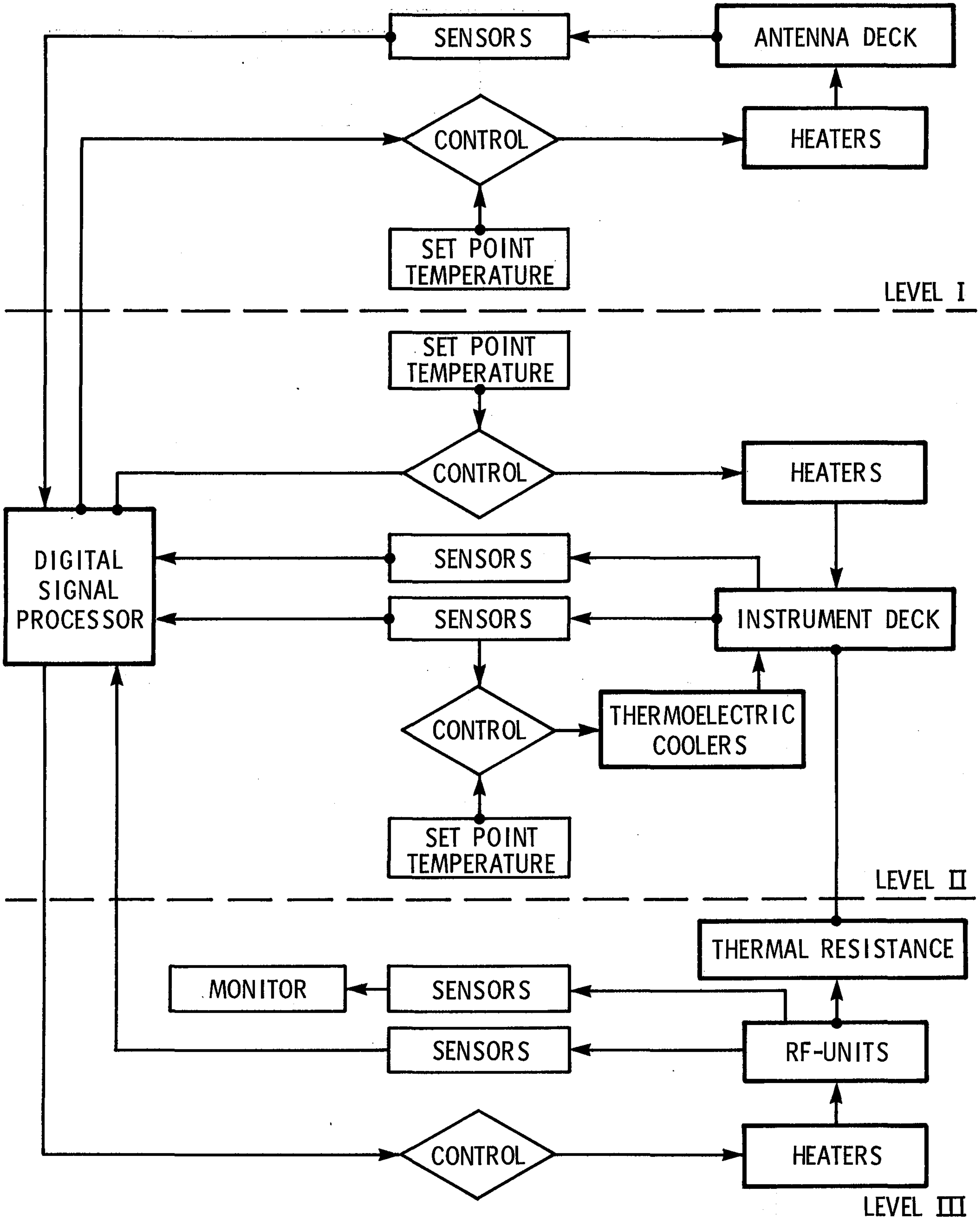

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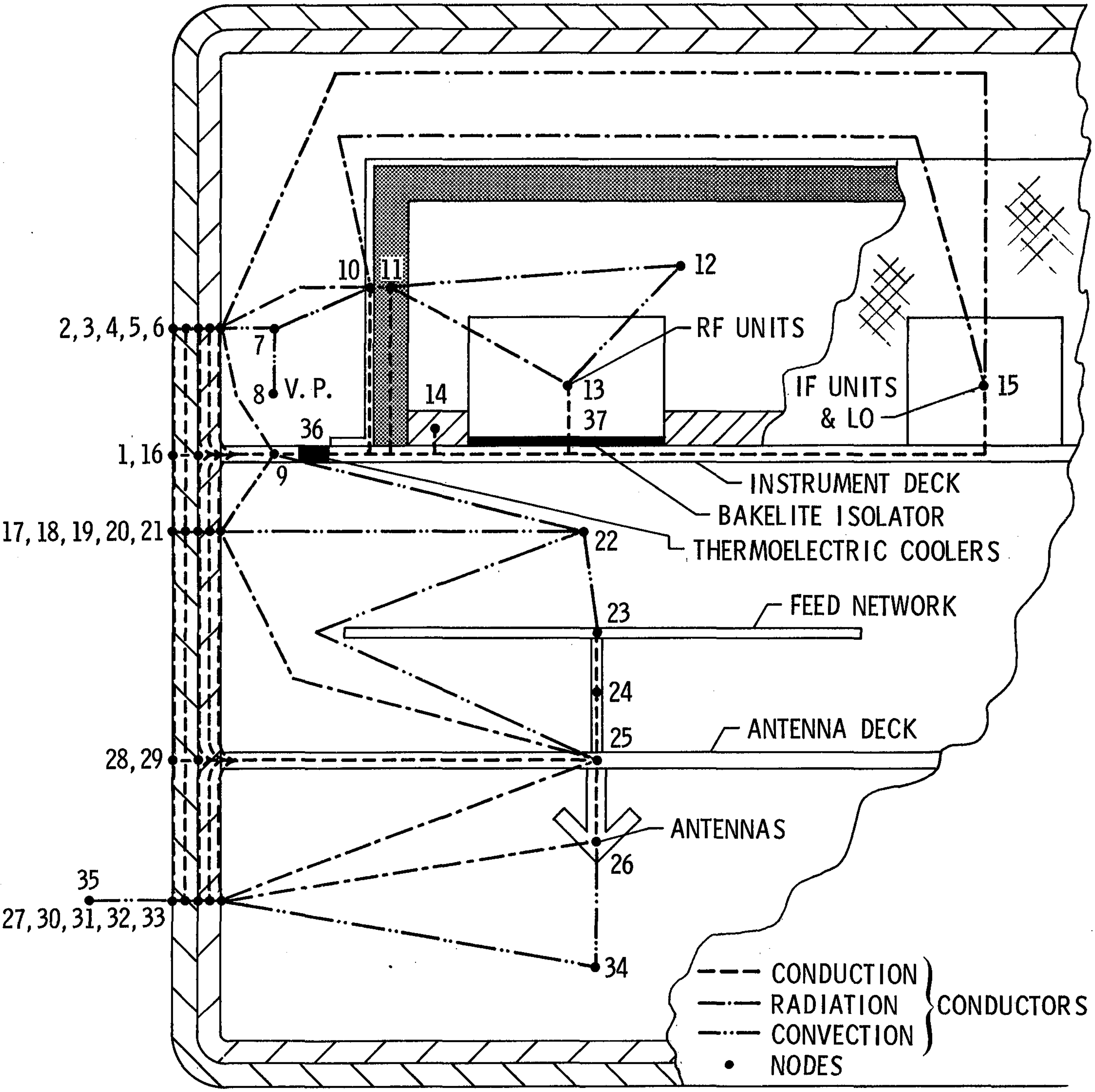


Figure 8. - PBMR MITAS computer model.

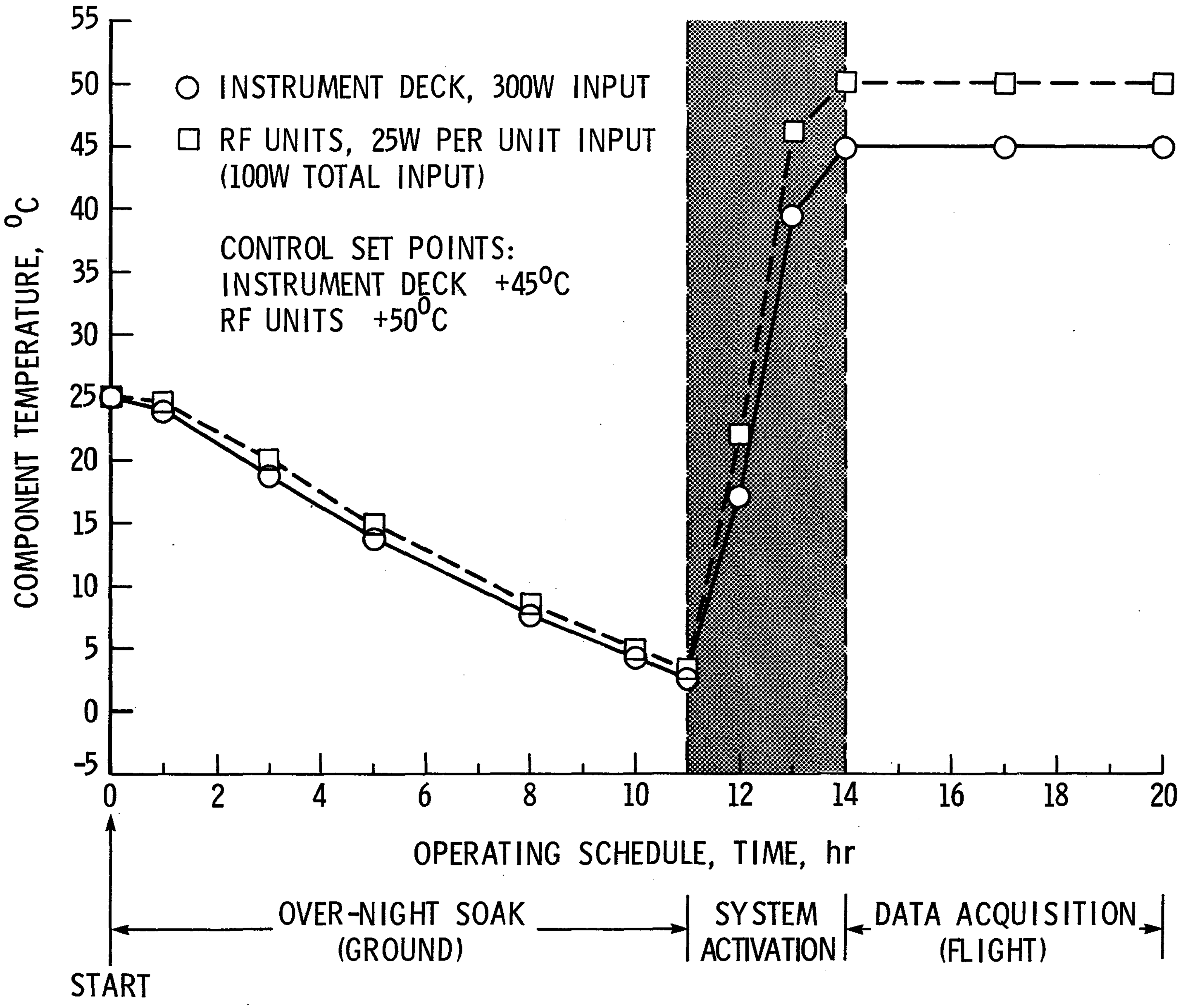
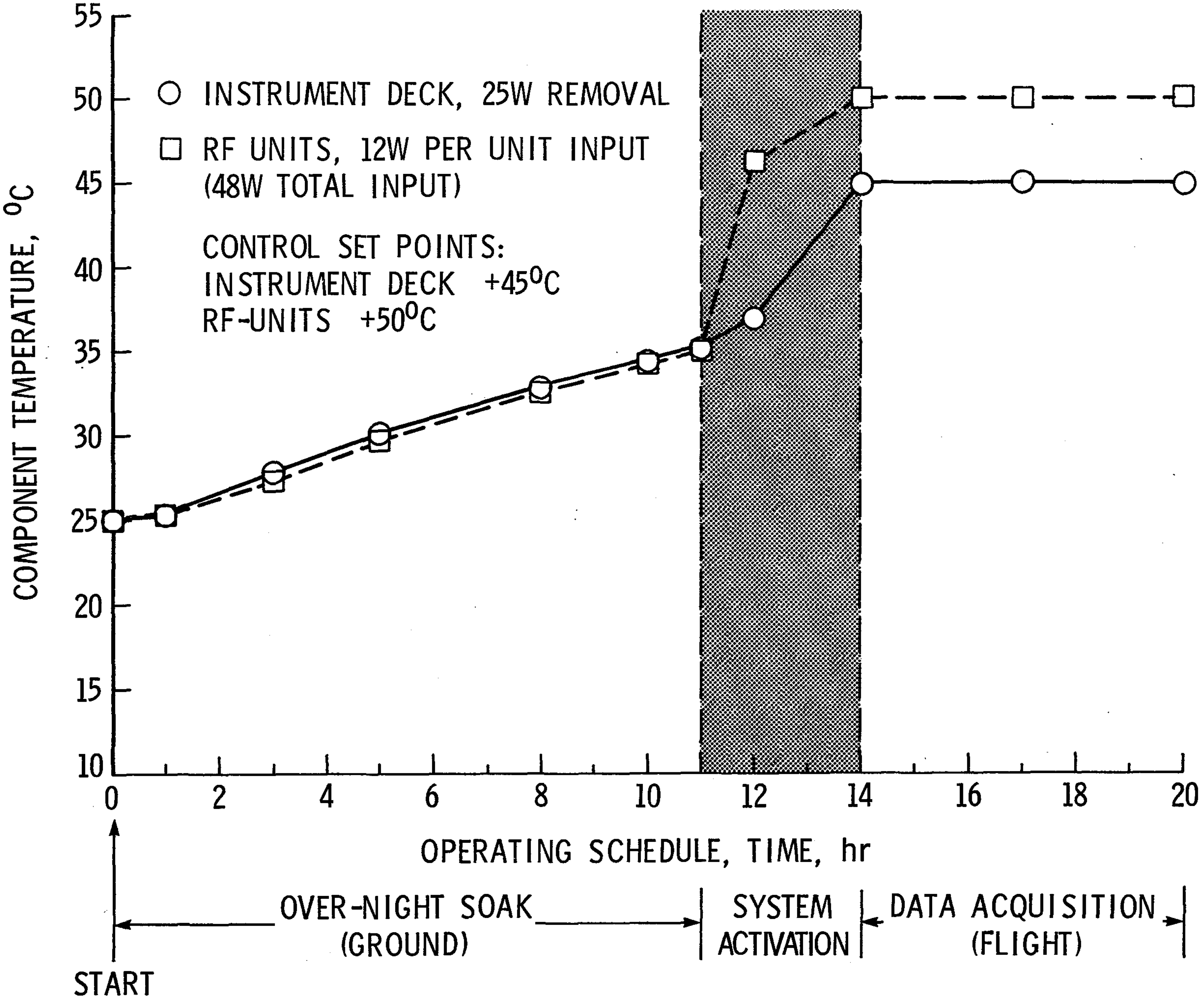


Figure 9. - Cold environment simulation (-40°C).



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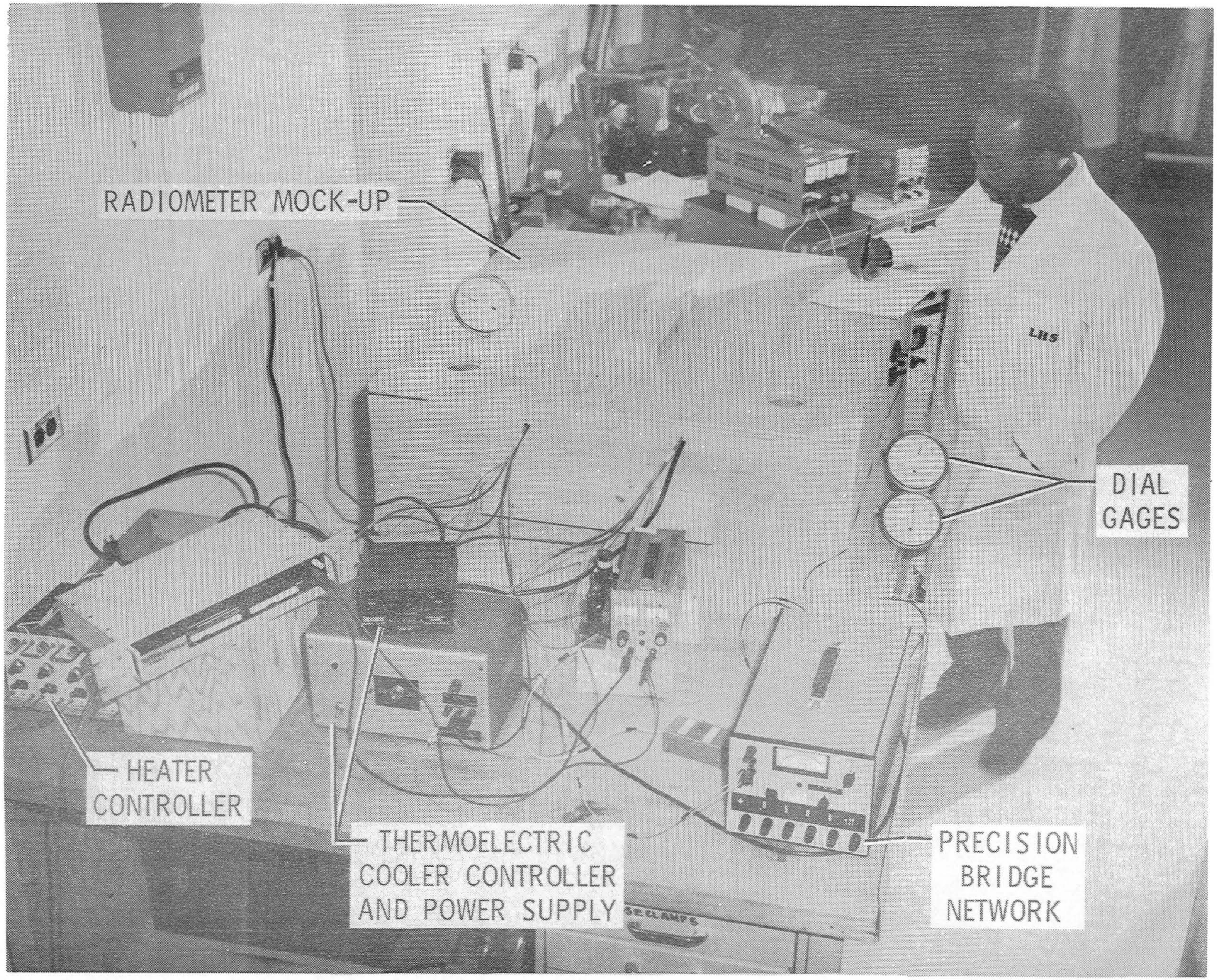
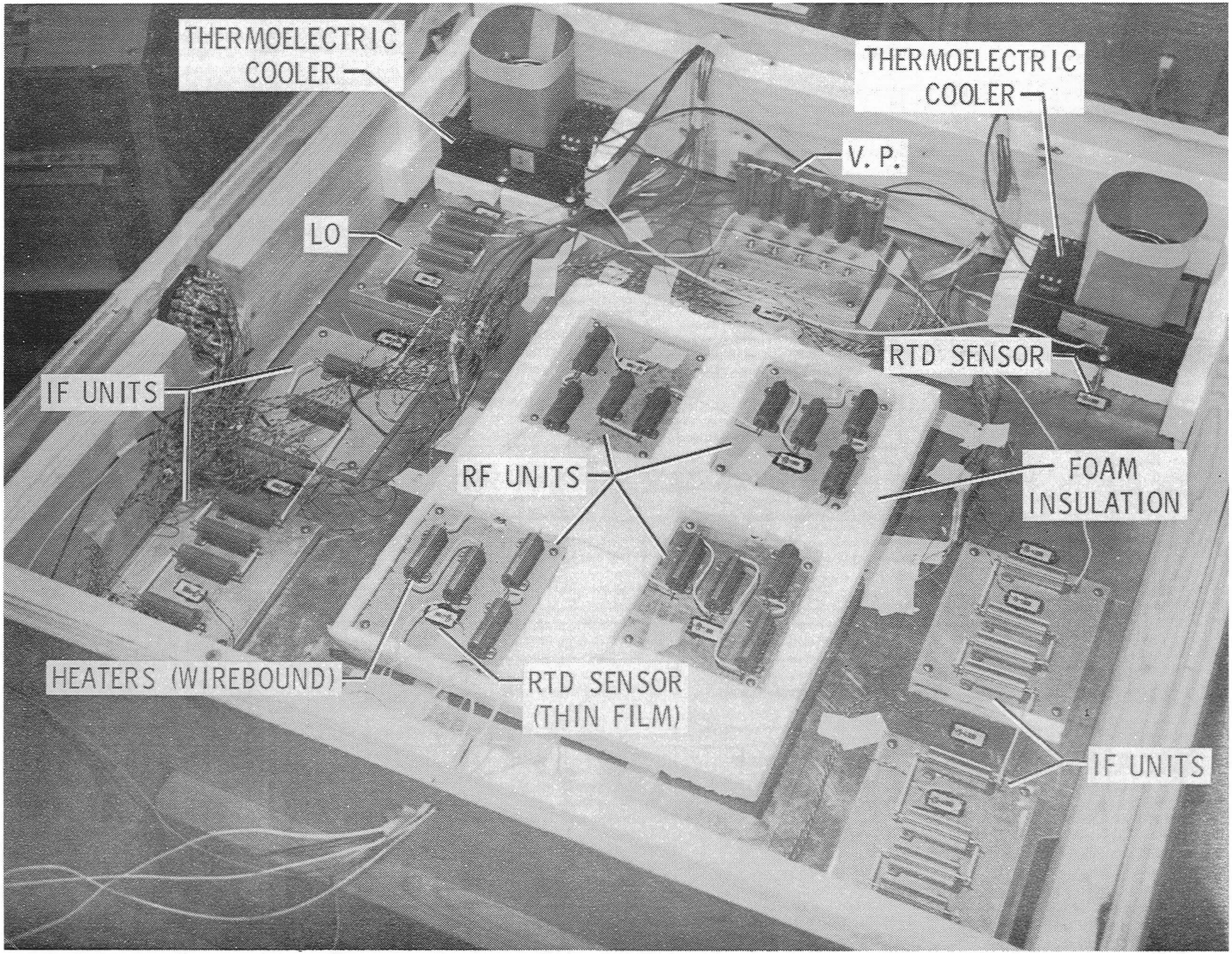


Figure 11a. - PBMR mock-up and test set-up.



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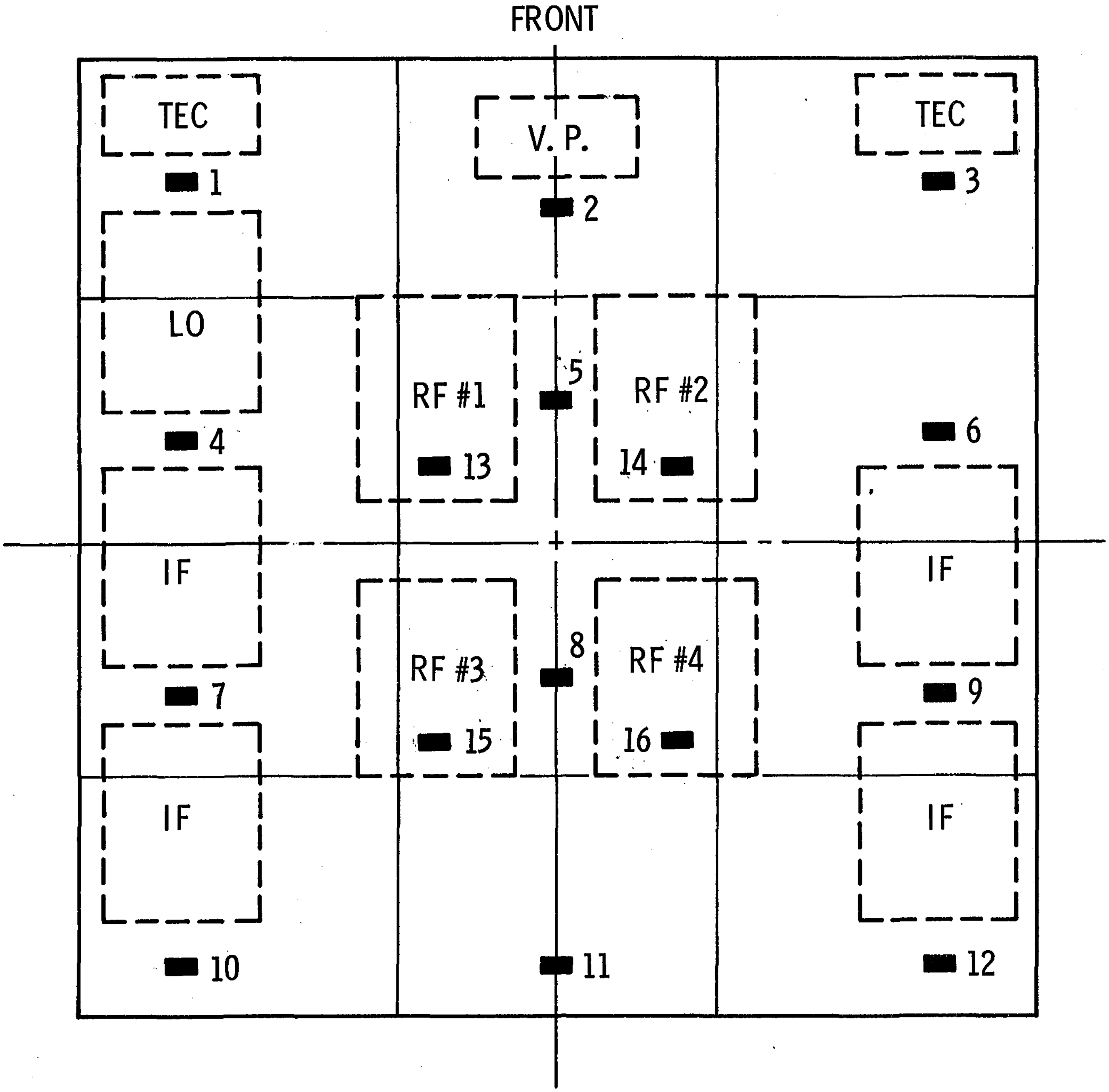
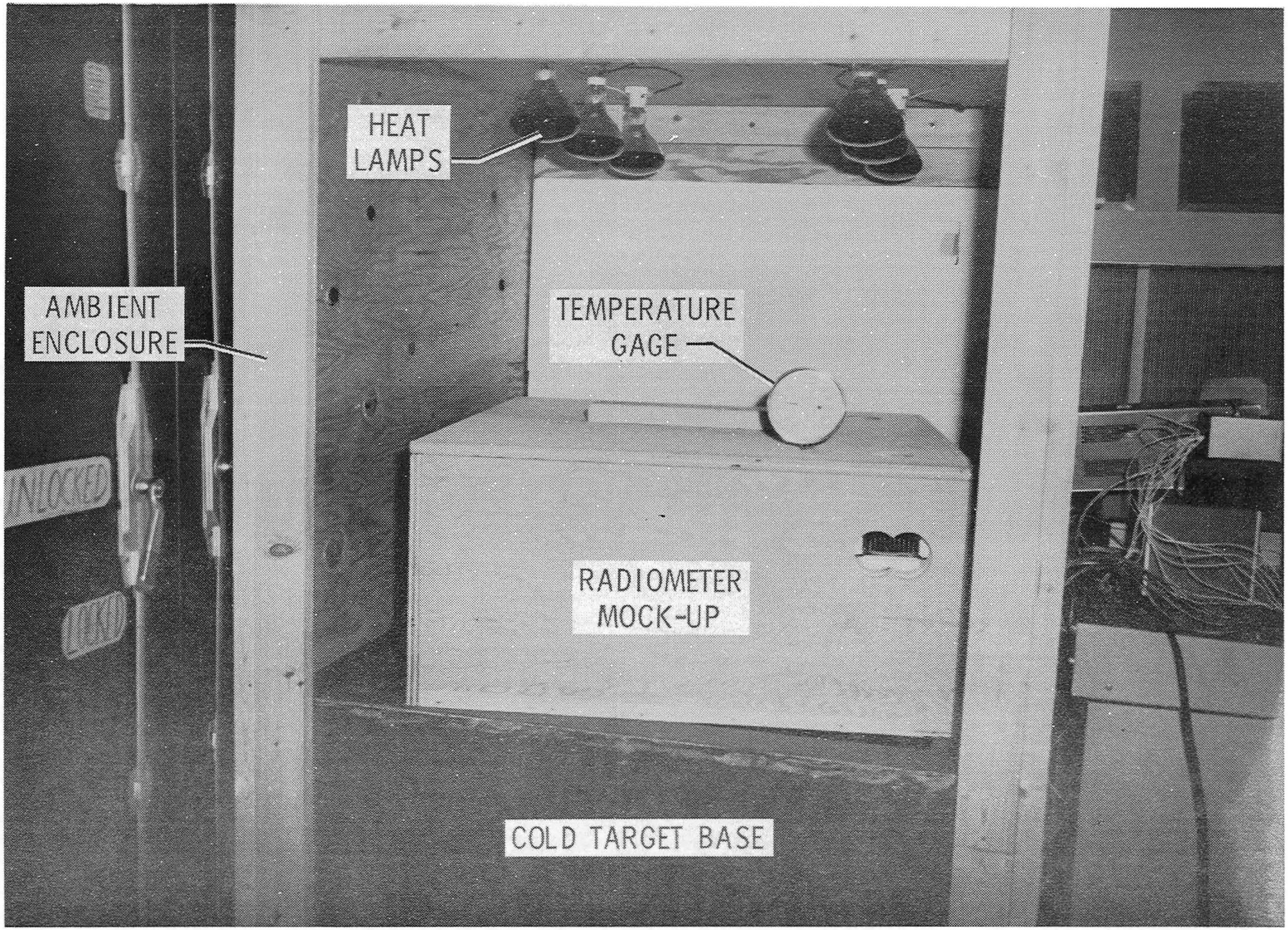


Figure 12. - RTD sensor locations on instrument deck.



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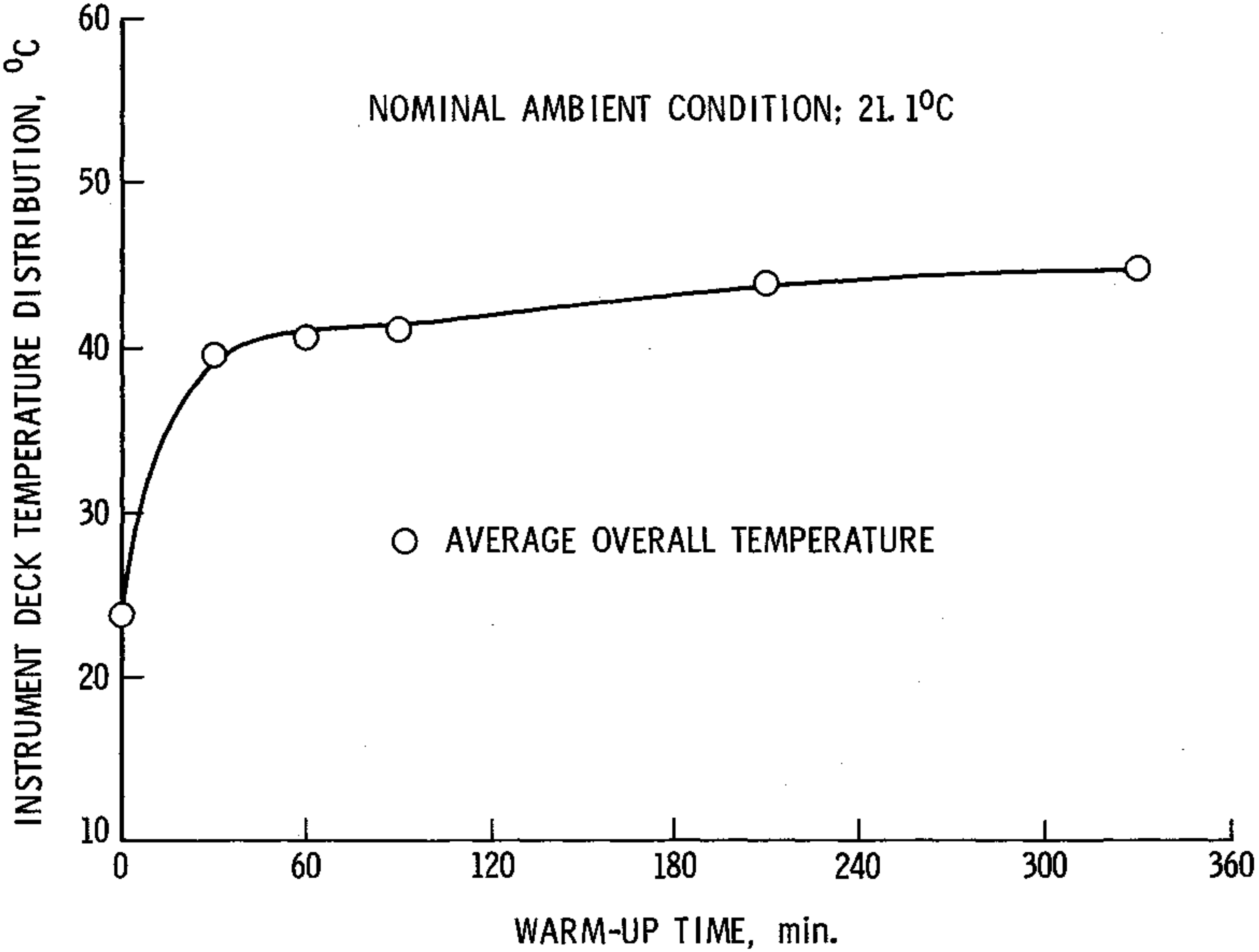

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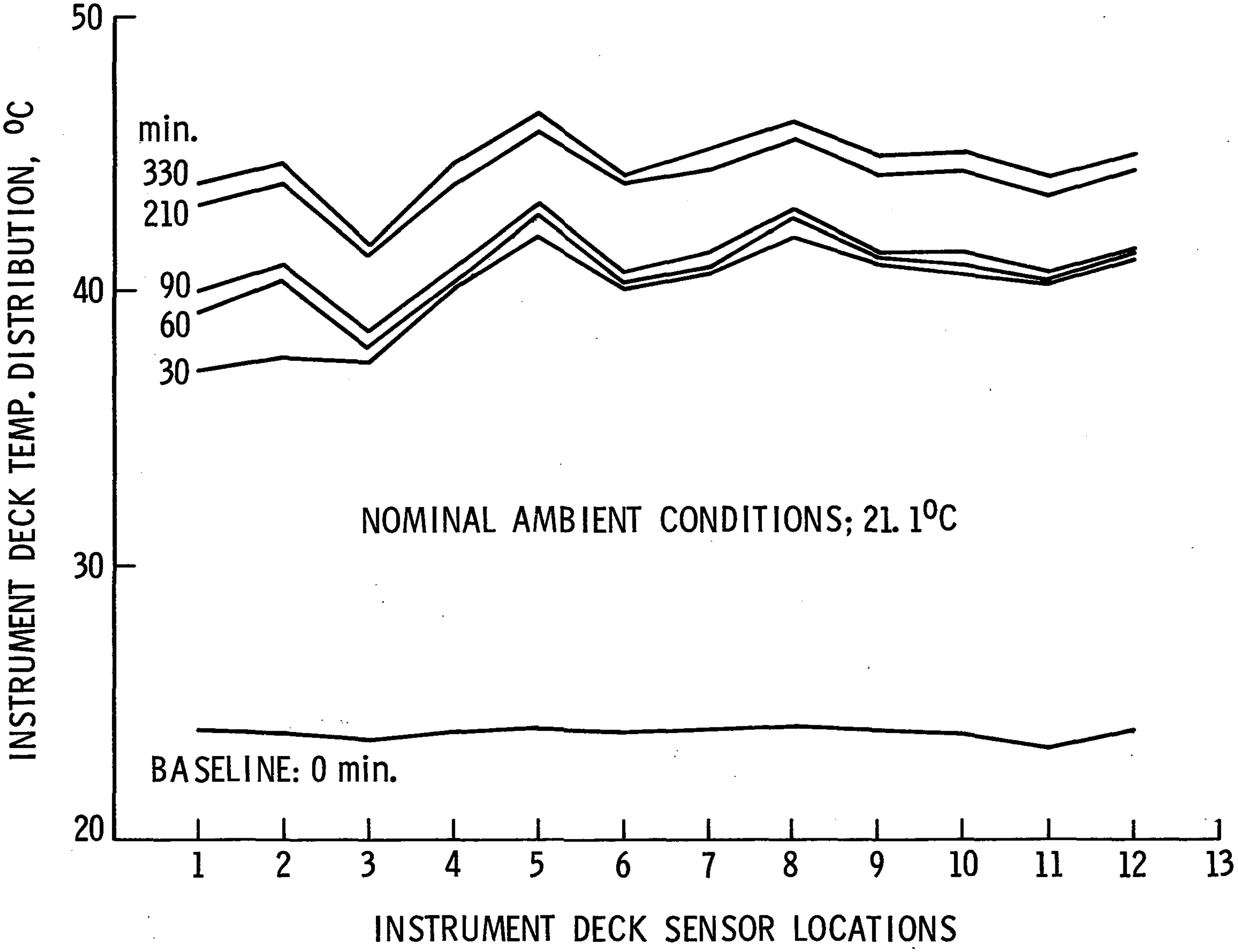
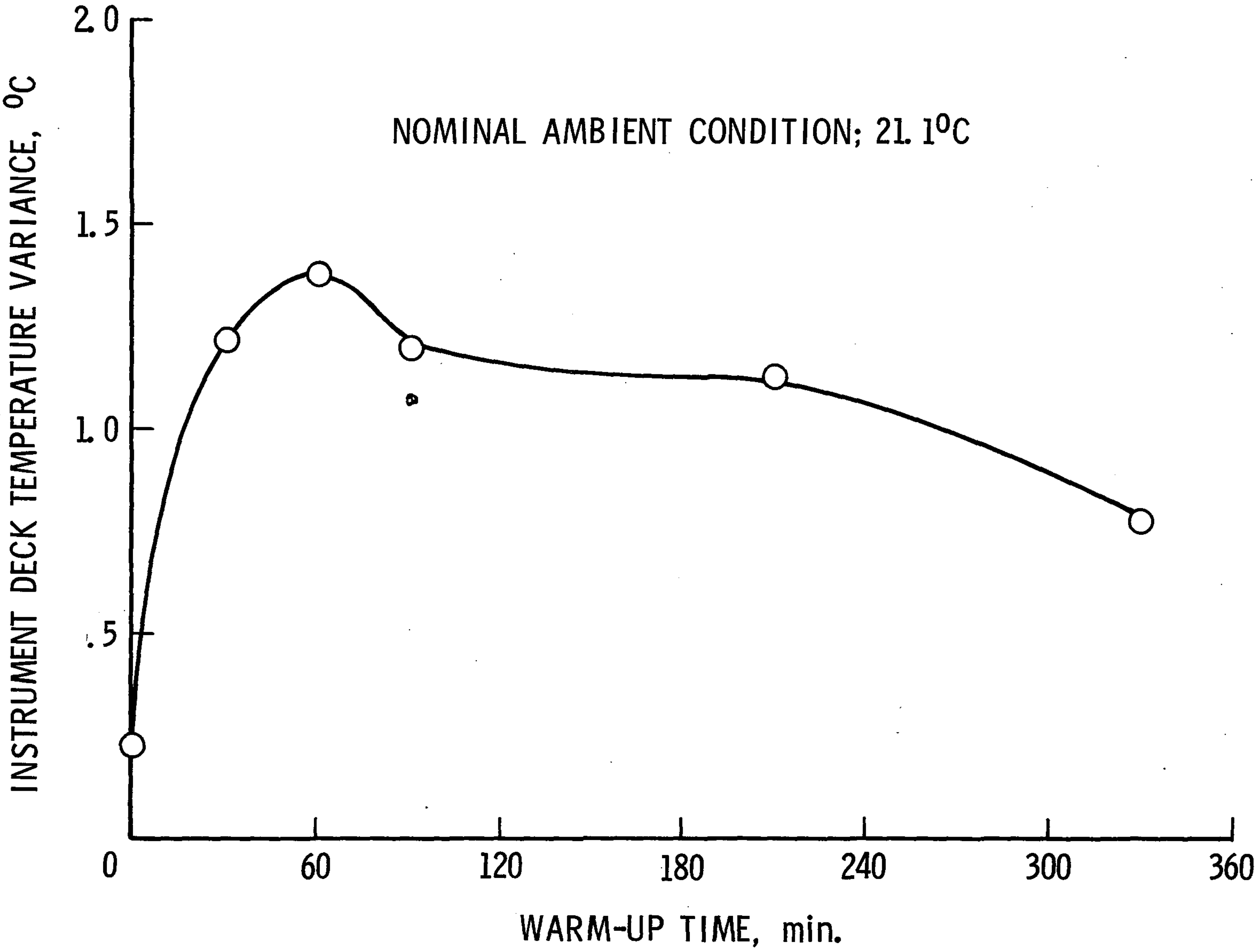


Figure 15. - Instrument deck temperature warm-up distribution.



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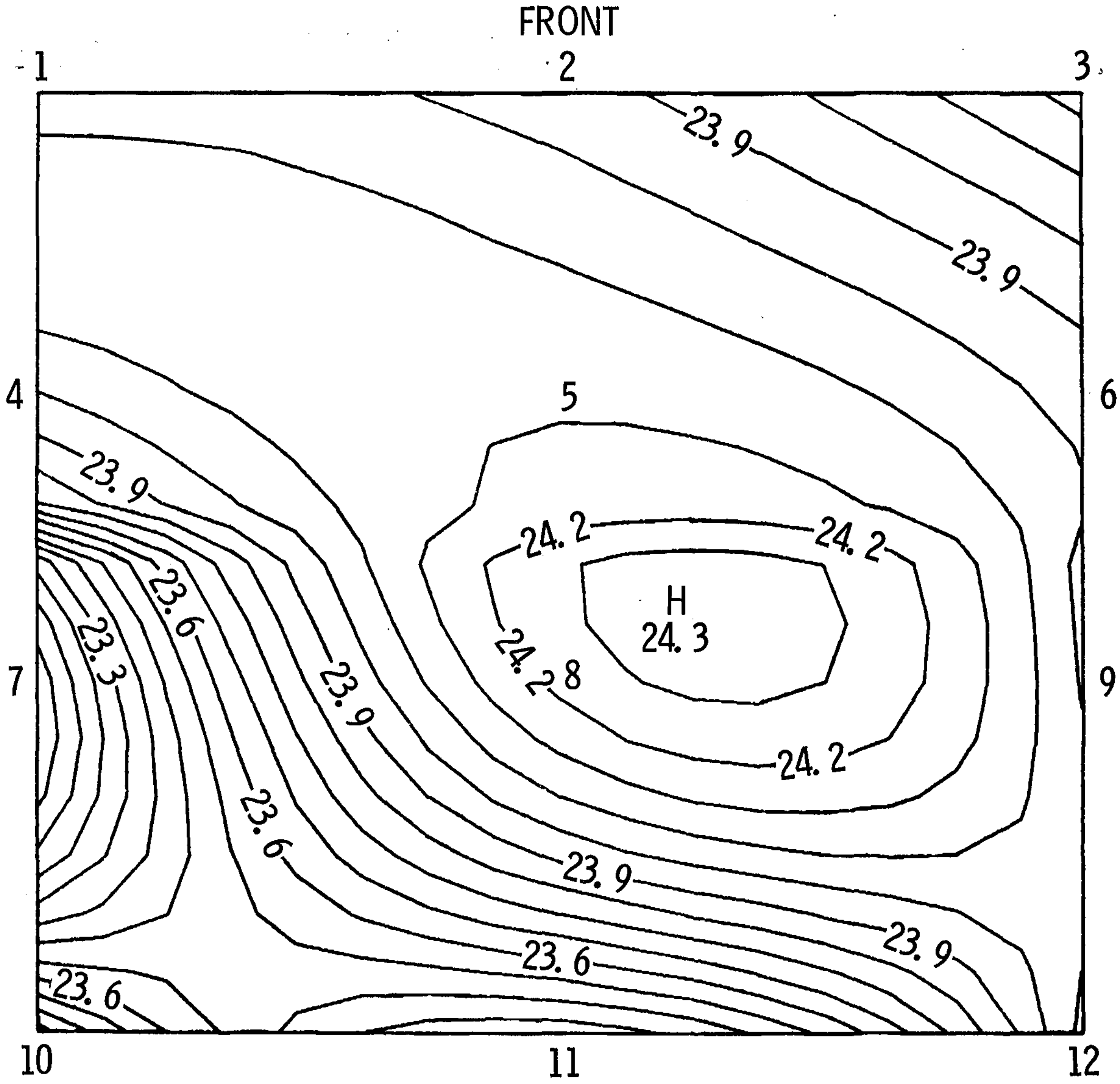
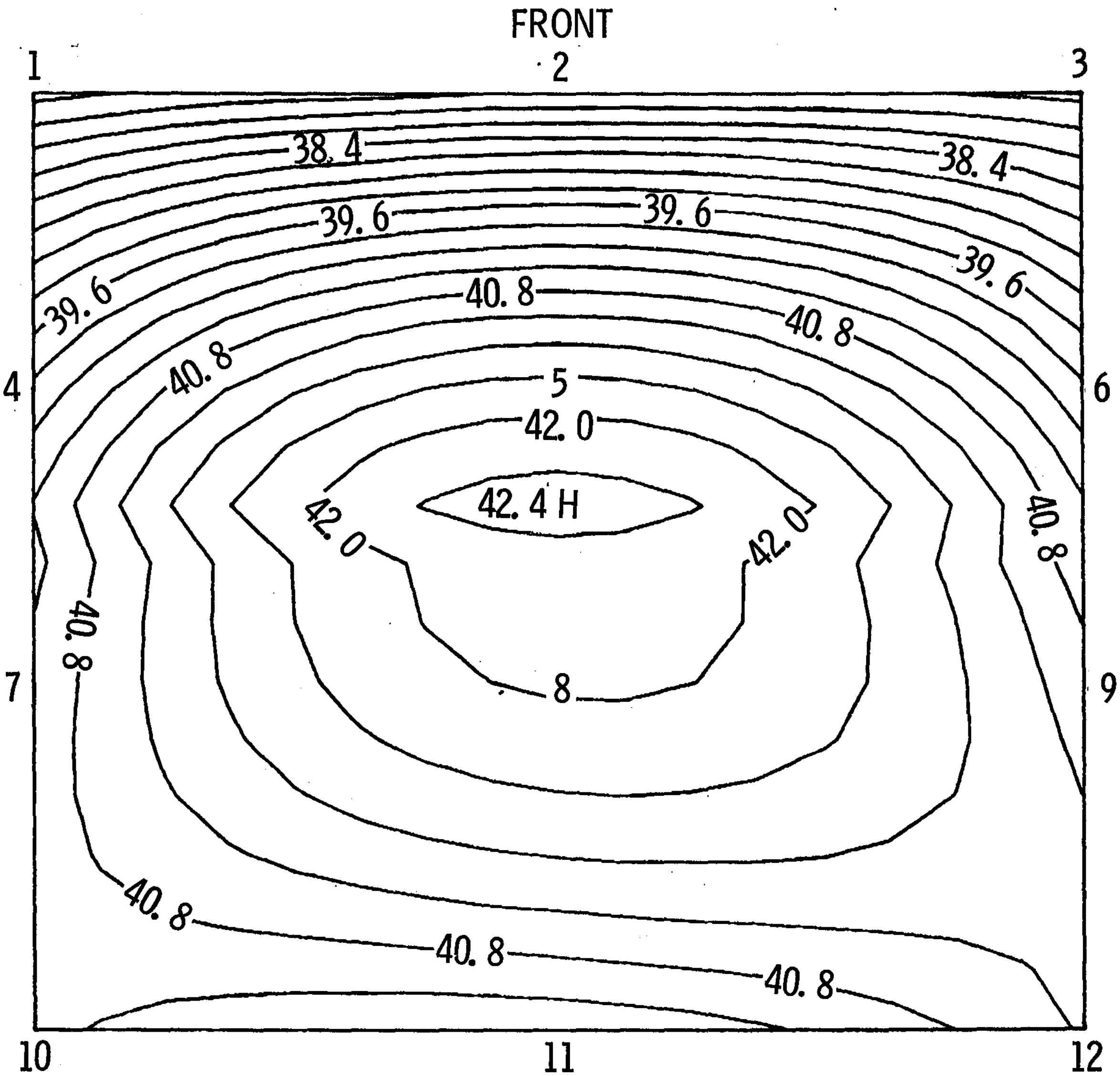


NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

NOMINAL CONDITION
TIME: 0 min.
CONTOUR INTERVAL IS 0.07°C

Figure 17. - Instrument deck temperature contour (°C).

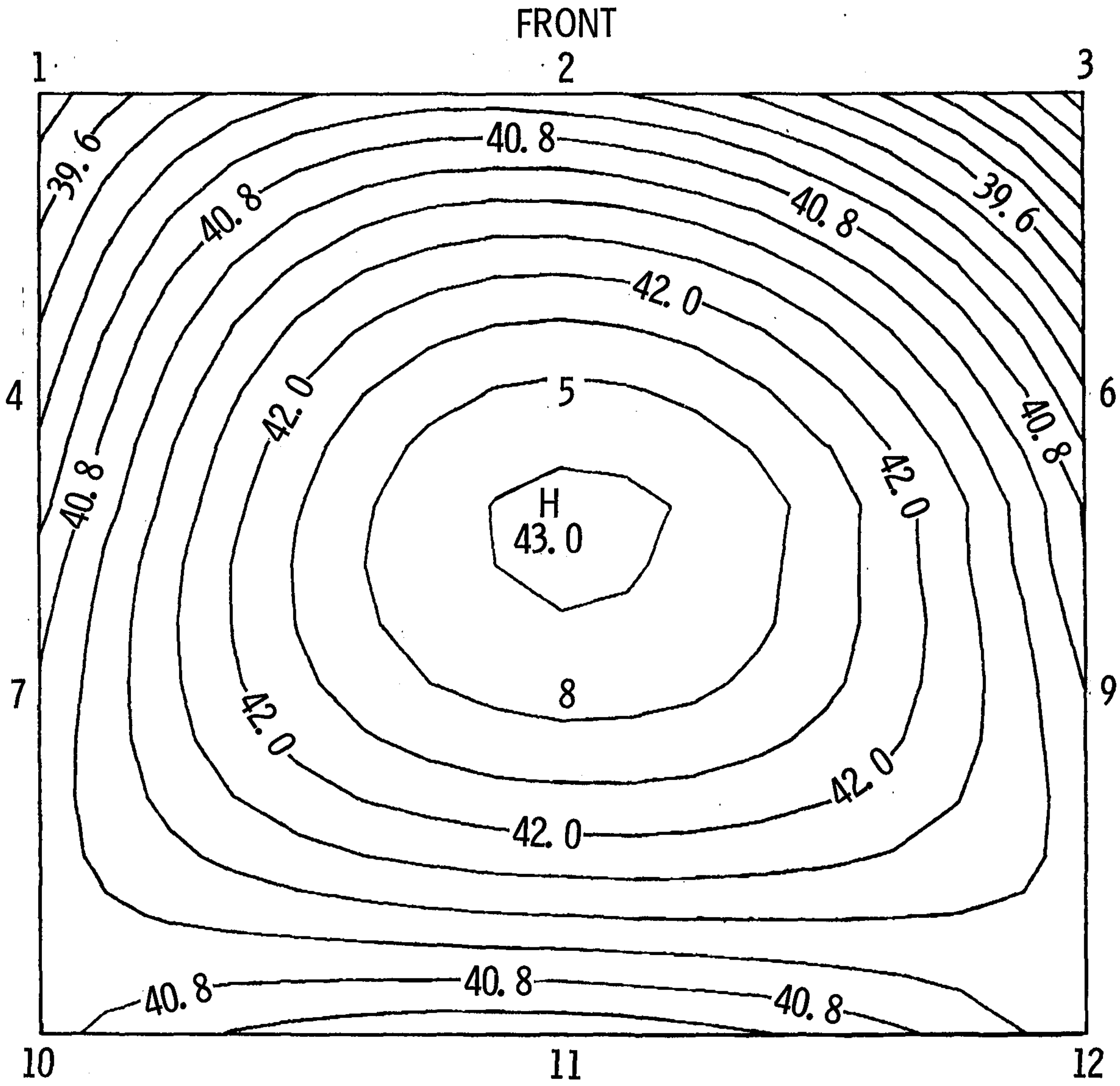


NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

NOMINAL CONDITION
TIME: 30 min.
CONTOUR INTERVAL IS 0.30^{0}C

Figure 18. - Instrument deck temperature contour (^{0}C).

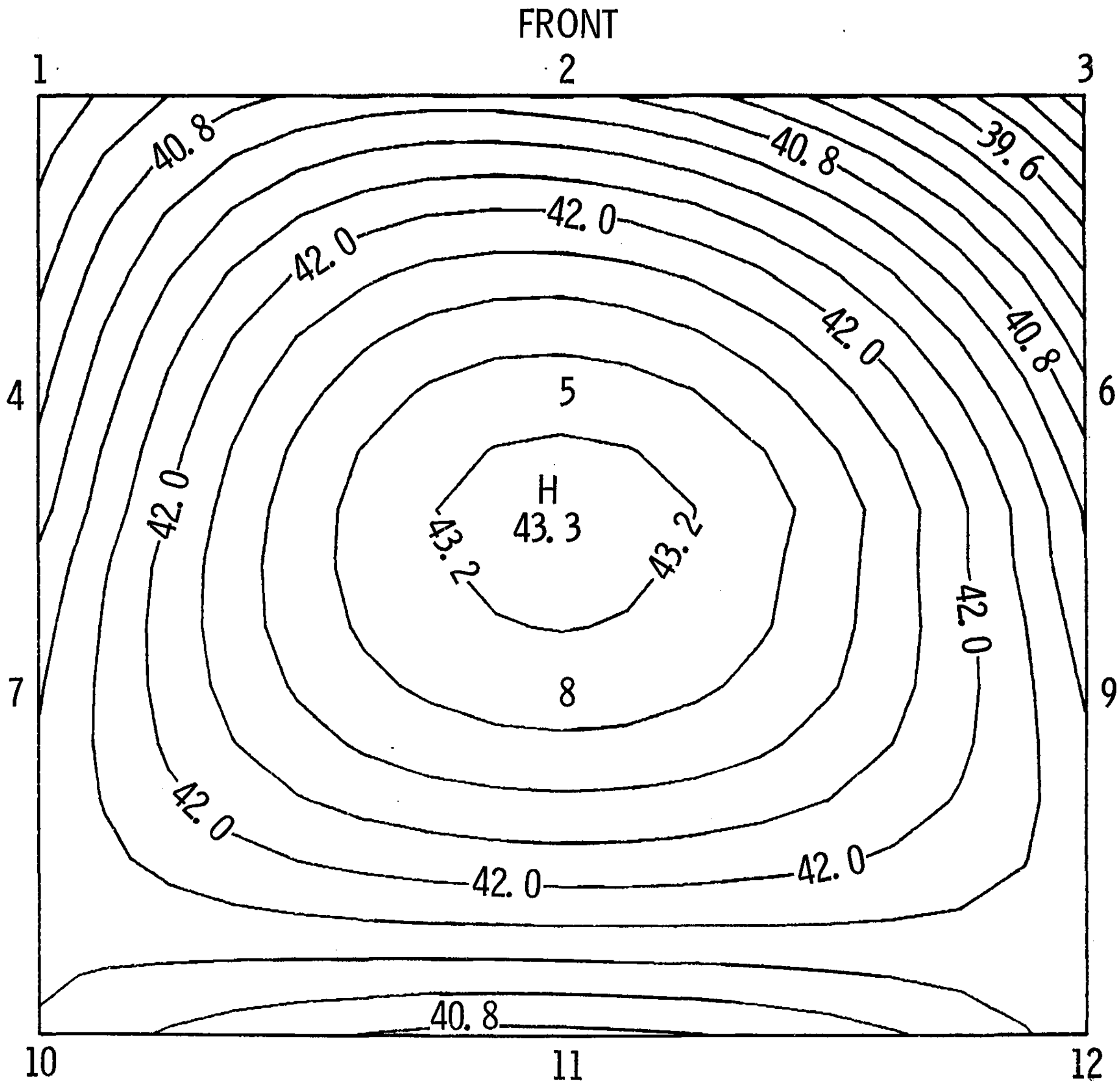
NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS



NOMINAL CONDITION
TIME: 60 min.
CONTOUR INTERVAL IS 0.30°C

Figure 19. - Instrument deck temperature contour (°C).

T=60

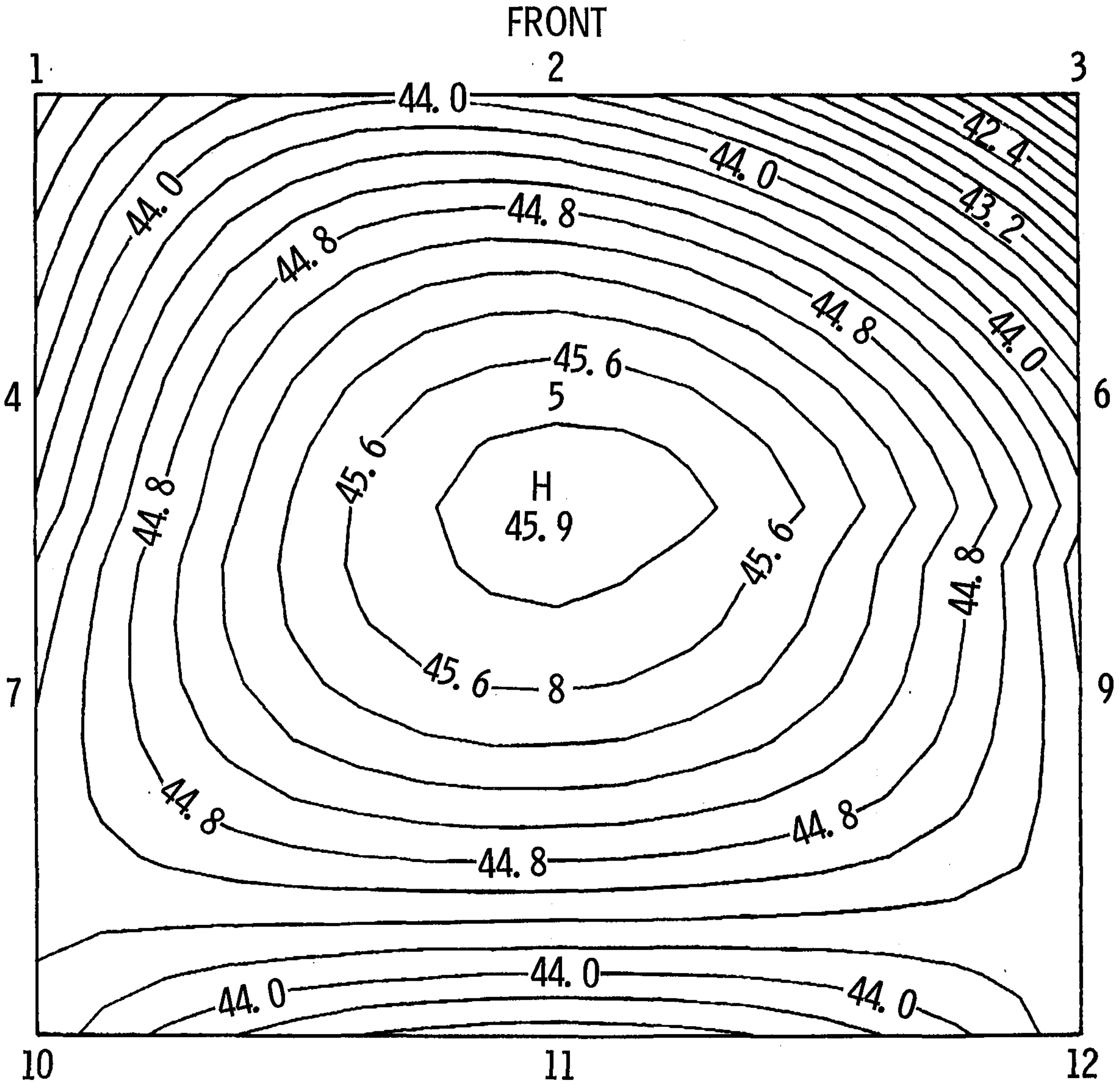


NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

NOMINAL CONDITION
TIME: 90 min.
CONTOUR INTERVAL IS 0.30°C

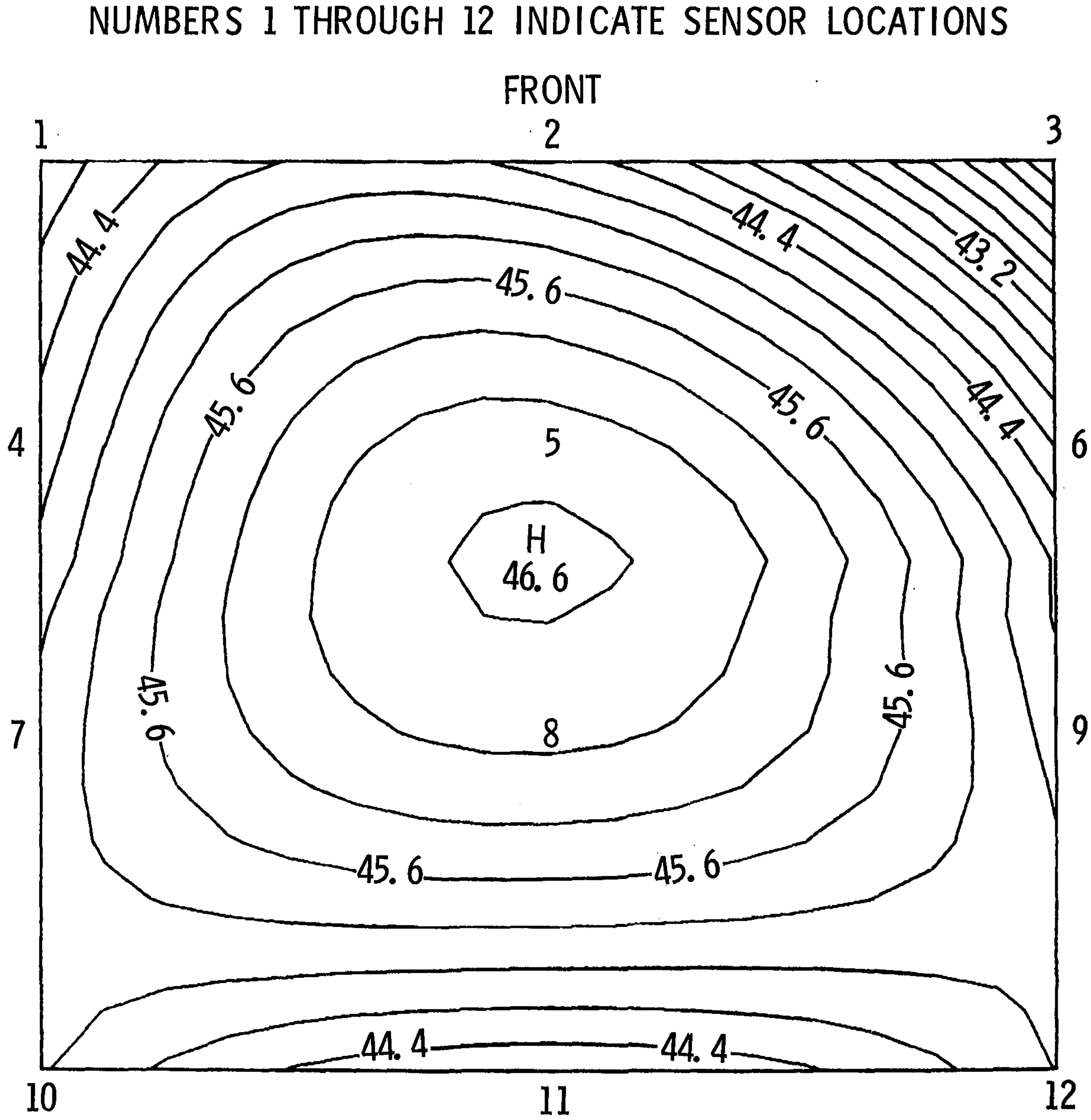
Figure 20. - Instrument deck temperature contour (°C).

NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS



NOMINAL CONDITION
TIME: 210 min.
CONTOUR INTERVAL IS 0.20°C

Figure 21. - Instrument deck temperature contour (°C).



NOMINAL CONDITION
TIME: 330 min.
CONTOUR INTERVAL IS 0.30°C

Figure 22. - Instrument deck temperature contour (°C).

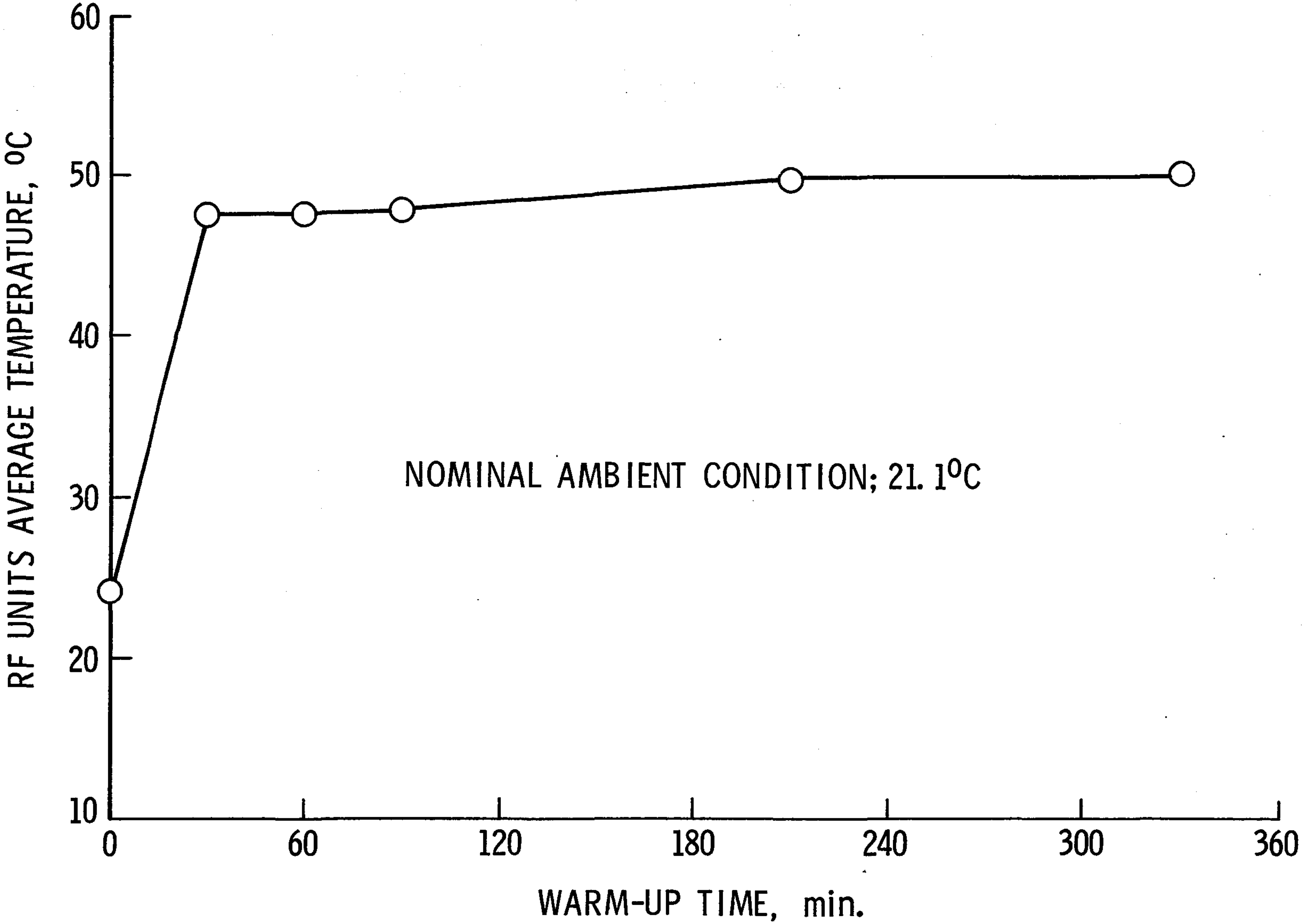


Figure 23. - RF units warm-up temperature profile.

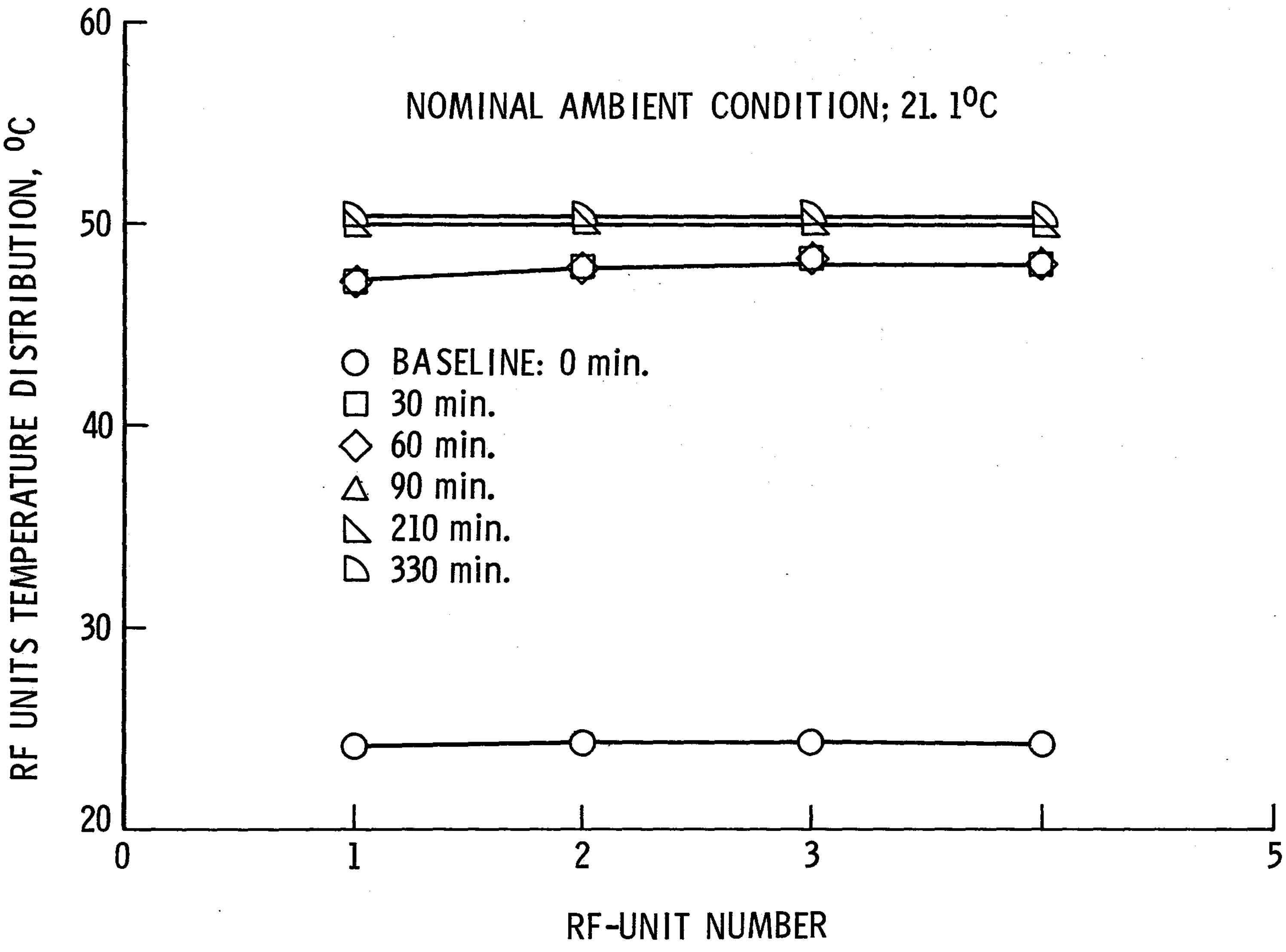


Figure 24. - RF units temperature distribution during warm-up.

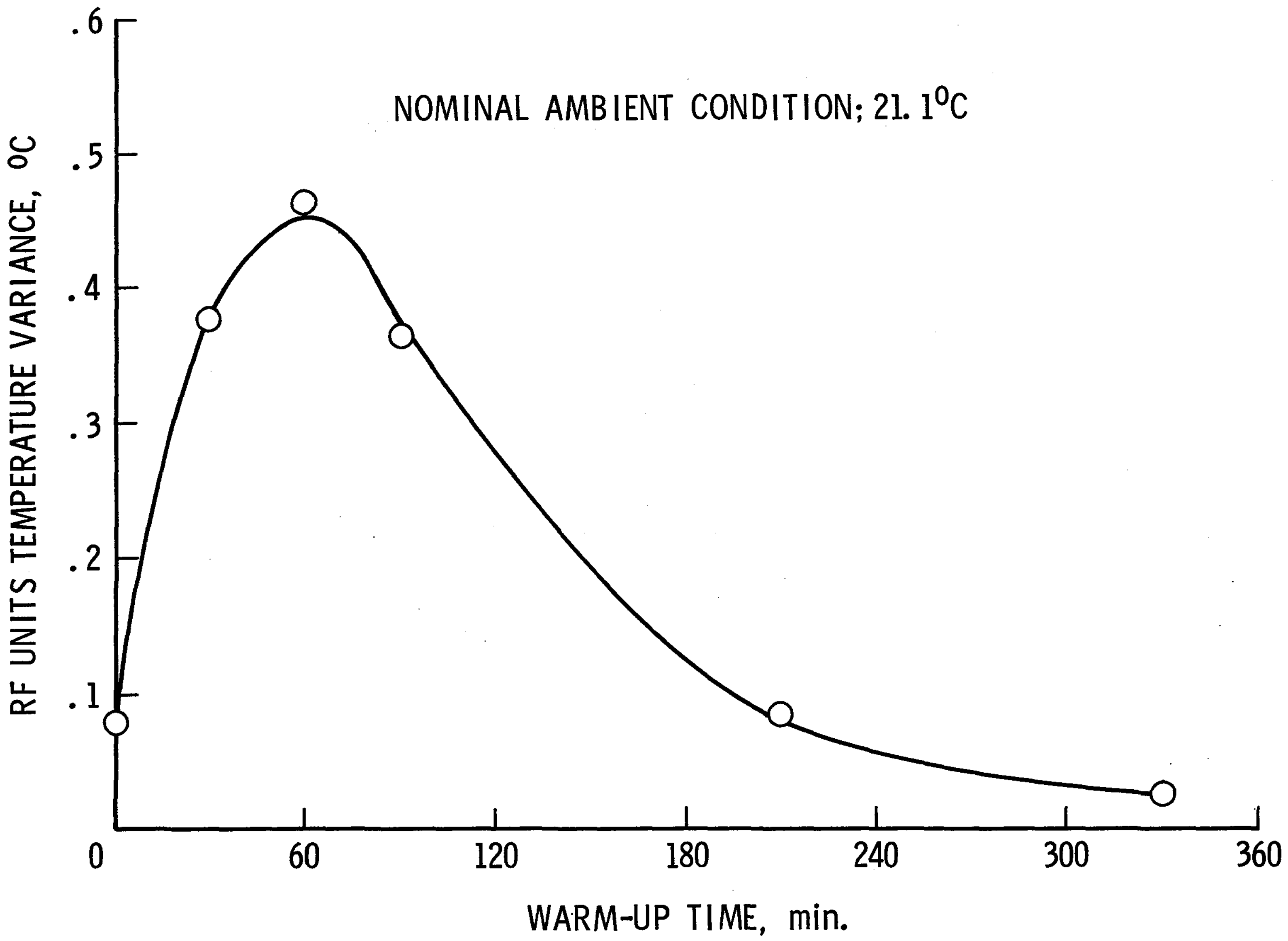


Figure 25. - RF units average temperature variance.

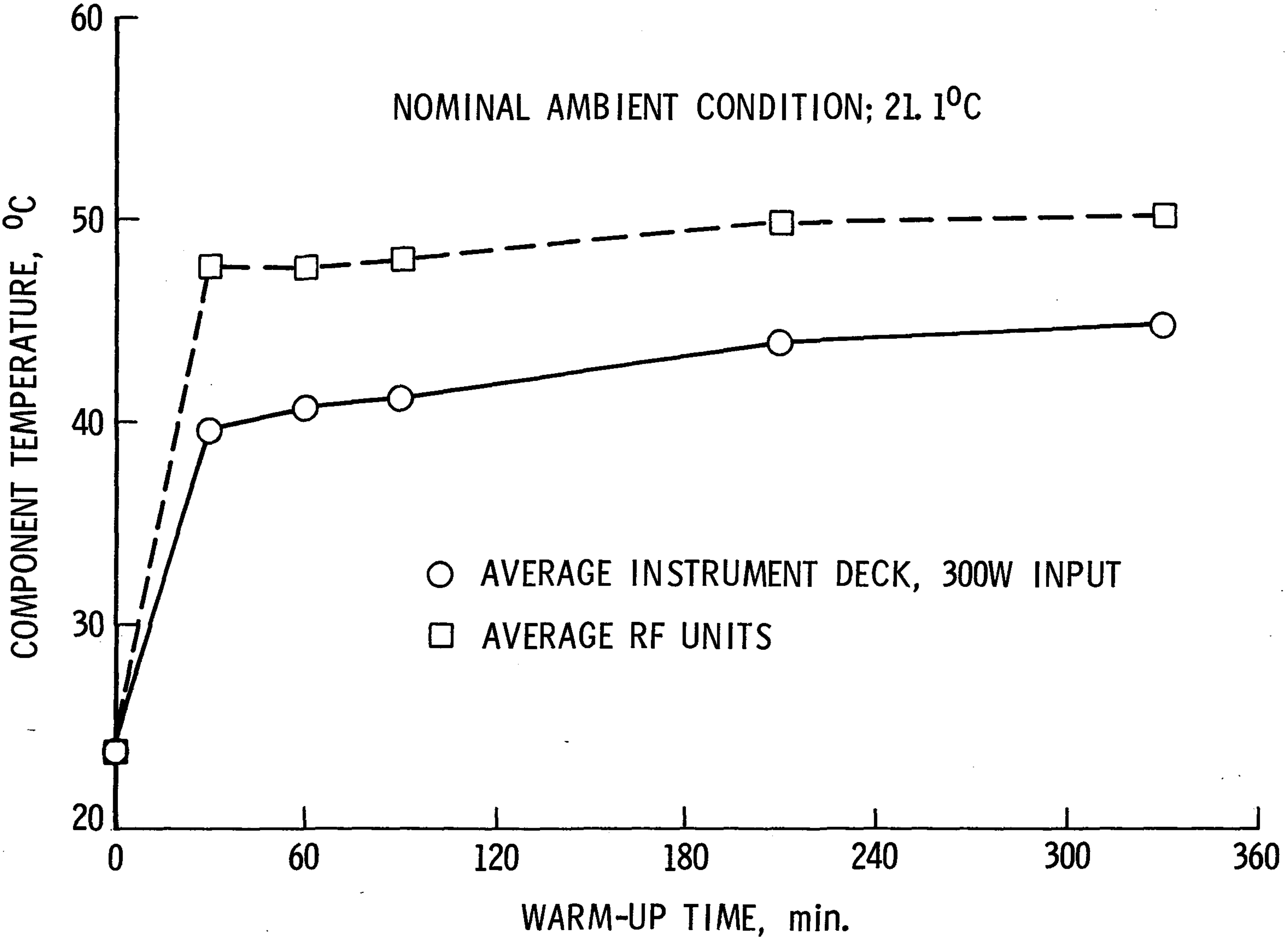


Figure 26. - Temperature differential between RF units and instrument deck.

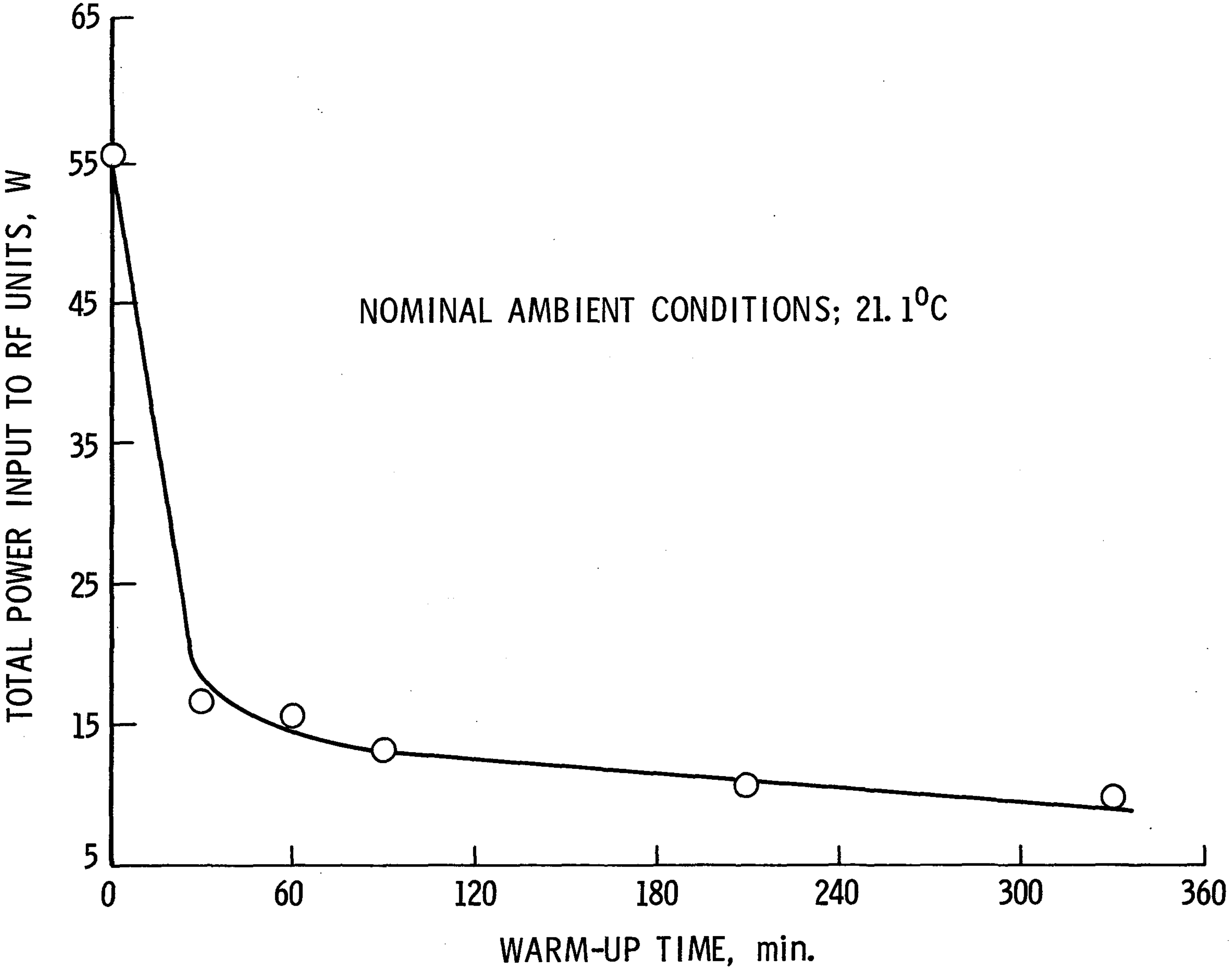


Figure 27. - Total power required by RF units.

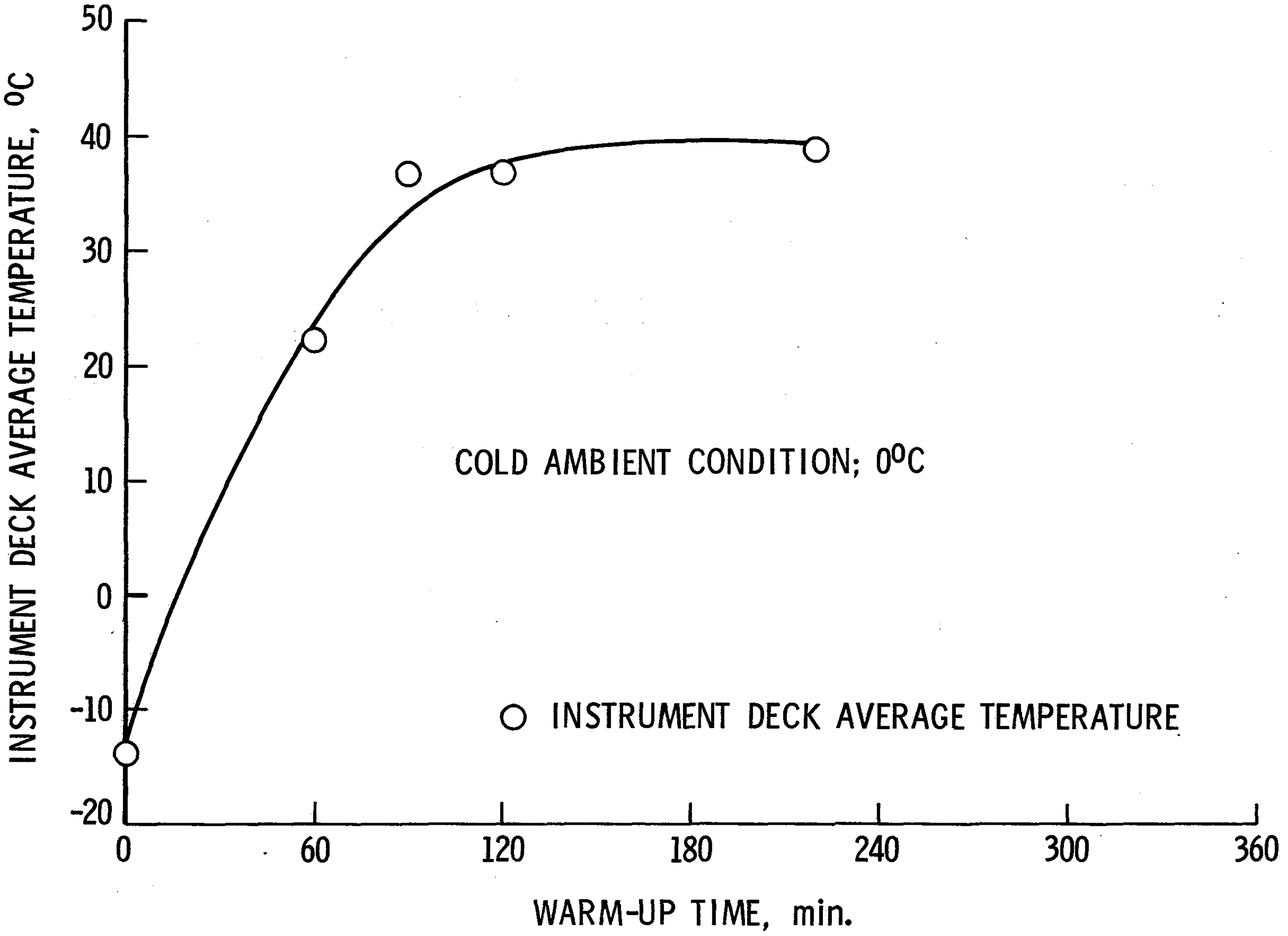
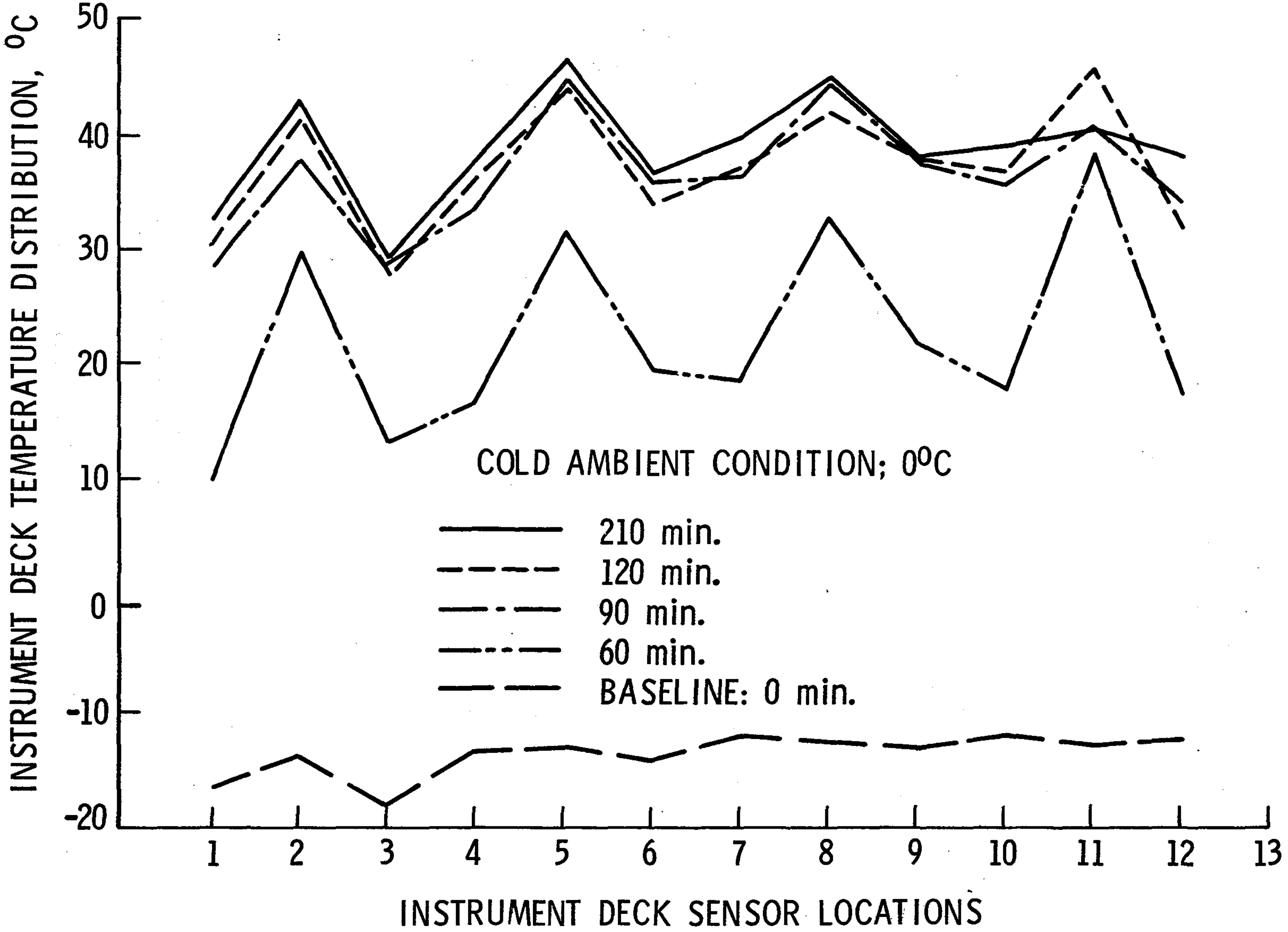


Figure 28. - Instrument deck warm-up temperature profile.



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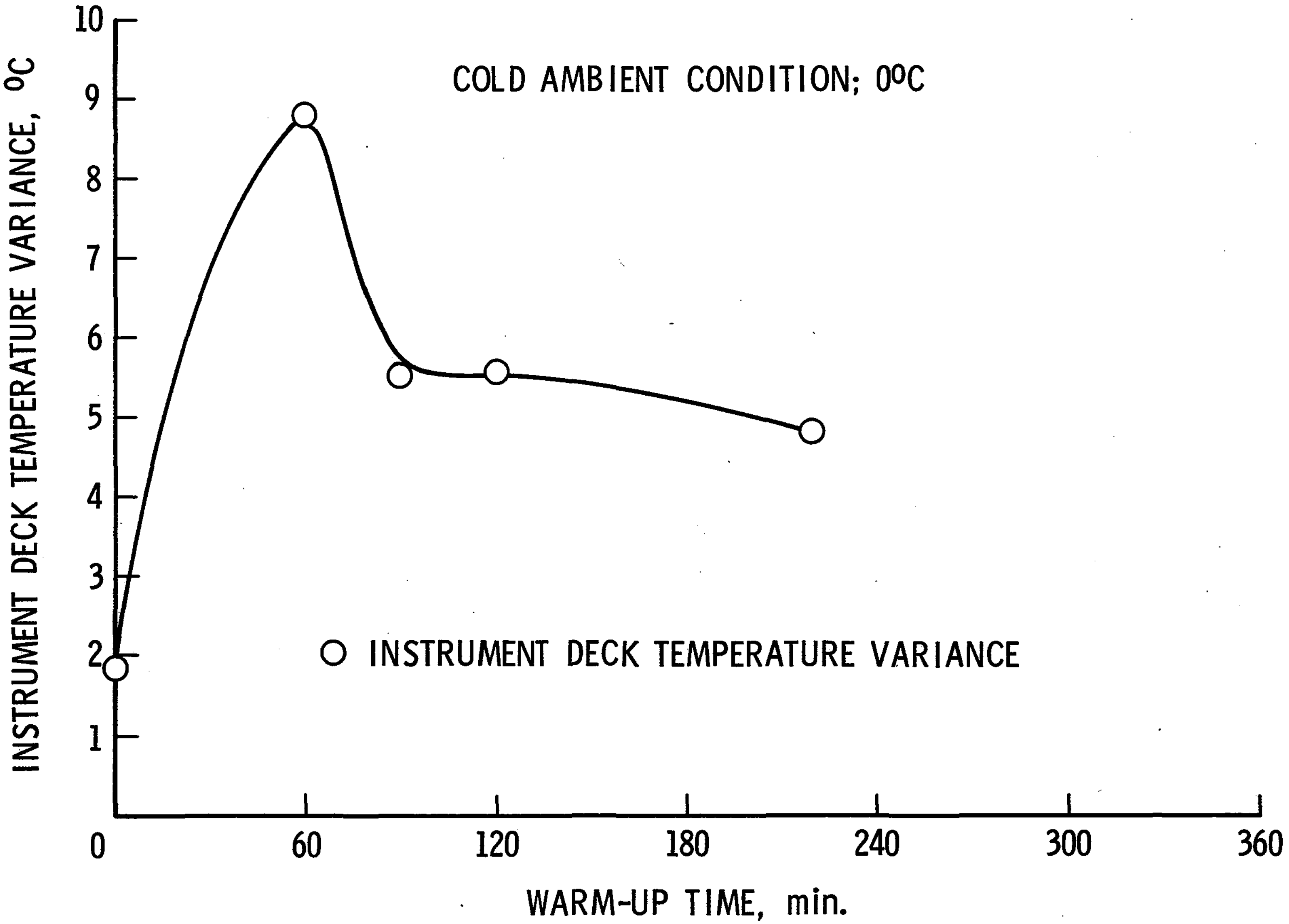
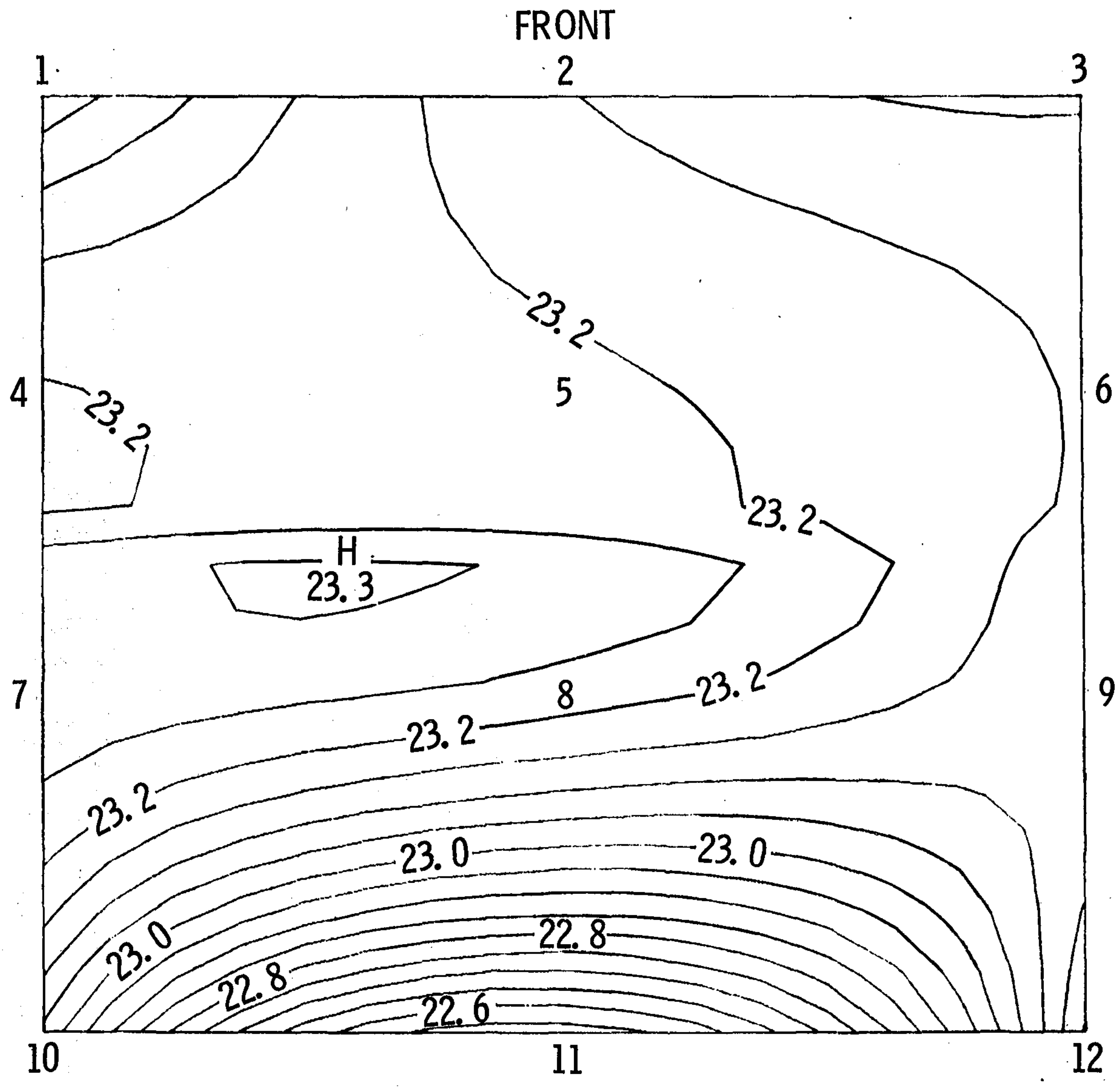


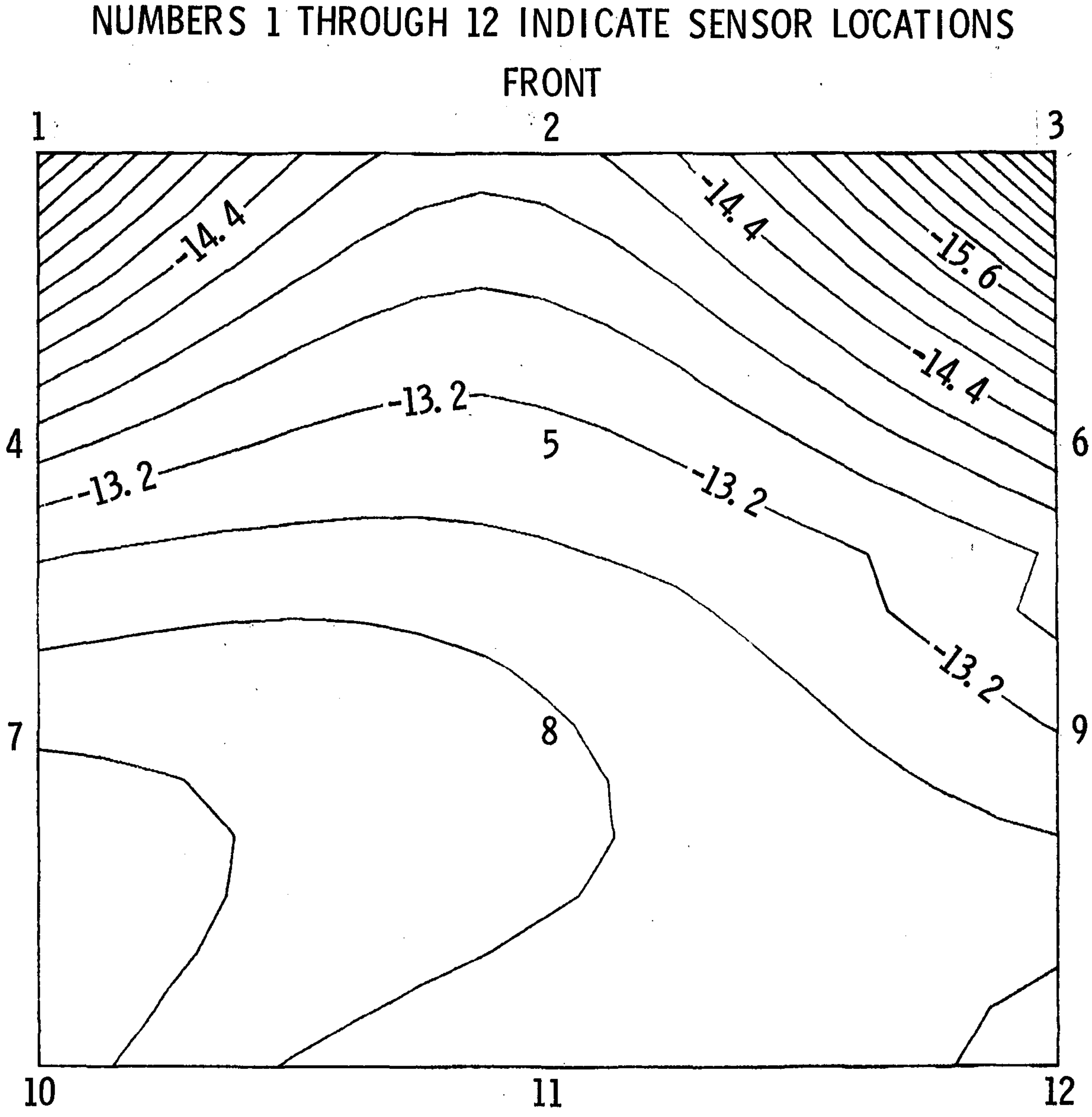
Figure 30. - Instrument deck temperature distribution variance.



NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

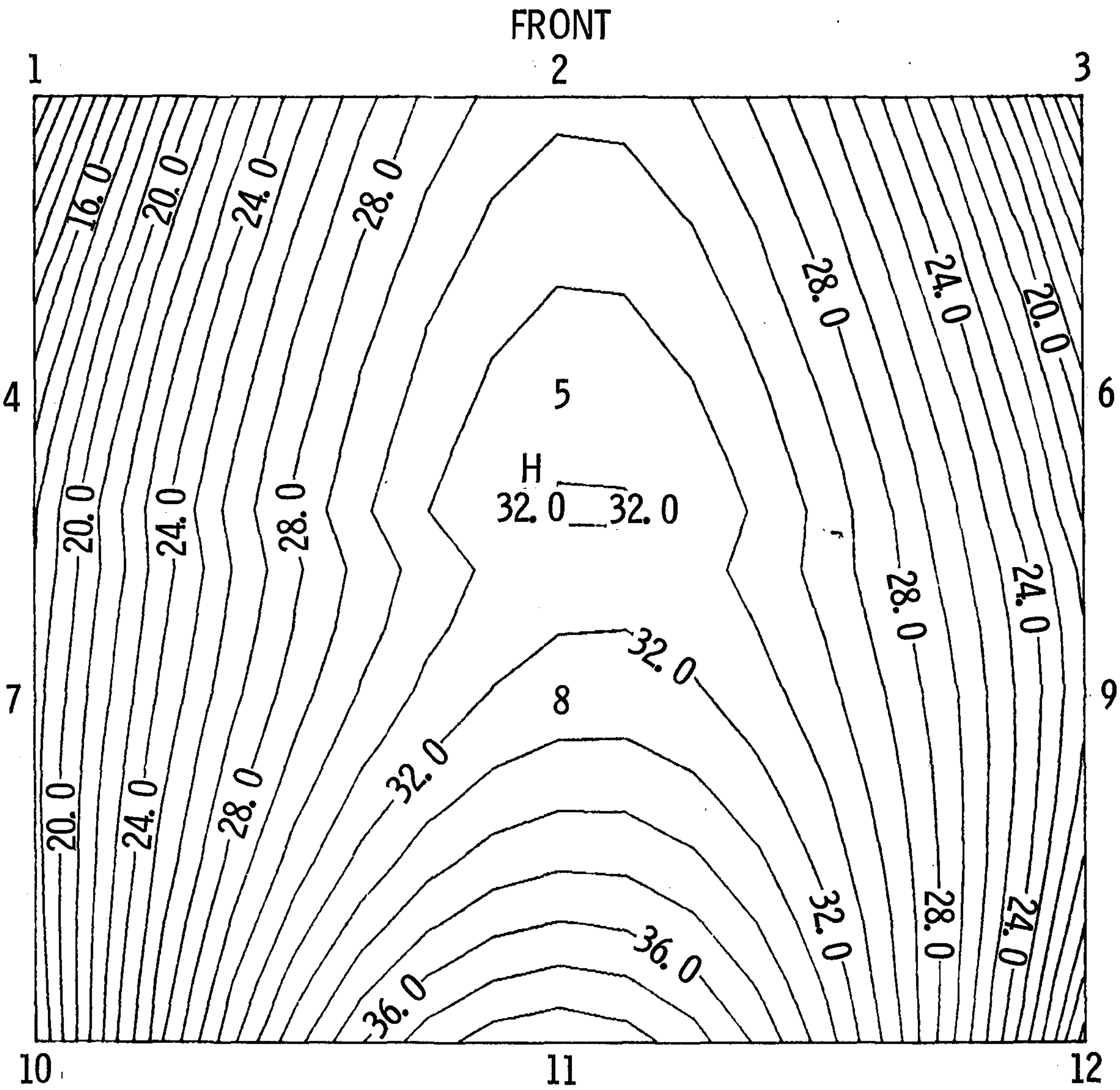
COLD CONDITION
TIME: BEFORE COOL DOWN
CONTOUR INTERVAL IS .50°C

Figure 31. - Instrument deck temperature contour (°C).



COLD CONDITION
TIME: 0 min. AT COOL DOWN
CONTOUR INTERVAL IS .30°C

Figure 32. - Instrument deck temperature contour (°C).

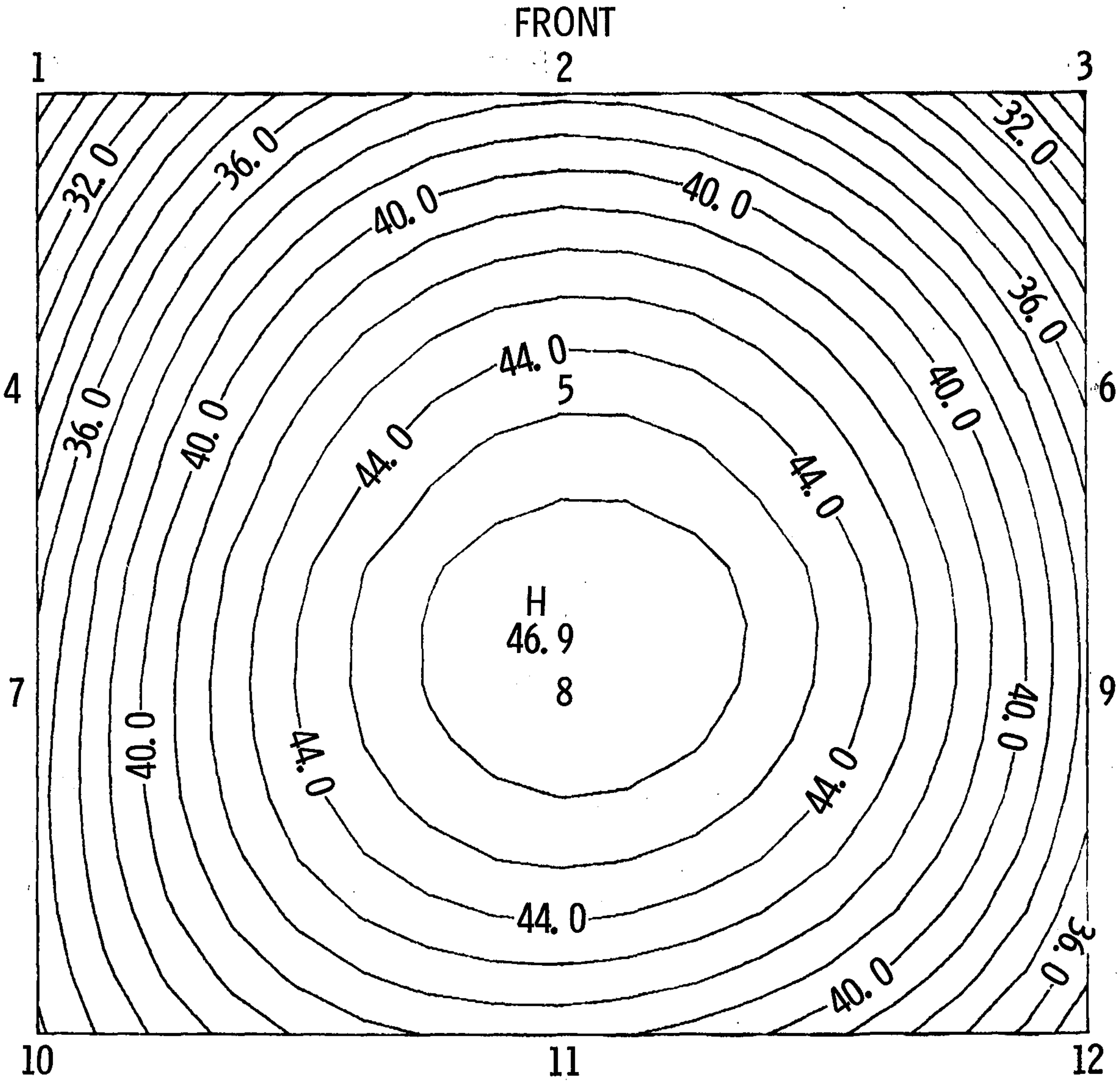


NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

COLD CONDITION
TIME: 60 min.
CONTOUR INTERVAL IS 1.00°C

Figure 33. - Instrument deck temperature contour (°C).

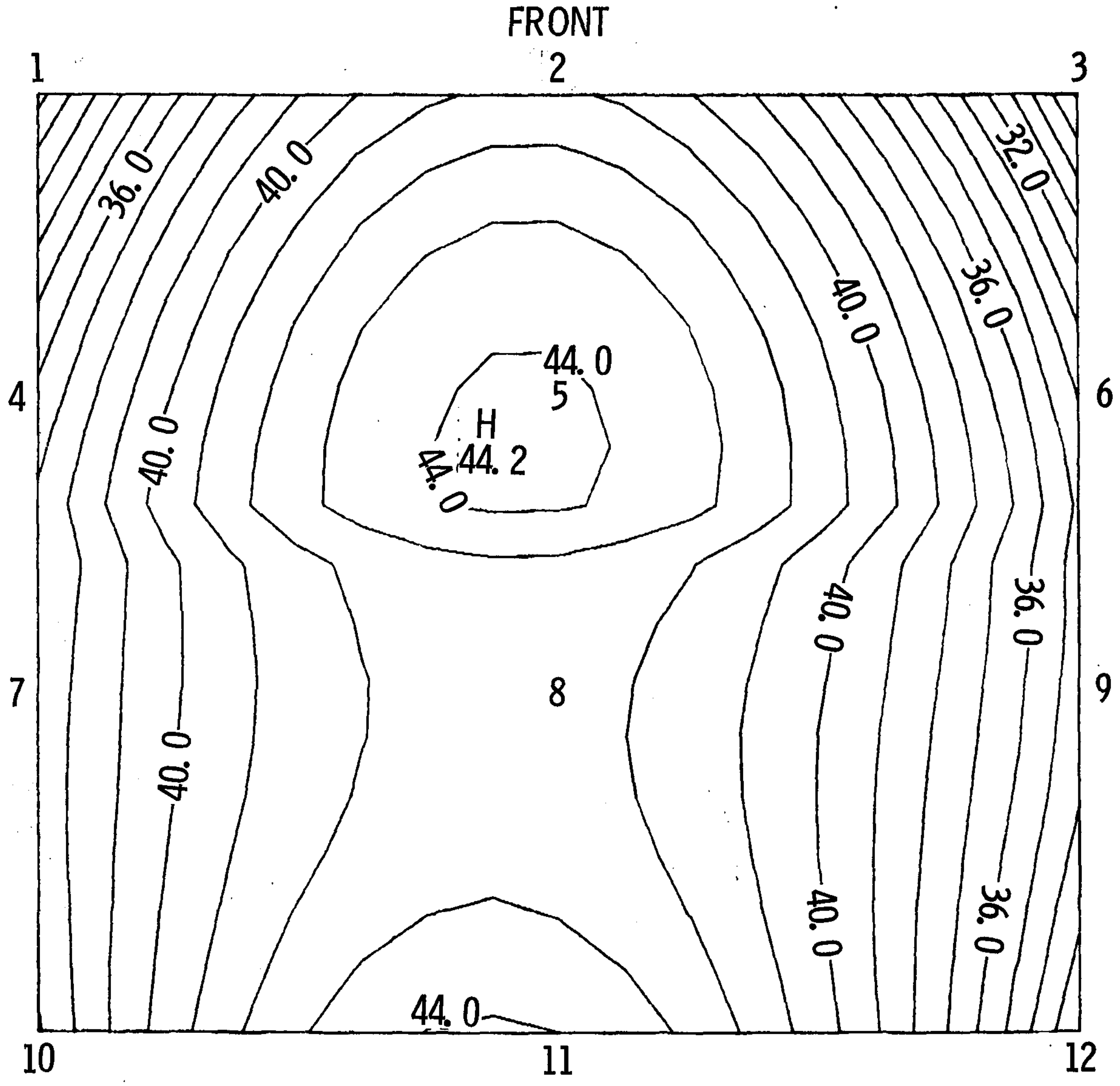
NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS



COLD CONDITION
TIME: 90 min.
CONTOUR INTERVAL IS 1.00°C

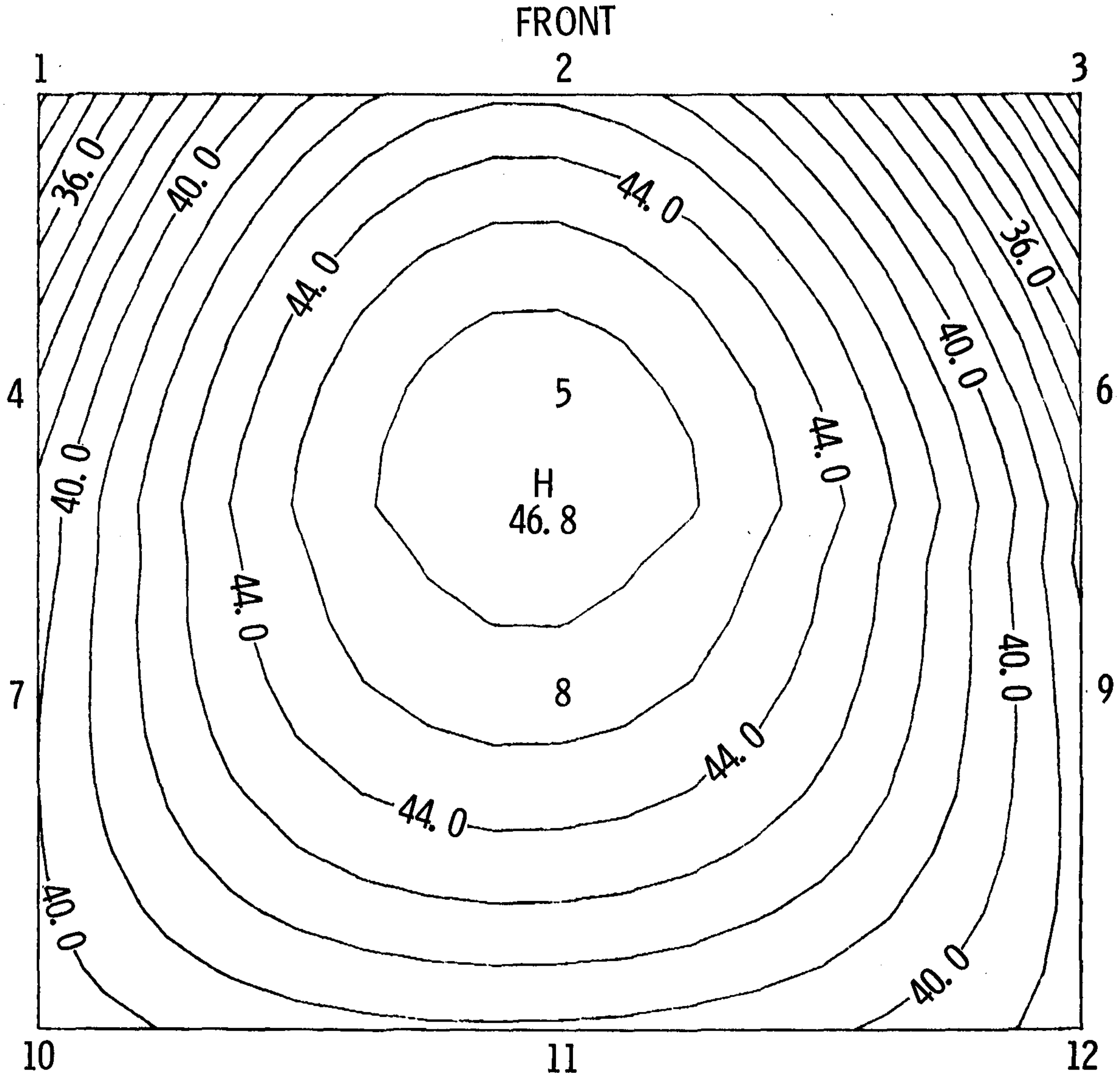
Figure 34. - Instrument deck temperature contour (°C).

NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS



COLD CONDITION
TIME: 120 min.
CONTOUR INTERVAL IS 1.00°C

Figure 35. - Instrument deck temperature contour (°C).



NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

COLD CONDITION
TIME: 220 min.
CONTOUR INTERVAL IS 1.00°C

Figure 36. - Instrument deck temperature contour (°C).

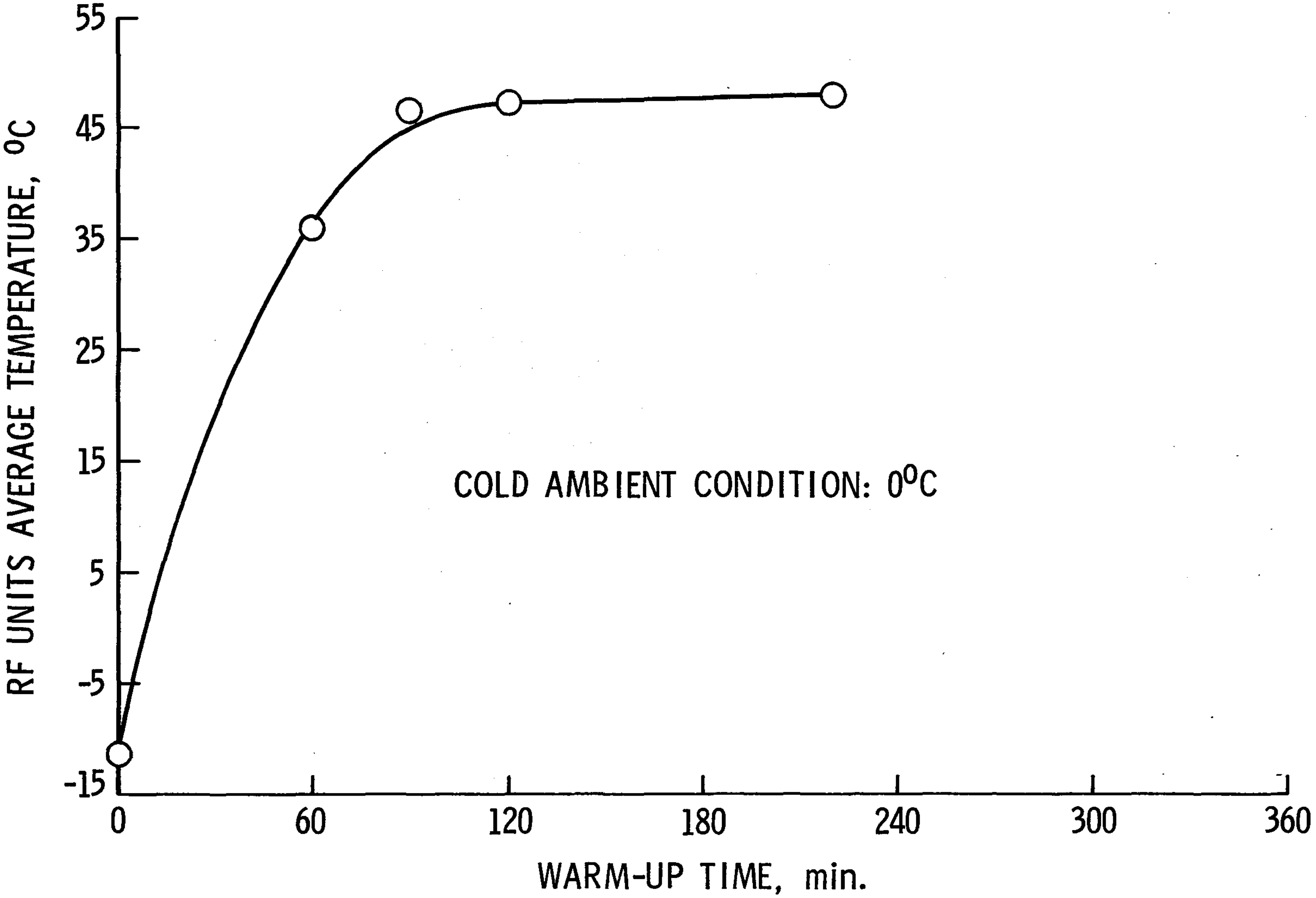


Figure 37. - RF units warm-up temperature profile.

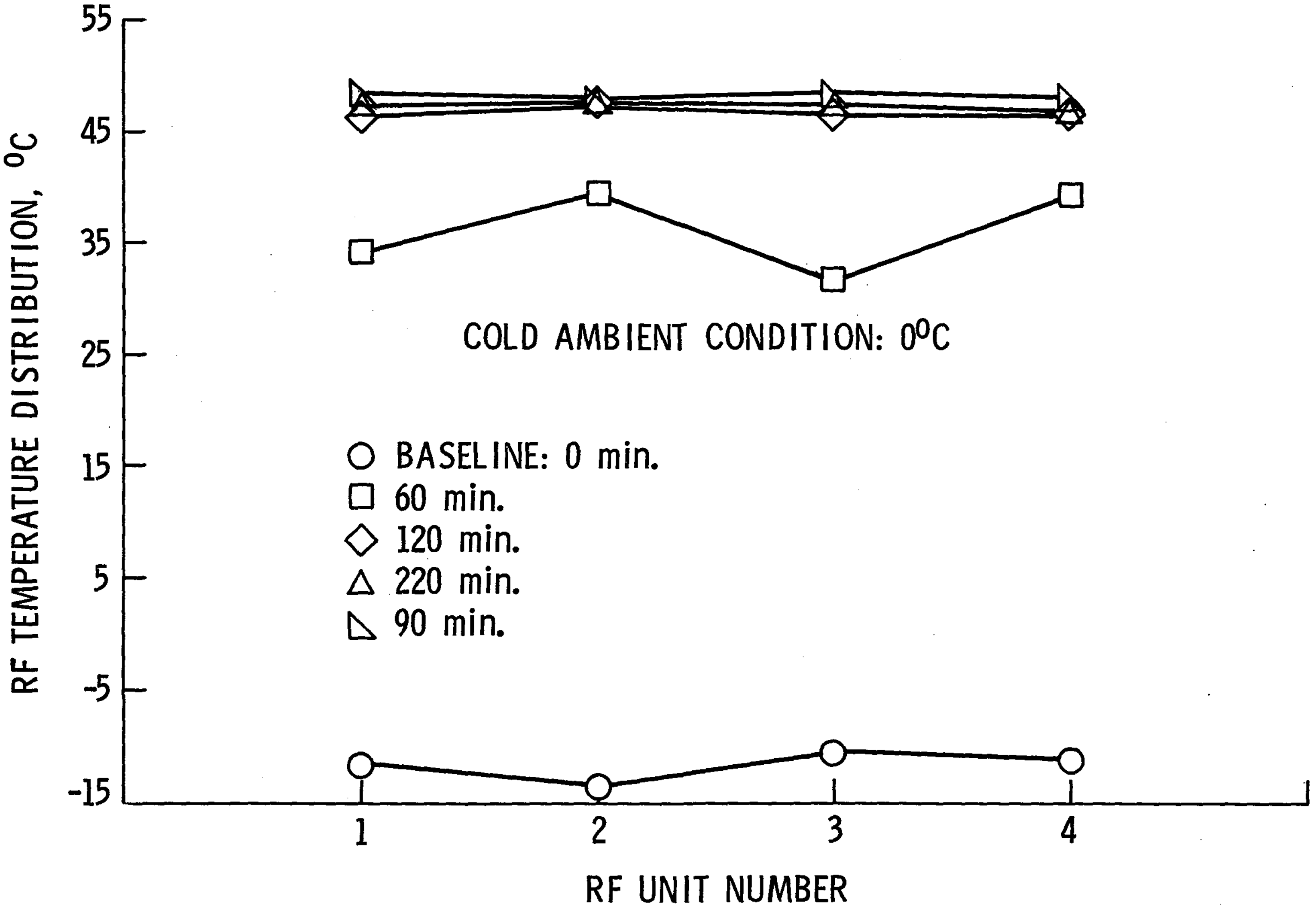


Figure 38. - RF warm-up units temperature distribution.

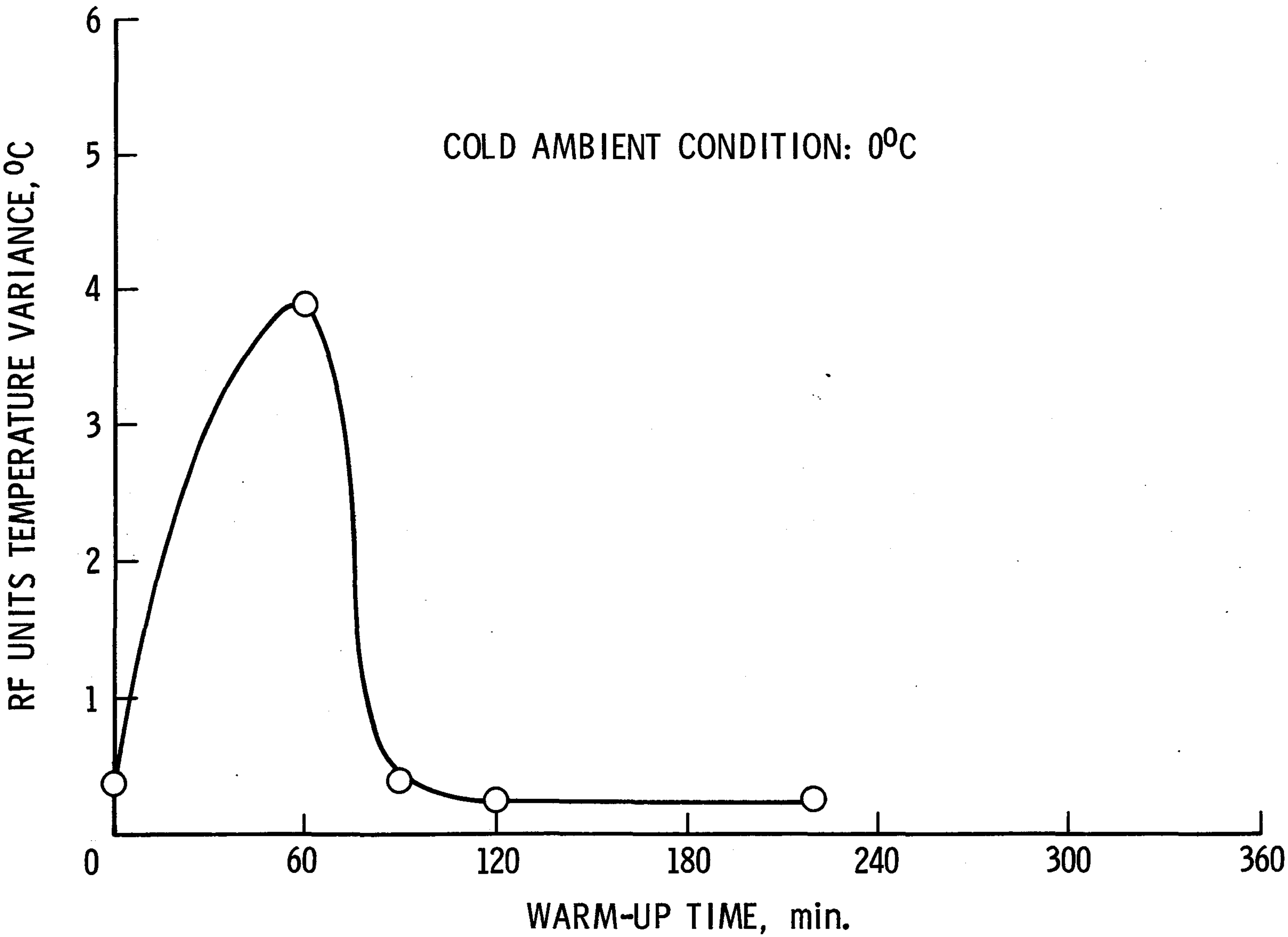


Figure 39. - RF units average temperature variance.

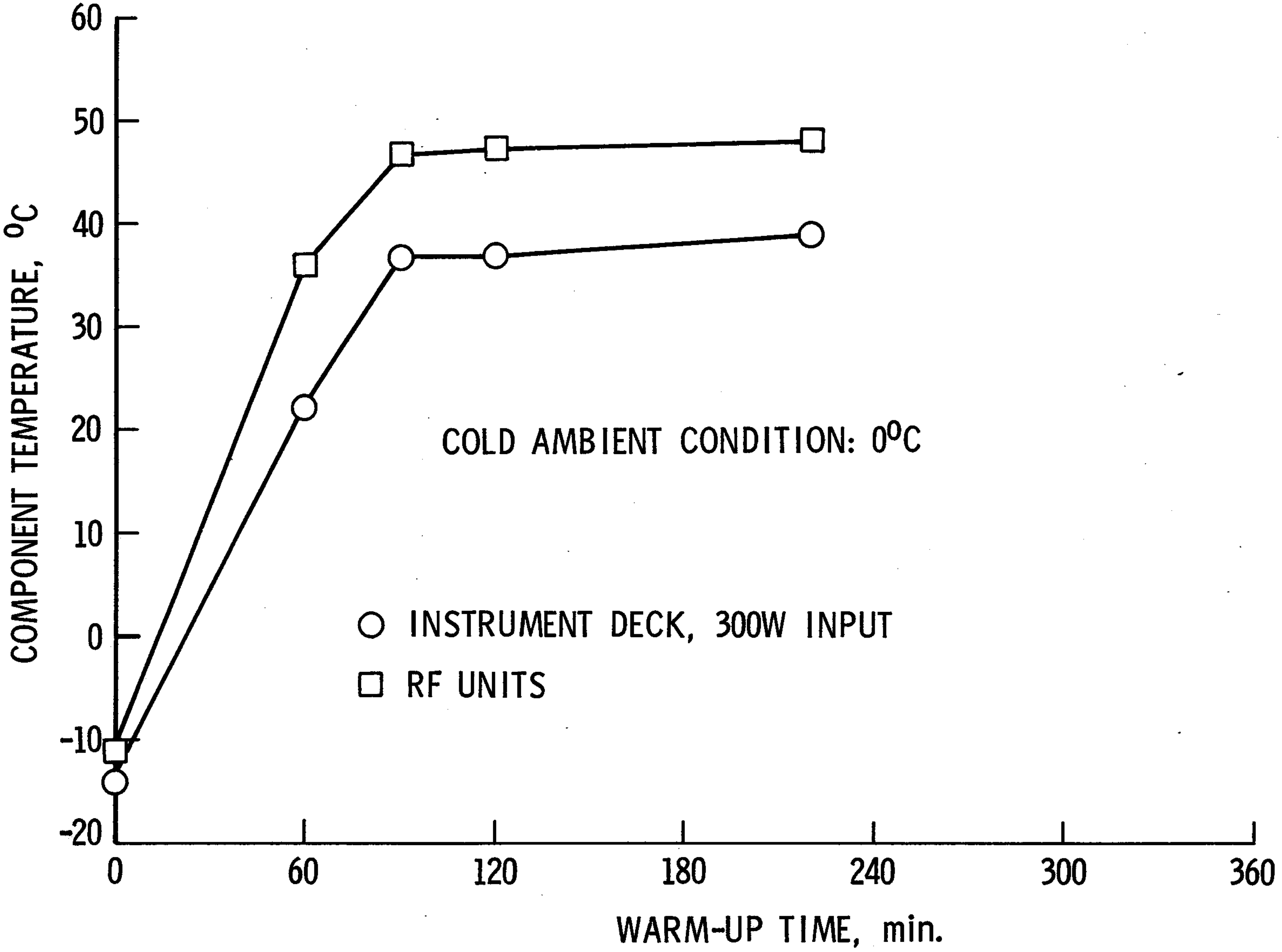


Figure 40. - Temperature differential between RF units and instrument deck.

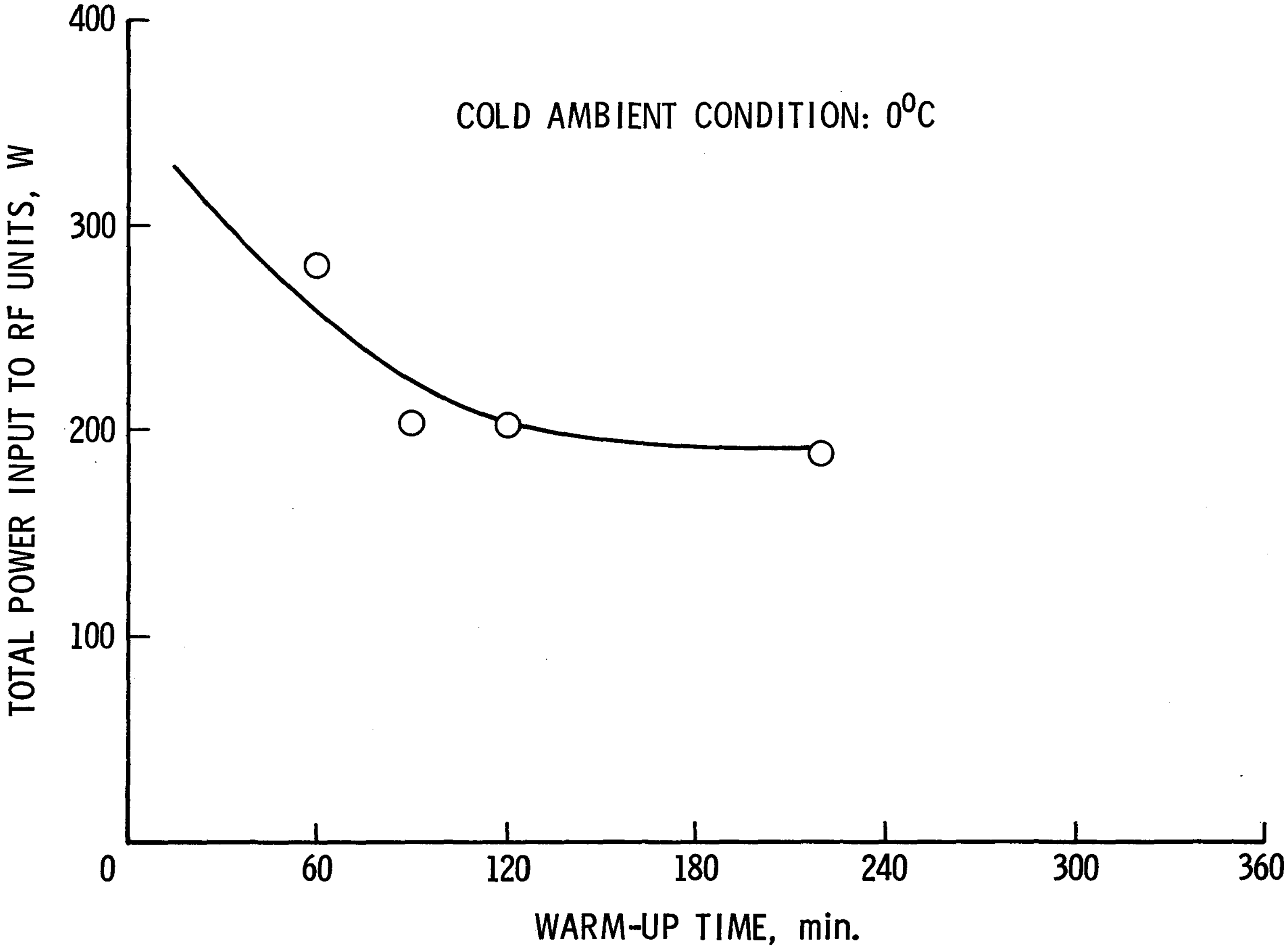


Figure 41. - Total power required by RF units.

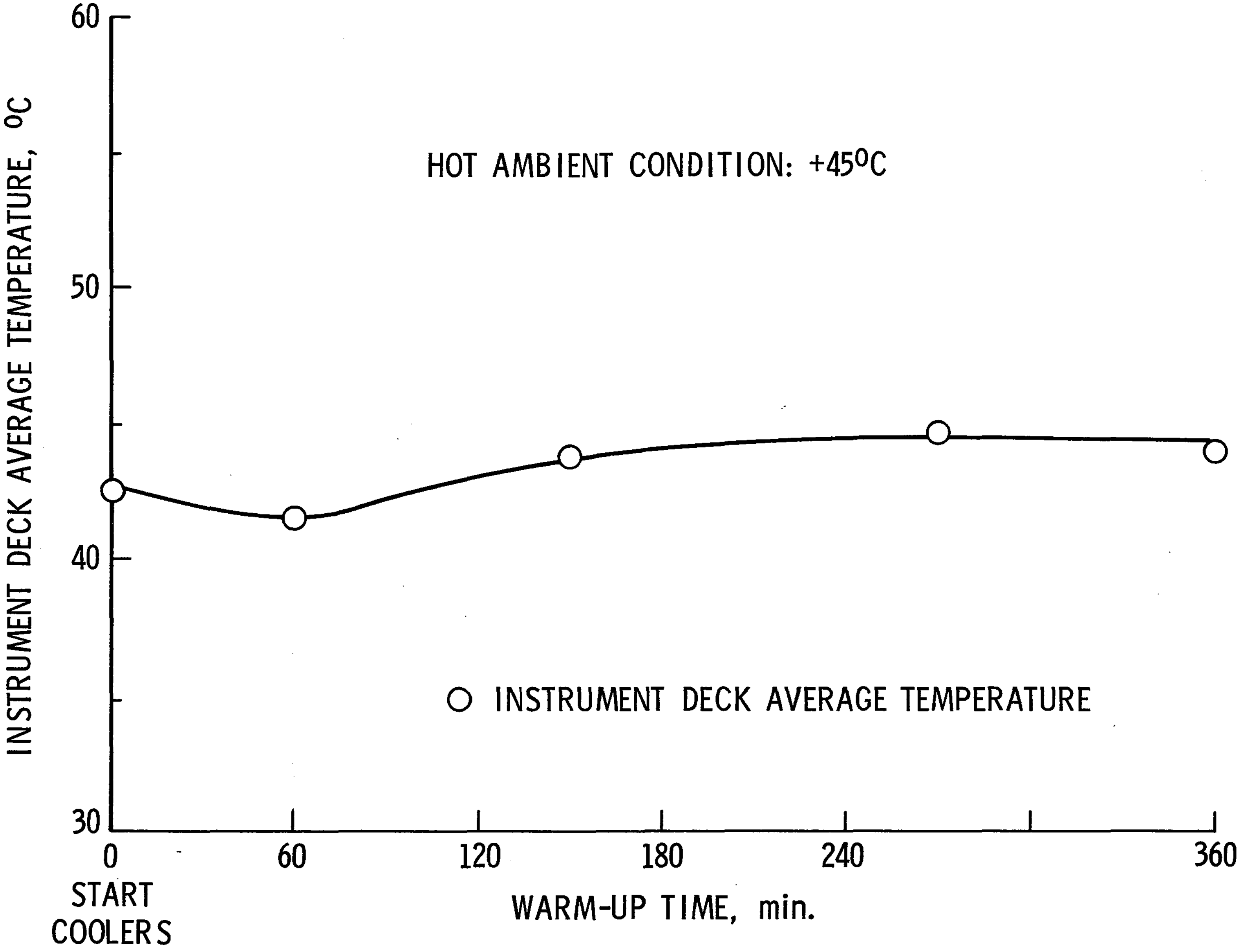


Figure 42. - Instrument deck cool-down temperature profile.

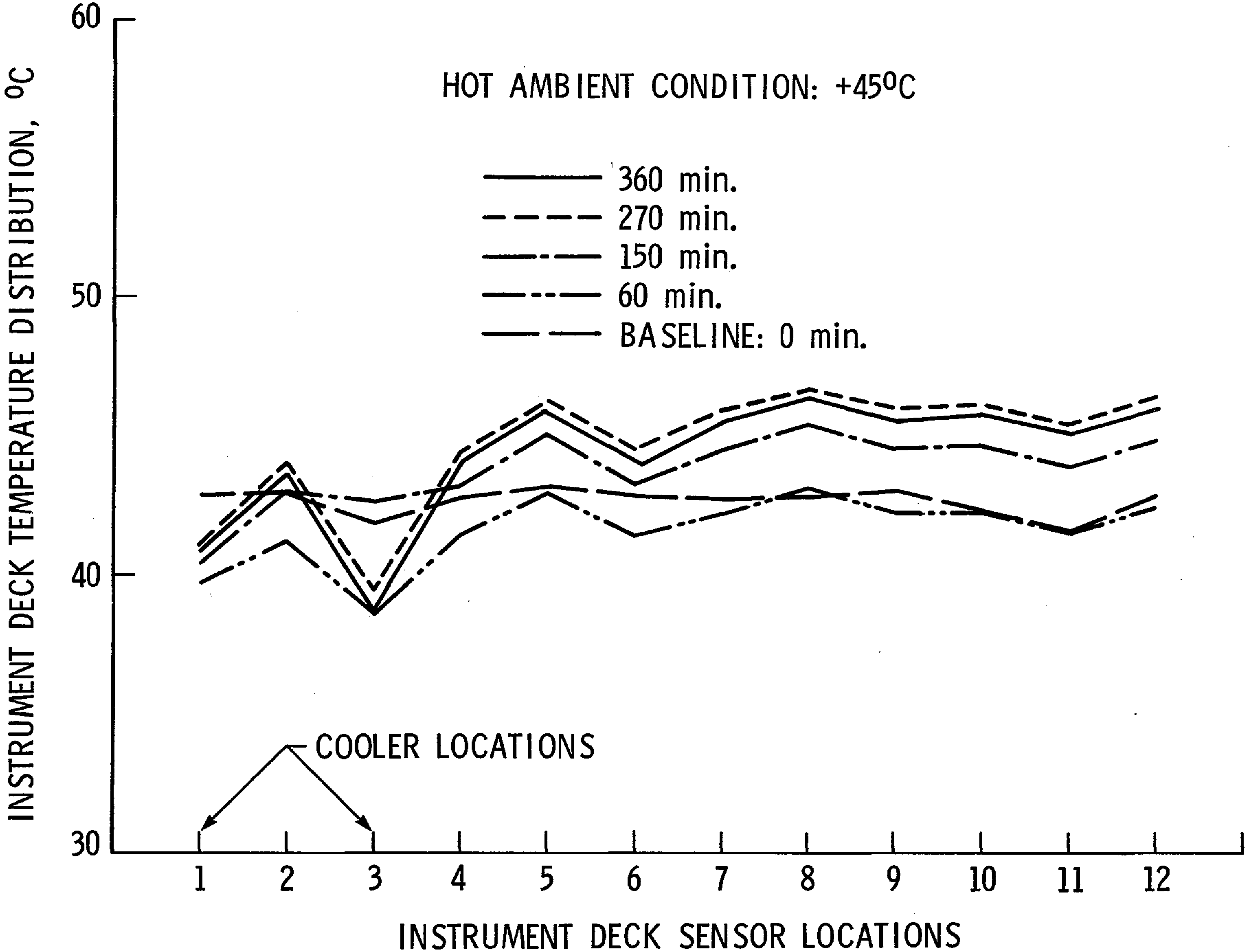


Figure 43. - Instrument deck cool-down temperature distribution.

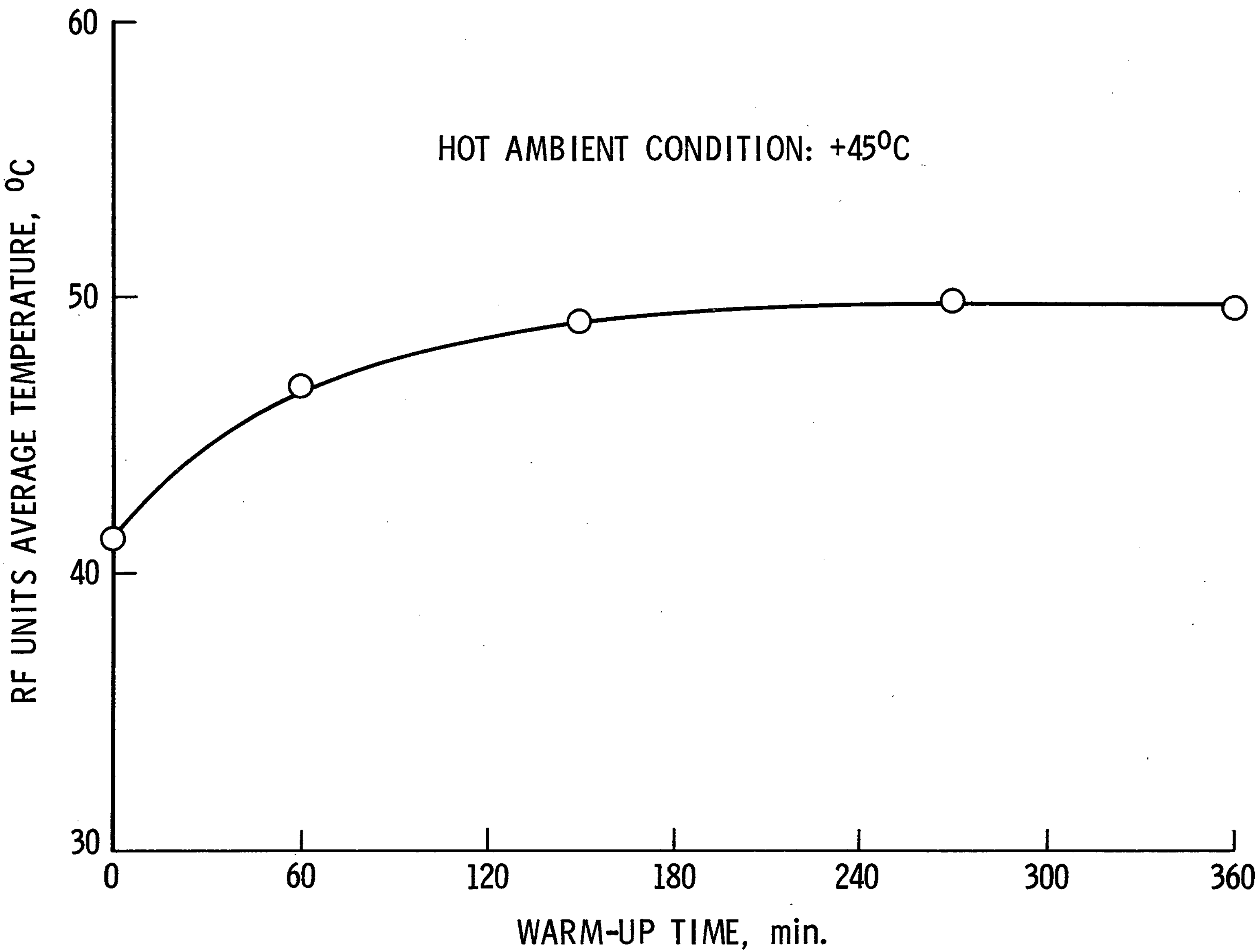
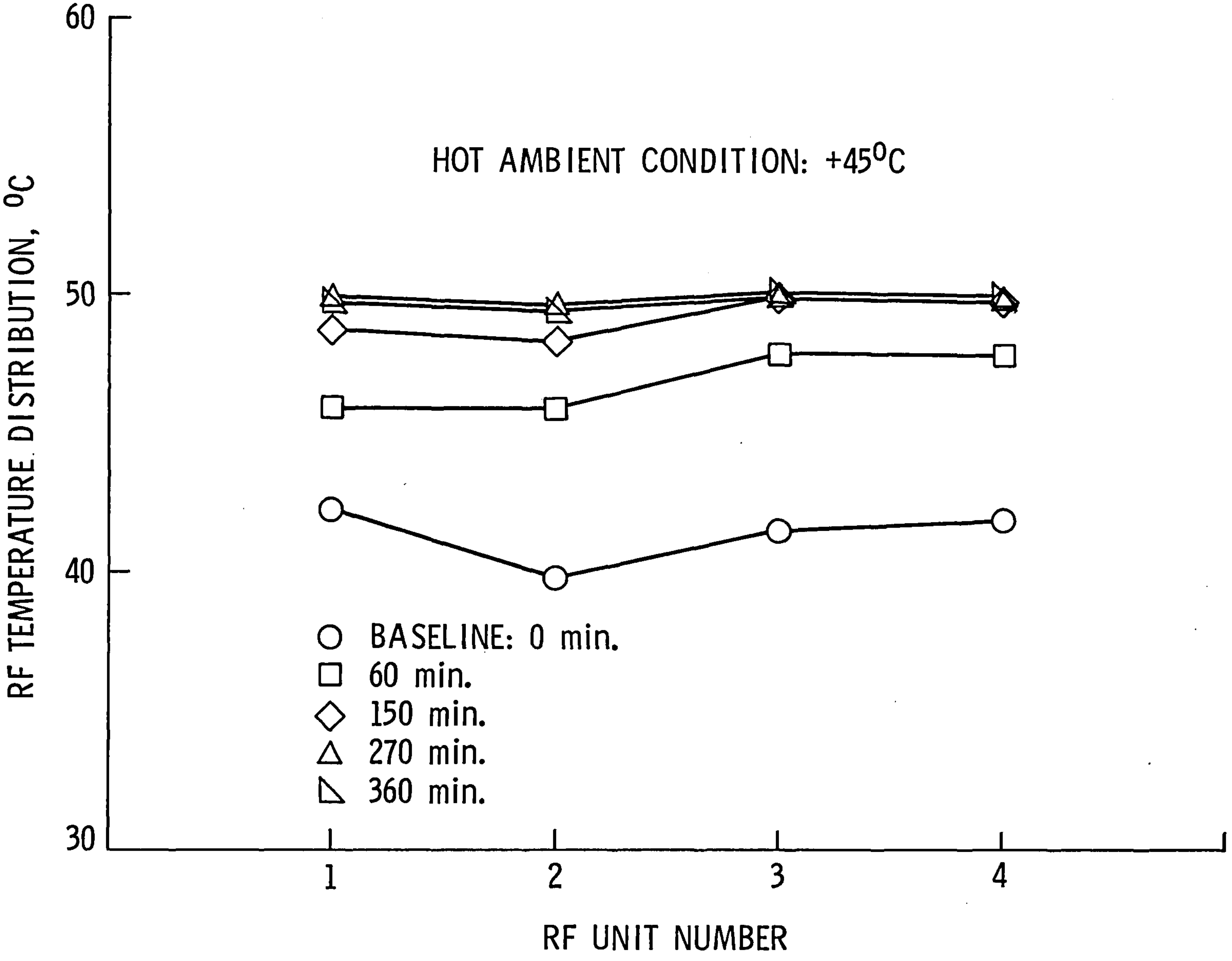


Figure 44. - RF units warm-up temperature profile.



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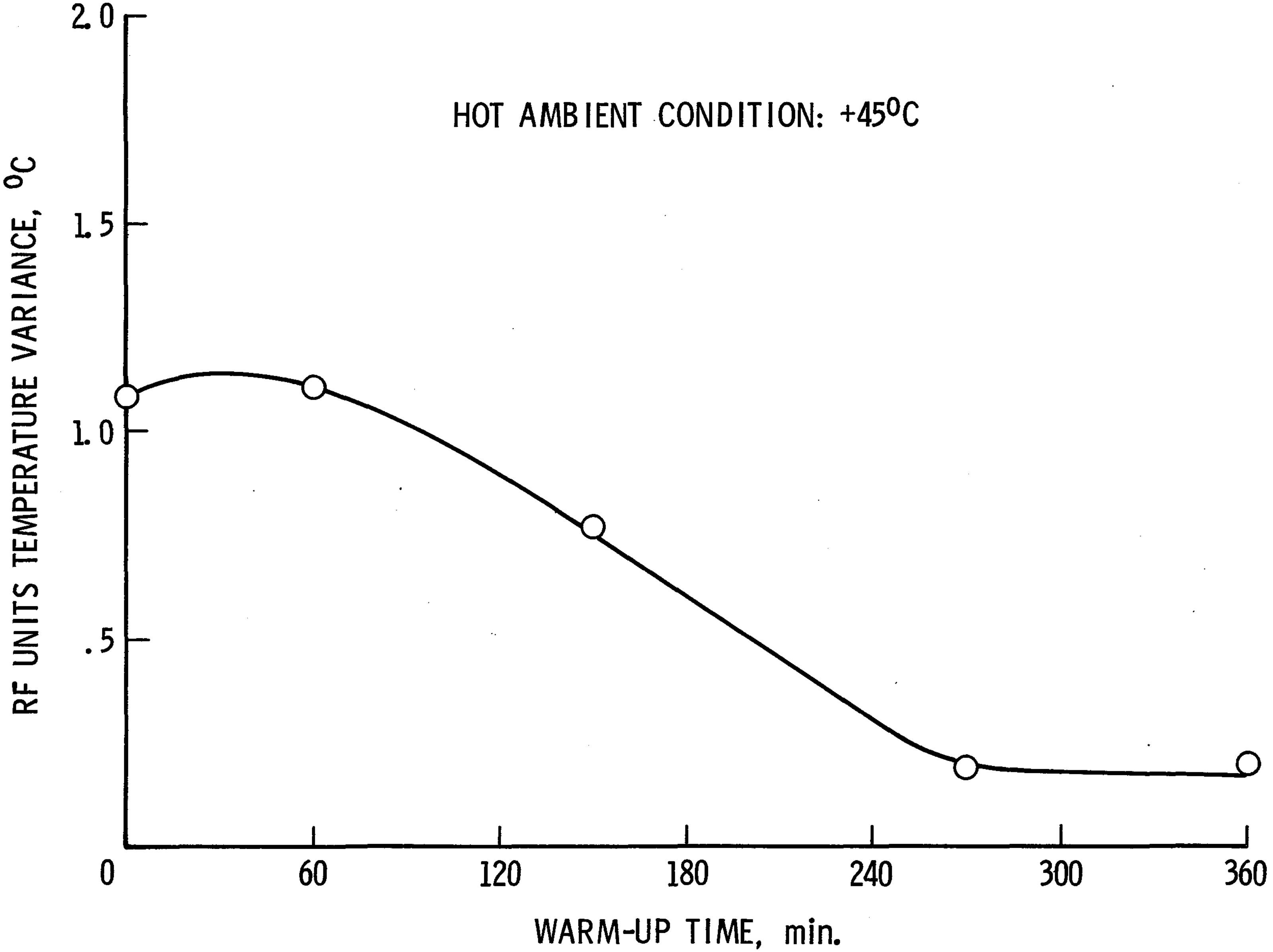


Figure 46. - RF units average temperature variance.

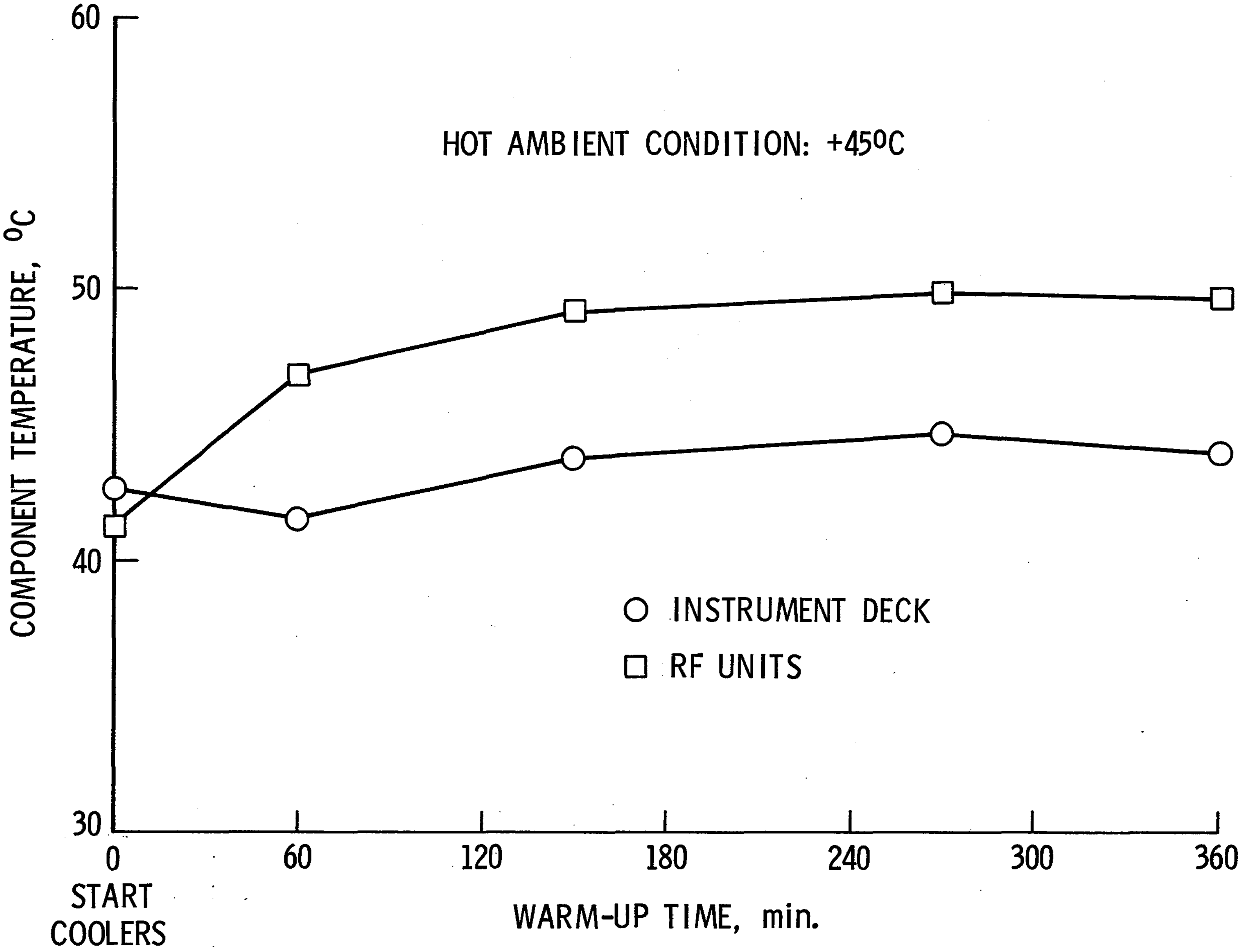


Figure 47. - Temperature differential between RF-units and instrument deck.

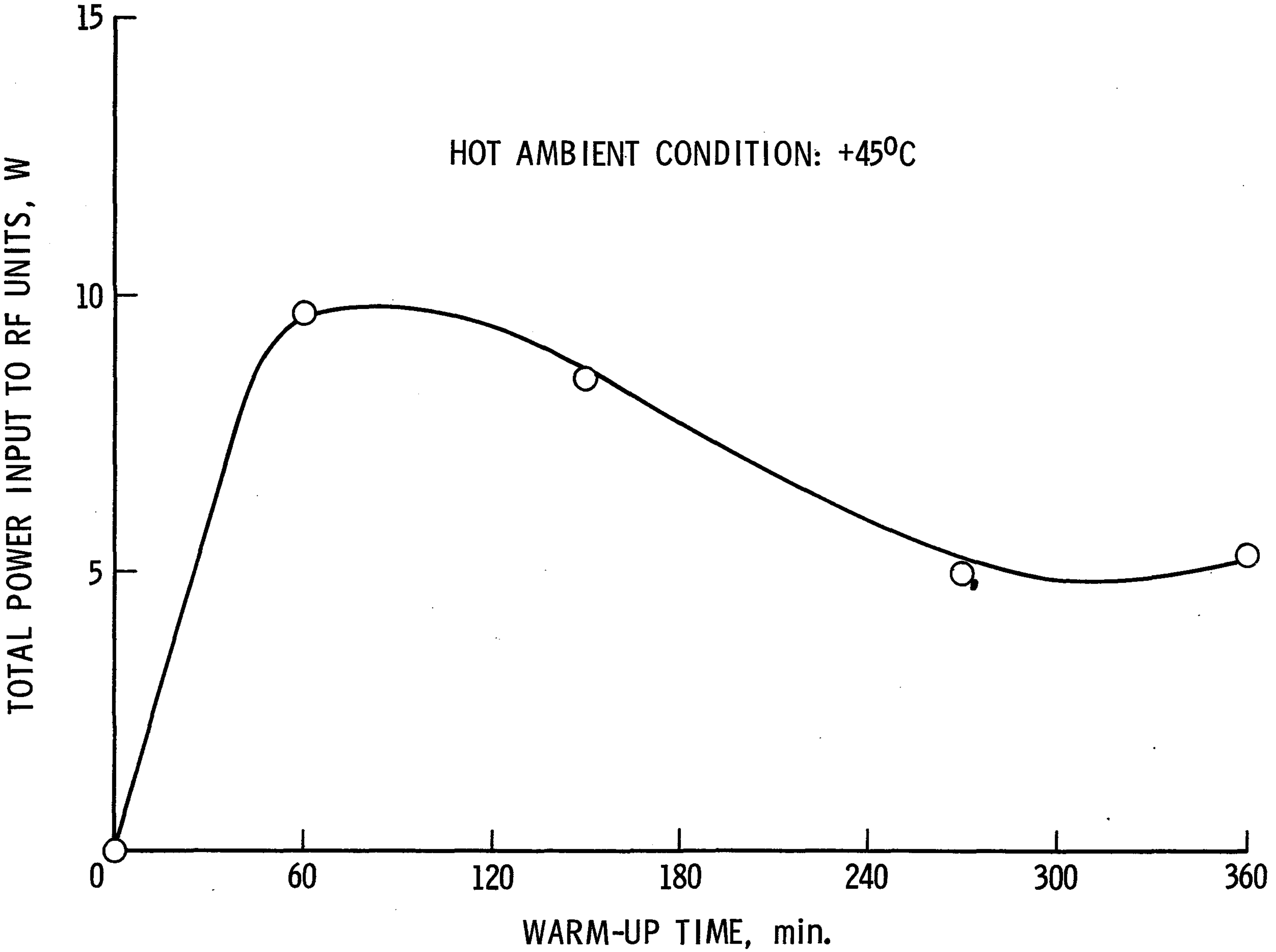
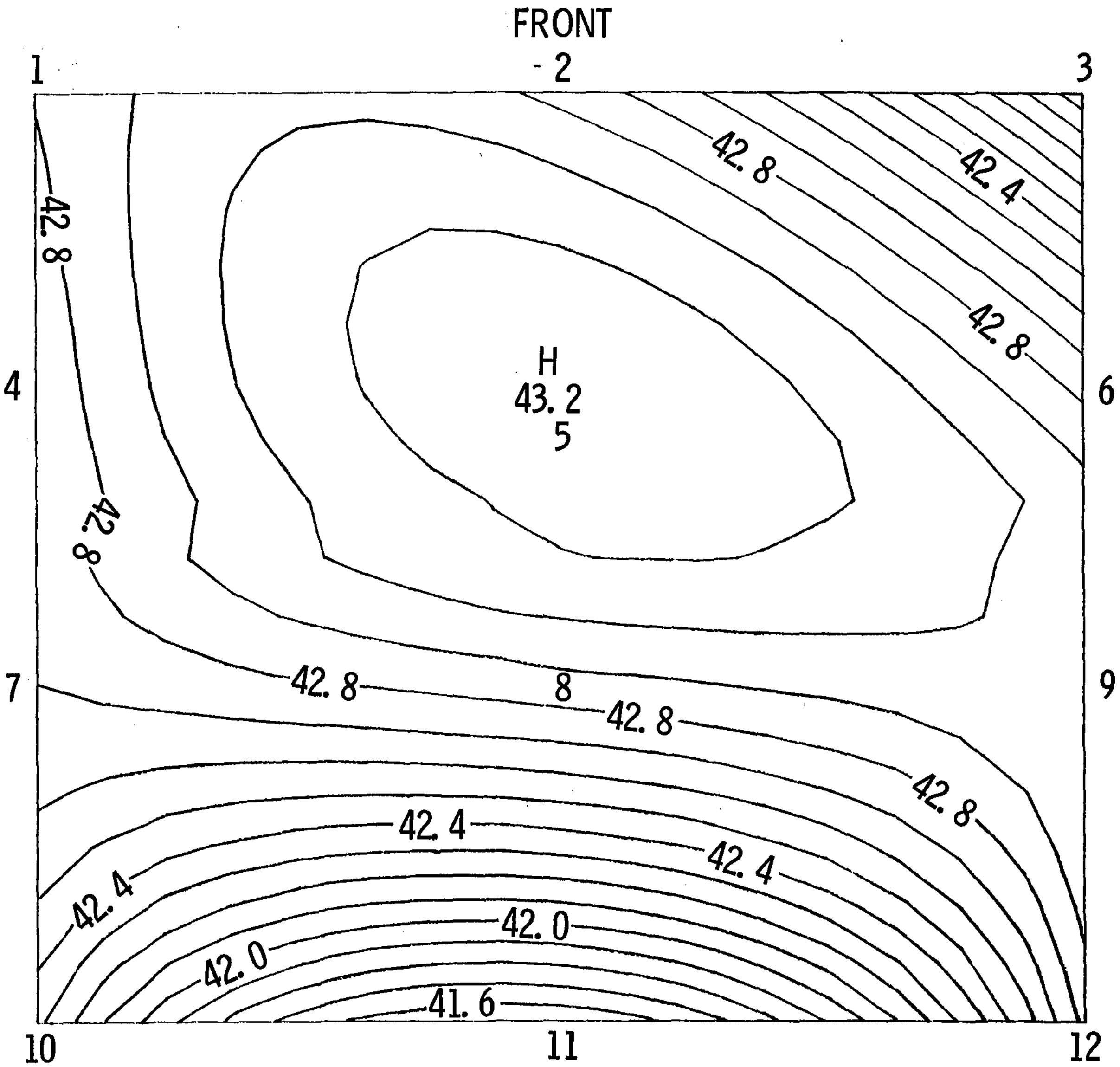


Figure 48. - Total power required by RF units.

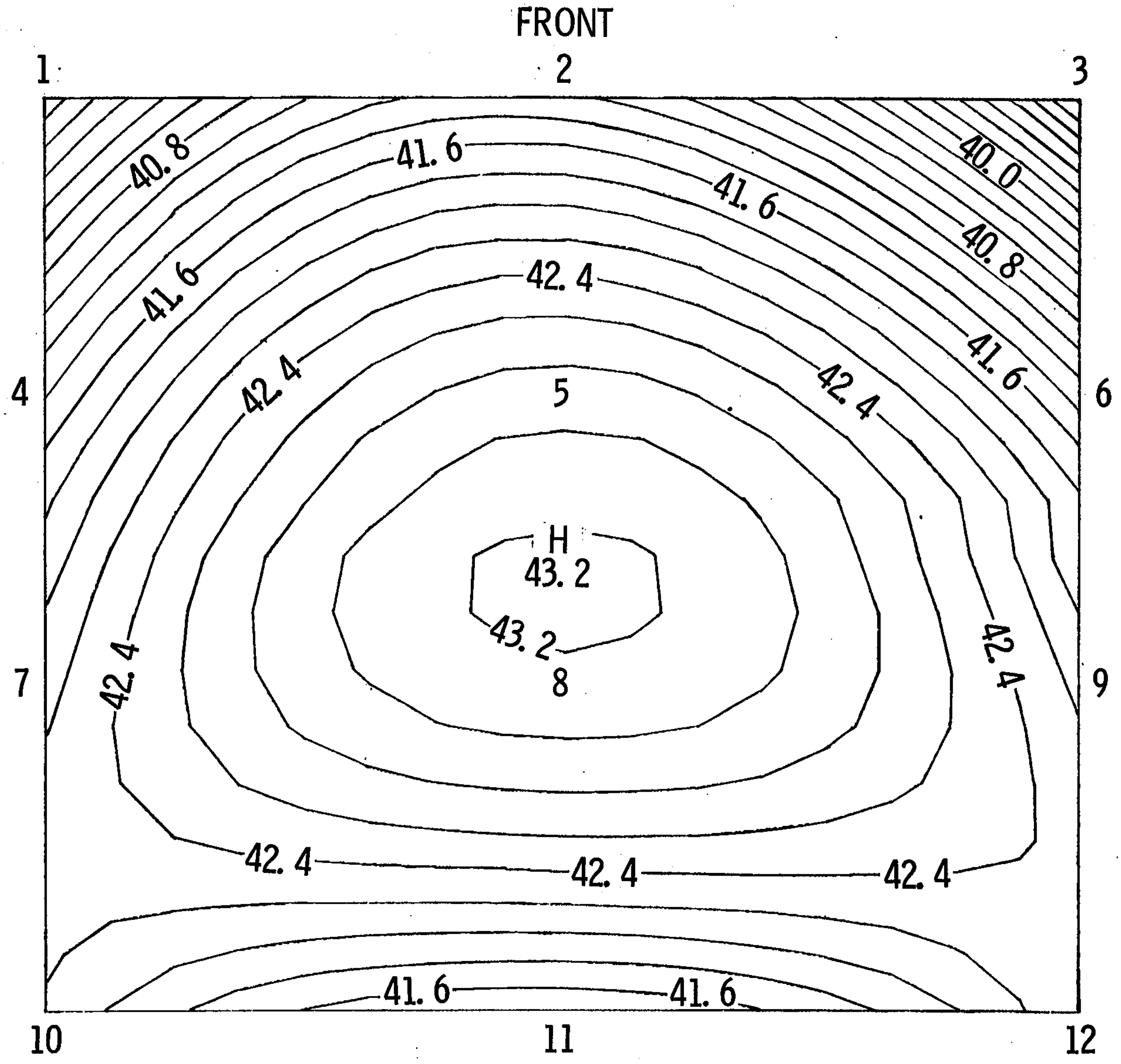
NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS



HOT CONDITION
TIME: 0 min.
CONTOUR INTERVAL IS .10°C

Figure 49. - Instrument deck temperature contour (°C).

NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

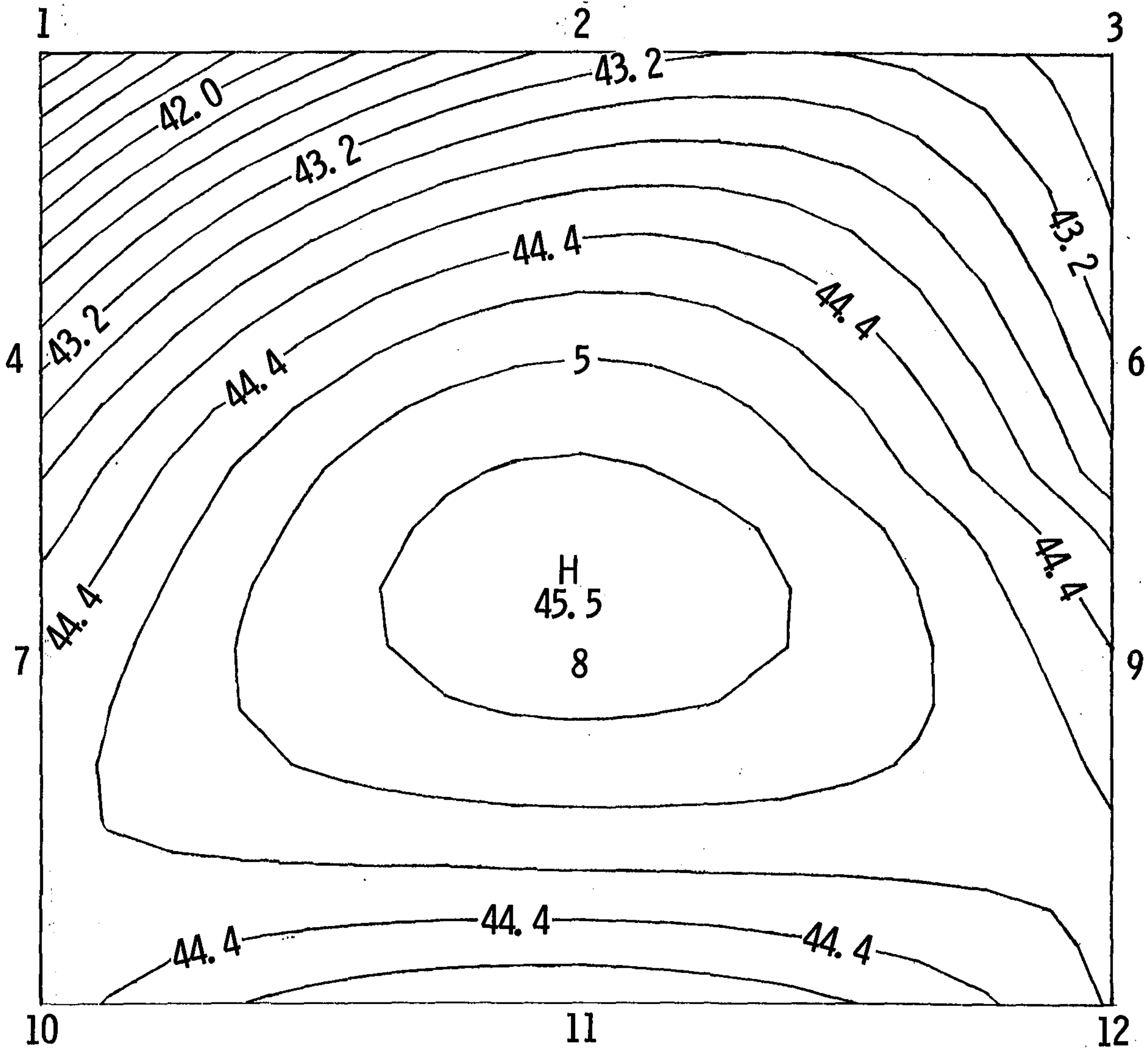


HOT CONDITION
TIME: 60 min.
CONTOUR INTERVAL IS .20°C

Figure 50. - Instrument deck temperature contour (°C).

NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

FRONT



HOT CONDITION
TIME: 150 min.
CONTOUR INTERVAL IS .30°C

Figure 51. - Instrument deck temperature contour (°C).

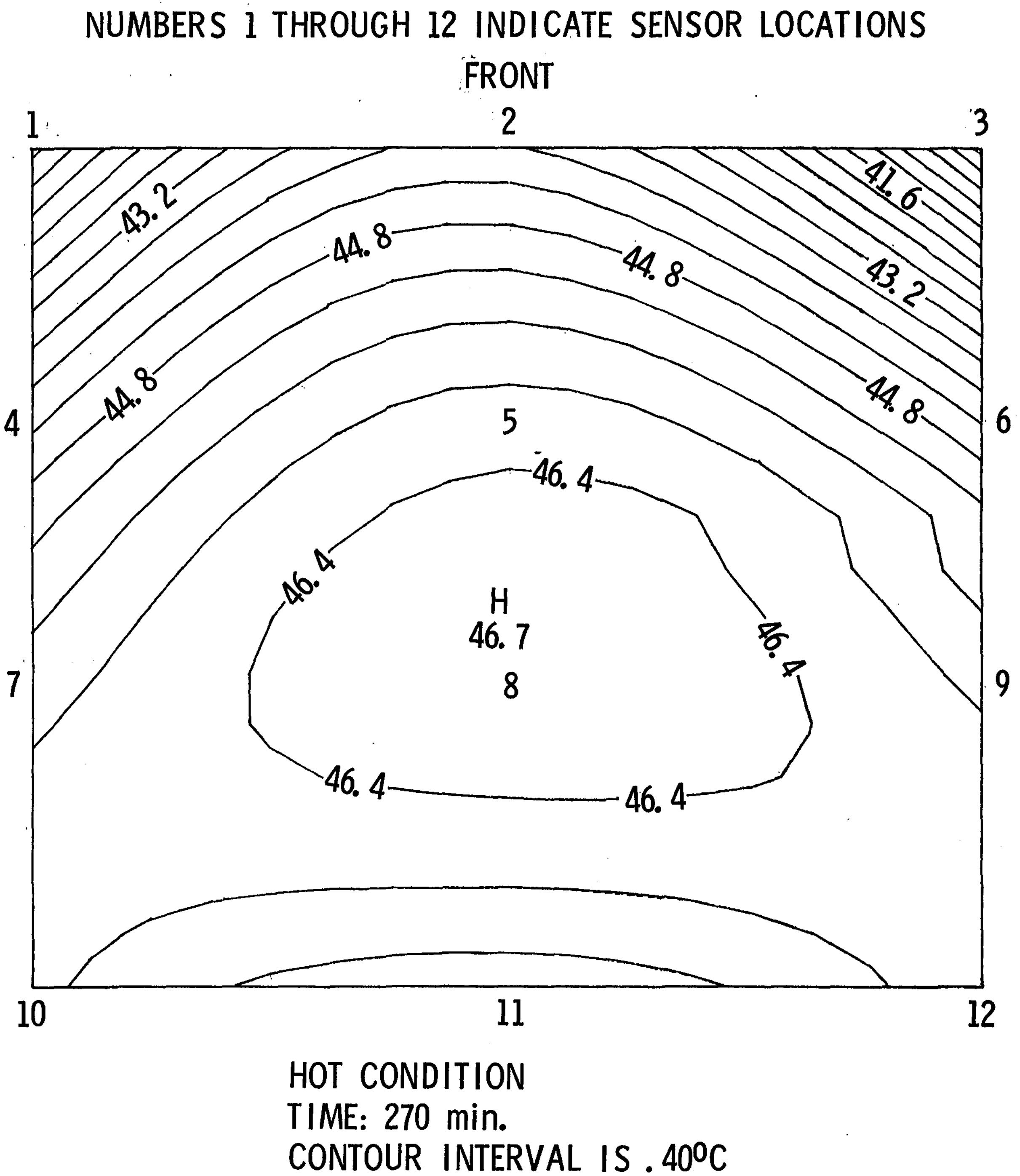
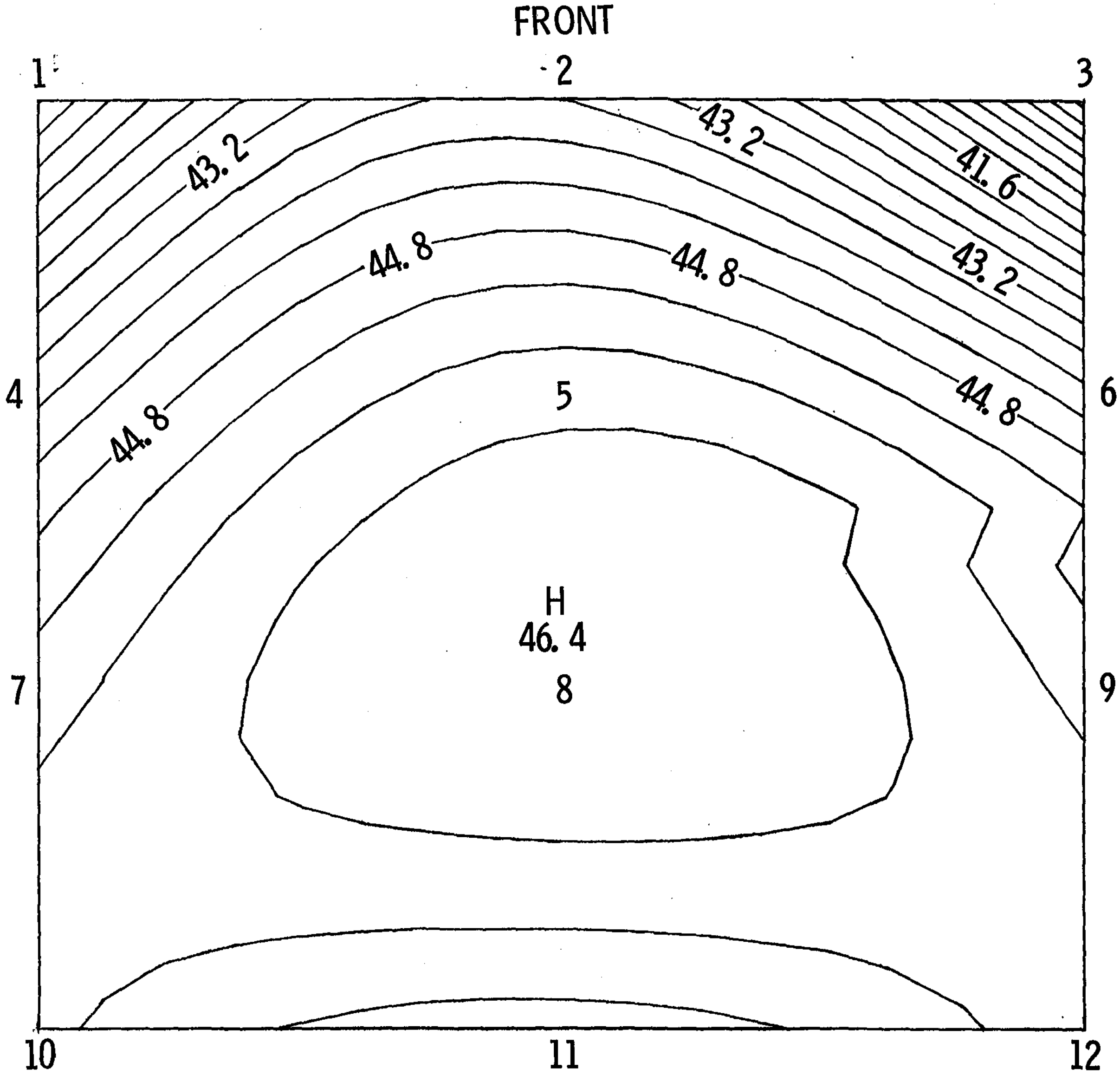


Figure 52. - Instrument deck temperature contour (°C).



NUMBERS 1 THROUGH 12 INDICATE SENSOR LOCATIONS

HOT CONDITION
TIME: 360 min.
CONTOUR INTERVAL IS .40°C

Figure 53. - Instrument deck temperature contour (°C).

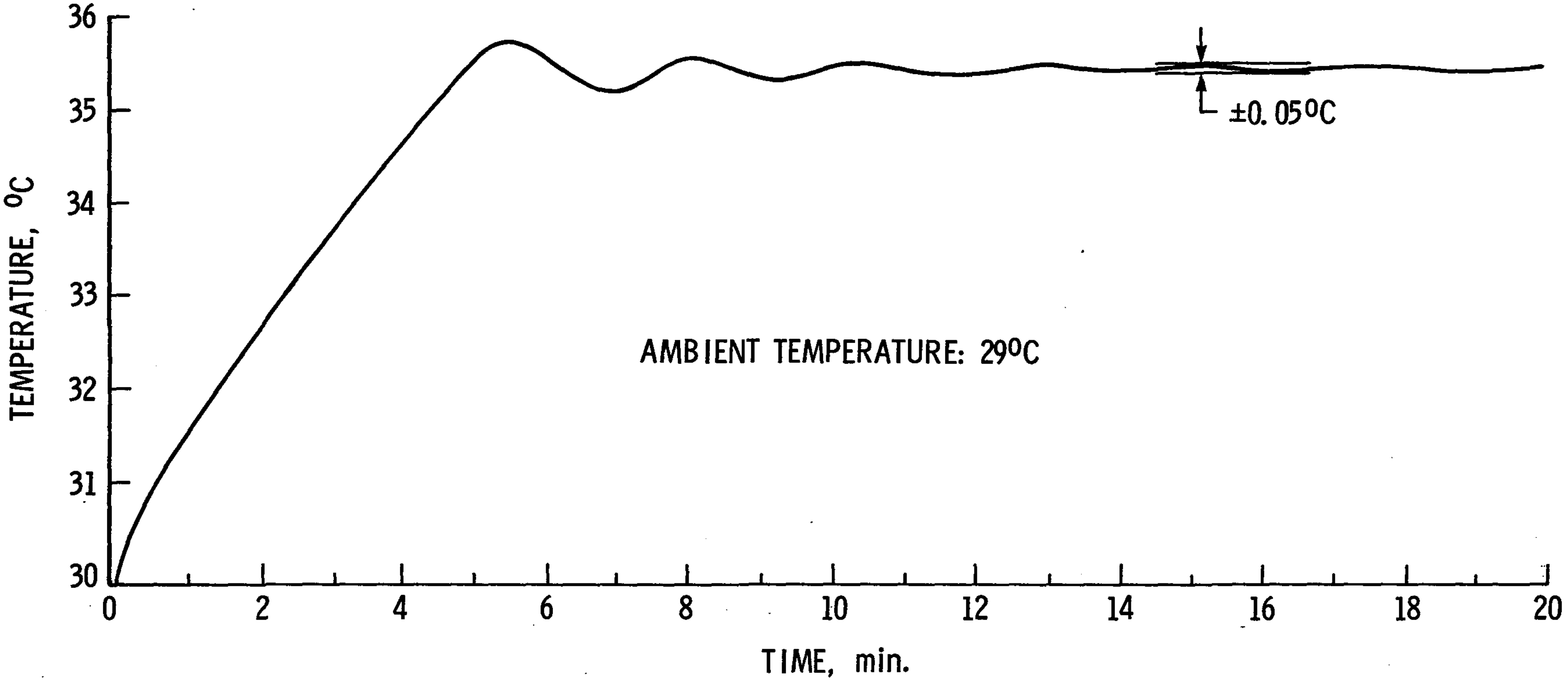


Figure 54. - Typical RF-unit stabilization temperature profile (lab).

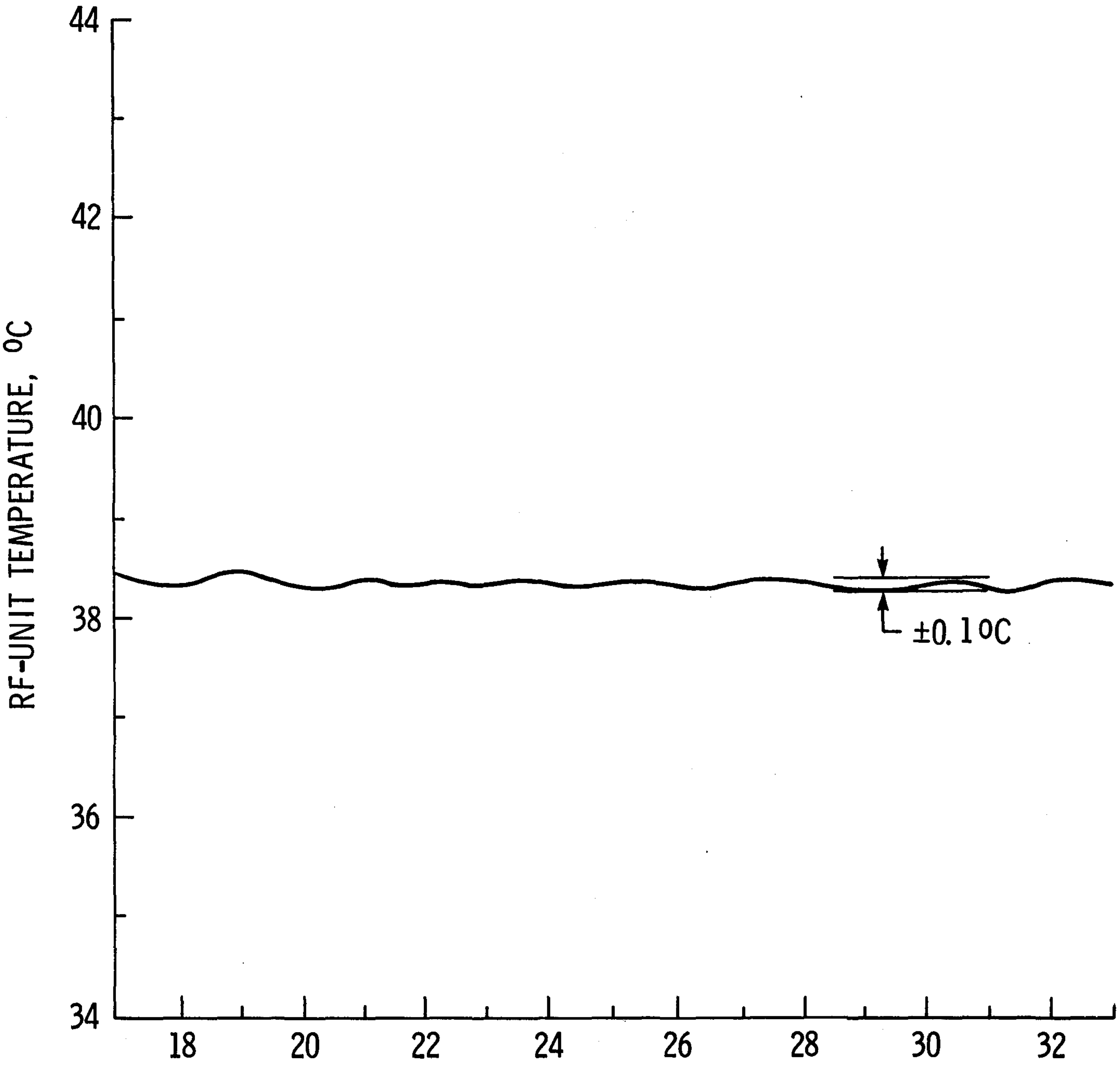


Figure 55. - RF-unit #1 temperature stability profile (flight).

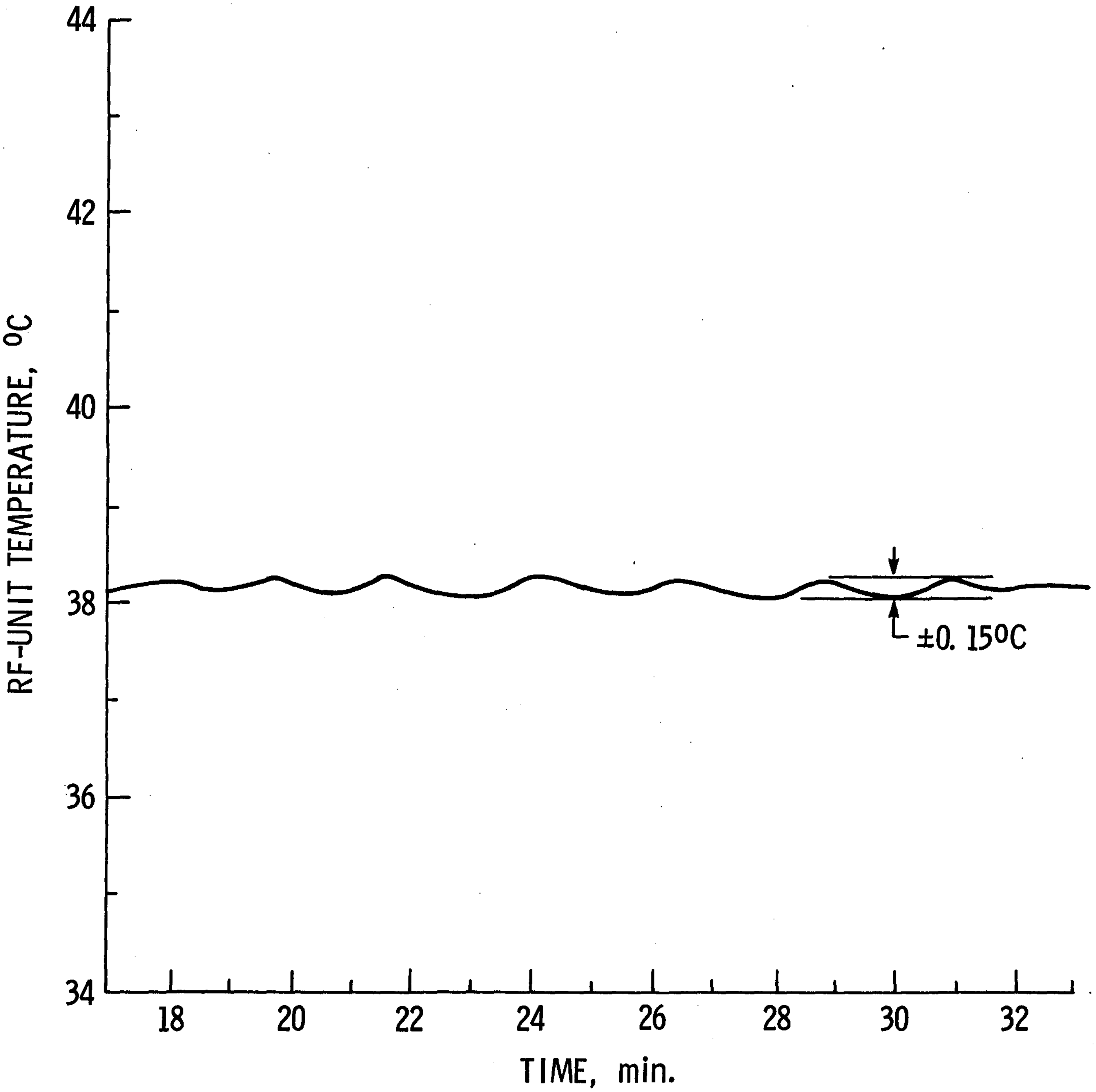


Figure 56. - RF-unit #2 temperature stability profile (flight).

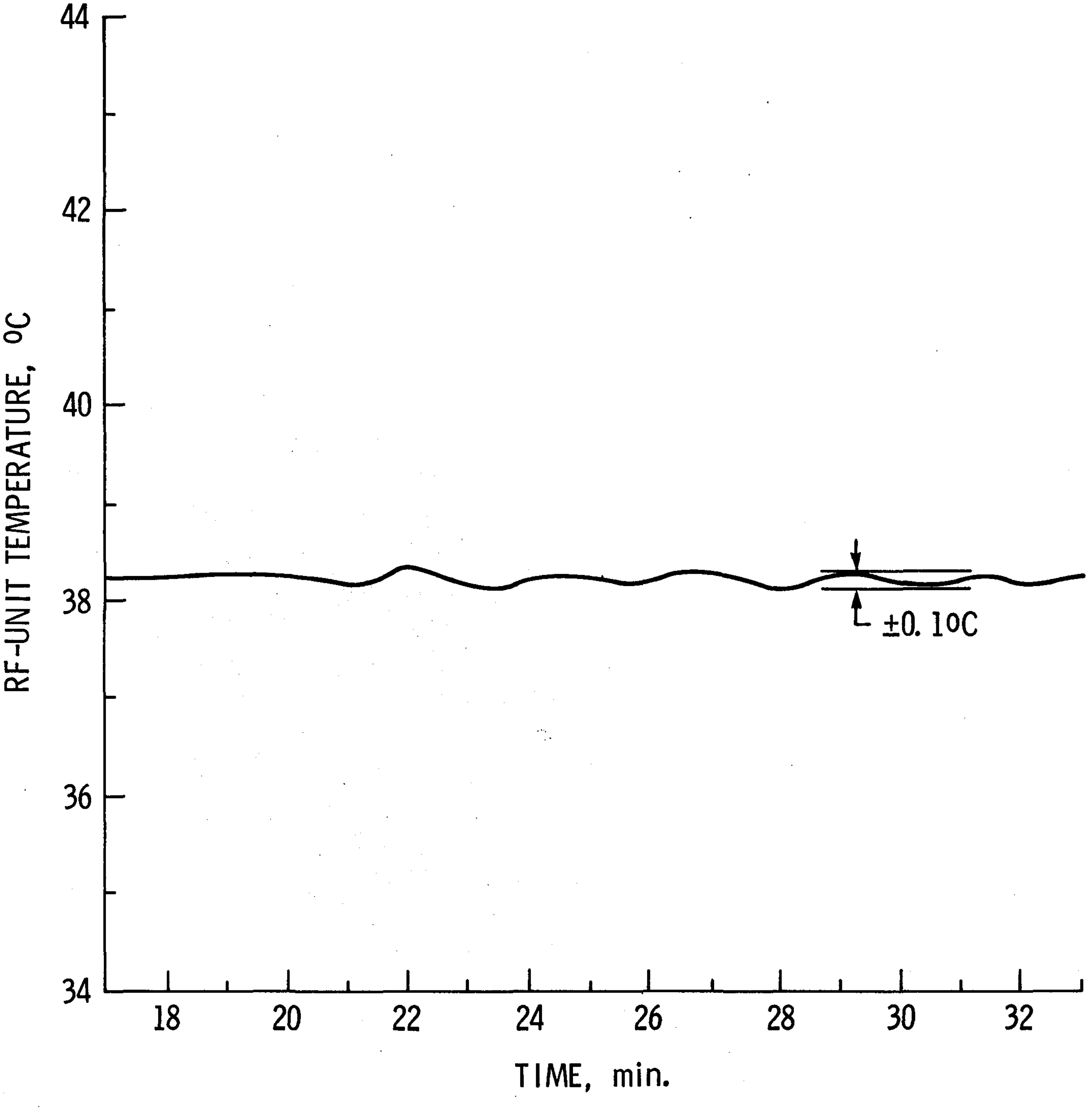


Figure 57. - RF-unit #3 temperature stability profile (flight).

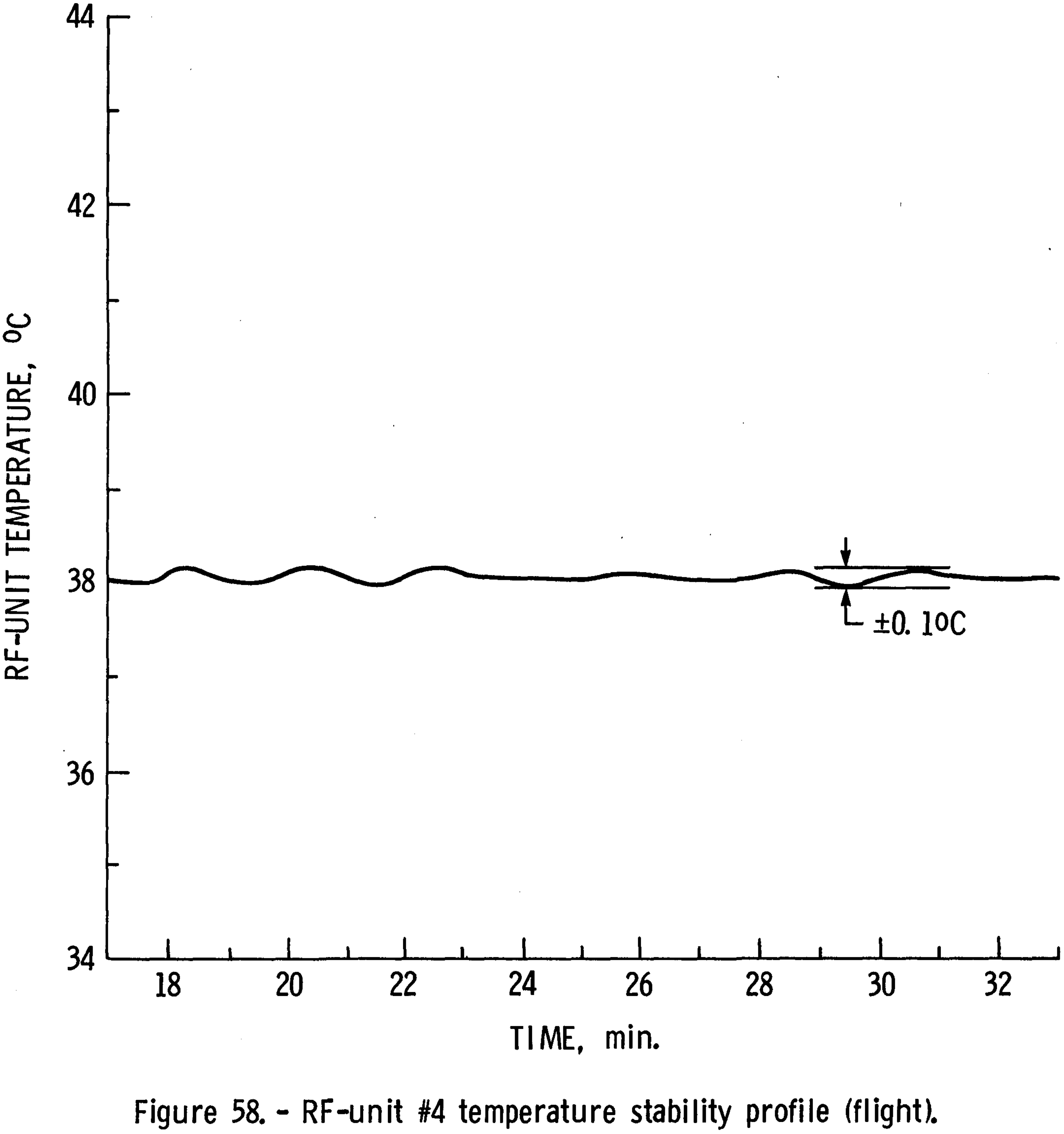


Figure 58. - RF-unit #4 temperature stability profile (flight).

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16. Abstract

A closed-loop thermoelectric temperature control system has been developed for stabilizing sensitive RF integrated circuits within a microwave radiometer to an accuracy of ± 0.1°C over a range of ambient conditions from -20°C to + 45°C. The dual mode (heating and cooling) control concept utilizes partial thermal isolation of the RF units from an instrument deck which is thermally controlled by thermoelectric coolers and thin film heaters. The temperature control concept was simulated with a thermal analyzer program (MITAS) which consisted of 37 nodes and 61 conductors. A full scale thermal mockup was tested in the laboratory at temperatures of 0°C, 21°C, and 45°C to confirm the validity of the control concept. A flight radiometer and temperature control system has been successfully flight tested on the NASA Skyvan aircraft.

17. Key Words (Suggested by Author(s))
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