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**ANALYTICAL AND EXPERIMENTAL STUDY OF
STARTUP CHARACTERISTICS OF A FULL-SCALE
UNFUELED NUCLEAR-ROCKET-CORE ASSEMBLY**

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ANALYTICAL AND EXPERIMENTAL STUDY OF STARTUP CHARACTERISTICS OF A
FULL-SCALE UNFUELED NUCLEAR-ROCKET-CORE ASSEMBLY (U)

by John S. Clark

Lewis Research Center

SUMMARY

A nuclear-rocket startup simulation experiment has been run at the Plum Brook station of the Lewis Research Center. Analytical methods have been formulated and the analysis of the core (presented as a program for a 7094 IBM digital computer) is described herein. Comparisons between calculated and measured values of nozzle chamber temperature, core material temperature, nozzle chamber pressure, core pressure drop, and axial pressure distribution are included.

The agreement between calculated and experimental results is very good. The maximum deviation between calculated and measured average nozzle chamber temperature for three different runs was 27° R or about 8 percent. The predicted core-material temperatures were compared with the average of several experimental temperature measurements at five axial positions within the core; the maximum difference noted was about 40° R. The nozzle chamber pressure was calculated to within 6 percent of the measured value for the three runs. Calculated core pressure drop and the axial pressure distributions were usually within the accuracy of the experimental data. Flow (and consequently, temperature) maldistributions within the system were observed; examination of the experimental data led to the conclusion that the particular nozzle used on the system, with its various camera windows, bleed ports, and inlet port positions, contributed heavily to the flow maldistributions.

INTRODUCTION

The development of nuclear-rocket systems requires the definition of performance characteristics in all modes of operation. Some of the most complex flow processes are incurred during the startup mode. The performance characteristics of the engine components during the early part of the startup transient are quite difficult to analyze because of large deviations from the requirements imposed on the system by steady-state full-power operation. Also, various transient flow phenomena are not amenable to precise analyses.

Accurate prediction of core operating conditions is extremely important to ensure the successful performance of a nuclear rocket. For example, the pres-

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sure drop across the core must be known in order to determine pumping requirements and to design the core support structure. The temperature and pressure of the core effluent are needed for thrust calculations. Core-material temperatures affect the rate of corrosion of the core material and influence the selection of power density. Also, core-stress calculations are dependent on material-temperature data used.

In order to obtain accurate predictions of fluid flow and heat transfer, great care must be exercised in the selection of appropriate correlation equations. Several exist for gaseous hydrogen and some of these will be discussed in appendix B; appendix A contains a list of the symbols used in this report. Because of the uncertainties involved in these correlations, however, it is important that any analytical procedure developed be compared with experimental data. Certain other assumptions are made in the analyses presented herein including (1) the neglect of flow maldistribution in the core, (2) the use of quasi-steady-state equations to predict transient results, and (3) the single-tube-model representation of the complex core geometry; the significance of these assumptions can only be assessed from experimental data.

A full-scale cold-flow nuclear-rocket-simulator experiment was conducted at the Plum Brook station of the Lewis Research Center. A description of the facility, the turbopump, and a comparison of predicted and experimental turbopump data are presented in reference 1. The information obtained from this experiment is intended to assist in the development of analog and digital computer calculation procedures for predicting the component and overall performance of nuclear-rocket systems. Of the many specific objectives of the experimental program, the following will be discussed in this report:

- (1) To obtain data to verify or improve calculation methods for predicting core pressure drop, fluid temperature, and material temperatures as a function of time
- (2) To determine local and gross overall hydrogen flow and temperature maldistributions in the nozzle and reactor

This report describes in detail the reactor core used in the engine system, presents analytical procedures for calculating core thermal and fluid flow information, and compares the results of the analytical predictions with experimental data of three typical runs. Although the comparisons presented in this report are for simulated startup conditions, the analytical procedures presented may be used to predict operating conditions during the startup, full-power, and shutdown modes. Reference 2 compares results of the analytical procedure with experimental data for a NERVA test that included power generation.

APPARATUS

A description of the facility is presented in reference 1. Figure 1 is a schematic diagram of the complete research apparatus.

Reactor

The reactor used in the experimental program is basically the same as the KIWI B-1B used initially in the ROVER program. A schematic drawing of this reactor is shown in figure 2. However, certain modifications and compromises to the KIWI B-1B hardware design were made to effect economy in fabrication but still satisfy the particular cold-flow-test requirements. The KIWI B-1B design specified various diameter cooling passages in the graphite fuel elements; these were averaged to a single diameter providing the same total fuel area as in the KIWI B-1B reactor. Additionally, the extruded graphite fuel element cooling passages were not coated for corrosion protection nor were the elements loaded with uranium. The reflector was made of aluminum rather than beryllium. The simulated control rods and poison plates were aluminum, and no provision was made for their external movement by actuators as in the KIWI hardware. The aluminum pressure vessel was provided with twelve $1\frac{7}{8}$ -inch-diameter viewing ports, six each at the plane of the reflector inlet and at the reflector outlet. These ports allowed visual recording by high-speed motion-picture photography and/or television of the qualitative condition of the propellant passing through the reflector system. Finally, extensive pressure and temperature instrumentation was installed, which was not included in the KIWI B-1B design.

Figure 3 illustrates the components within the reactor. Figure 3(a) is a photograph of a regular graphite module with the fuel elements removed that shows some of the installed instrumentation (discussed in the section Instrumentation). Figure 3(b) is a schematic drawing of a regular module assembly that shows the six full-length fuel elements and one shorter fuel element in position. Irregularly shaped modules are located at the core periphery to fill in the circular shape of the core. Also shown are the attachment threads at the support plate end of the module. A module assembly attached to the core support plate can be seen in figure 2. The fuel-element support collars are shown in figure 3(b) at the nozzle end of the module, and the inlet and outlet fuel-element plenums are also shown. The six full-length fuel elements are $50\frac{1}{2}$ inches long and the shorter center element is about 49 inches long. The outside diameter of the fuel elements is 0.746 inch, and the elements contain seven 0.153-inch-diameter holes. Figure 3(c) is a photograph of the assembled core with the cylindrical graphite reflector installed. Figure 3(d) illustrates the assembled outer aluminum reflector assembly.

Instrumentation

Location. - Figures 4 and 5 show the location of the temperature and pressure sensors discussed in this report for the core and the nozzle chamber, respectively. The following symbols are used for the item number designation:

- RP - reactor pressure
- RT - reactor temperature
- NP - nozzle pressure
- NT - nozzle temperature

[REDACTED]

Thus, RP-28 indicates a pressure measurement at an angular position of 15° , a radius of 17.3 inches, 0.25 inch below the core inlet plane. Similarly, RP-29 indicates a pressure measurement at an angular position of 15° , a radius of 17.3 inches, 51.6 inches from the core inlet plane. A pressure differential measurement from RP-28 to RP-29 is denoted RP-28/29.

The z locations shown in the scale of figures 4 and 5 show approximately the major instrumentation stations. The pressure sensors are strain-gage-type transducers, and the temperature sensors are copper-constantan thermocouples. Figure 6 shows details of the typical pressure and thermocouple installations.

The pressure measurement locations shown in figures 4 and 5 are generally such that the pressure transducer cannot be located at the sense point. The pressure is therefore transmitted through long, small-diameter ($1/16$ in.) tubing to the transducer, which is mounted outside the pressure vessel. Rapid changes in pressure due to slow dynamic response of the measuring system can introduce errors. The error in the measured values due to dynamic response was considered to be negligible, however, and was neglected.

Three methods were used on the facility for the measurement of flow rate. One foot below the tank discharge opening (see fig. 1) a calibrated 4-inch-diameter turbine-type flowmeter was installed that was capable of measuring liquid-hydrogen flow. A venturi-type flowmeter with a 1.9-inch-diameter throat was located $1\frac{1}{2}$ feet downstream of the pump discharge. Finally, the reactor nozzle provided a method of determining the flow rate leaving the system.

Data acquisition. - The instrumentation recorded for a particular run was connected to a program board at the base of the test stand. From this program board the measured signals were sent by transmission cables to a similar patch-board in the control room, which was approximately $1/2$ mile from the test stand. When the signal arrived at the control building it was transmitted to the Data Acquisition and Recording Building for digital recording or recorded in the control room on the various analog recording devices.

The digital recording equipment consisted of a 100-channel 10-kilocycle low-level multiplexer and a 192-channel 4-kilocycle low-level multiplexer. Each channel on the 10-kilocycle multiplexer was sampled at 100 samples per second while each channel on the 4-kilocycle multiplexer was sampled 20.8 times per second.

The analog system consisted of FM tape recorders, pen-type oscillographs, light-sensitive oscillographs, and voltage-balance strip charts.

Data processing. - The digital data tapes were brought to Lewis from the Recording Building at Plum Brook. The millivolt outputs recorded on the tapes were first averaged over several samples to eliminate some of the 60-cycle noise effects. Next, the millivolt output was converted to engineering units and the results listed.

Accuracy estimates. - The accuracy estimates for all measurements included

[REDACTED]

errors inherent in the sensors themselves, line noise, and errors in the recording system. The errors due to line noise and the recording system were measured for each parameter before the run and were found to be less than 0.5 percent of full scale.

The errors associated with the pressure transducers, approximately ± 1 percent of full scale, included a hysteresis effect, nonlinearity, and temperature shift. Any zero shift was eliminated in the data processing by use of a prerun calibration. Measurements made of transducer temperatures during various runs indicated the temperature effect to be completely negligible. The effects of hysteresis and nonlinearity were estimated by use of the average errors of all transducers in a given range taken from individual calibrations.

The calibration used for copper-constantan thermocouples conforms to the calibrations published by the National Bureau of Standards to within the following limits:

200° to -75° F, $\pm 0.75^\circ$ F,

-75° to -300° F, ± 1 percent

Calibration information below -300° F was obtained from an average of some thermocouples individually calibrated; no accuracy estimate has been made. In addition to the calibration errors just discussed, the curve fit of the calibration data in the data reduction program is not exact and is estimated to contribute errors of $\pm 1.1^\circ$ F. In addition to the preceding effects, thermocouple time-lag also contributes to errors. More work is required in this area, however, and no estimate will be made of the error involved in neglecting it. Because of the uncertainties in the calibration below -300° F, temperatures in this range will be excluded.

The 4-inch turbine-type flowmeter was rated by the manufacturer to measure liquid-hydrogen flows from 0 to 20 pounds per second. The flowmeter was calibrated by an independent laboratory with flow rates from 0 to 14 pounds per second. The calibration is estimated to yield results within 2 percent. Above 14 pounds per second, an estimate of the accuracy has not been made.

The accuracy of the flow rates determined from the pump discharge venturi measurements was believed to be poor. The installation was not standard; the venturi was mounted a short distance downstream of a 90° elbow, and no calibration in place was made. Thus, the venturi flow rate is not used in this report.

The use of the nozzle as a flowmeter will be discussed further in the section RESULTS AND DISCUSSION; no estimate of the accuracy of this method has been attempted.

It should be noted that in the preceding discussion, the accuracies discussed were only estimates; more work is required in the area.

Test Procedure

A complete description of the test procedure is given in reference 1. Some

[REDACTED]

[REDACTED]

of the highlights are discussed here briefly. Before the run tank was filled with liquid hydrogen, the tank, pump, and feed lines upstream of the pump main discharge valve (see fig. 1) were evacuated and purged three times with helium. The tank was then filled with 1800 gallons of liquid hydrogen.

Since the turbopump used had to be chilled to liquid-hydrogen temperature before rotating, the tank shutoff valve was opened and liquid hydrogen was allowed into the system up to the pump main discharge valve. After about an hour, the pump was at operating temperature and the test could begin.

The steam ejector system was started, and when the nozzle pressure was down to 3 pounds per square inch absolute, the automatic sequencer was initiated. A 30-second helium purge of the engine and nitrogen purge of the ejector were made, and the run-tank pressurization system ramped the tank pressure to the predetermined level. At this point the steam ejector system had the nozzle pressure down to 0.5 pound per square inch absolute or less and the data acquisition systems had been sequenced on. Flow of hydrogen through the system was initiated from the controlled opening of the pump discharge valve. Time zero ($\tau = 0$) on all the runs corresponds to the time when the pump discharge valve began opening.

For most of the bootstrap runs, a finite length of time was allowed for system cooldown. (Bootstrapping, as used here, means that the power required to drive the turbopump during startup was obtained from the latent heat of the system.) After the cooldown period, the turbine power control valve was opened, and bootstrapping was initiated.

The test was terminated by a manual initiation of the shutdown sequencer when it was determined that the test objectives had been met. After the pump stopped rotating, the tank shutoff valve was closed, and the system was completely purged.

ANALYTICAL PROCEDURE

Core Analytical Code - (CAC)

A core analytical heat-transfer and fluid-flow program was written in FORTRAN IV to be accepted by an IBM 7094 computer which predicts axial and radial fluid conditions, flow rates in each passage, coolant wall temperatures, and approximate material temperatures as a function of time. A brief discussion of CAC follows; a detailed description of the program is presented in appendix C.

Flow diagram. - A simplified flow diagram for CAC is presented in figure 7. It should be kept in mind that the reactor analyzed in this report had no orificing and had only one passage size. Thus the flow is assumed to be the same in each passage and only one passage had to be analyzed. CAC, however, was written to accept multipassages (several orifices), and the following discussion of CAC includes the multipassage capabilities of the program. The program begins by reading the input data (block 1, fig. 7). Then the core inlet conditions are determined as functions of the initial time (block 2). The initial

[REDACTED]

flow rate in each coolant passage is assumed to be the same. Calculations begin at radial passage $j = 1$ and axial station $I = 1$, and the orifice outlet conditions for passage 1 are calculated (block 3). A trial value for the heat flux iteration is obtained (block 4), based on station inlet conditions, and the pressure drop across the first station is calculated (block 5). The pressure-drop calculation is an iterative one since outlet pressure depends on outlet density, which likewise depends on outlet pressure.

When the pressure drop across the station has been determined, the outlet and average fluid properties in the station are determined (block 6), and a new value of heat flux is computed (block 7). This value is compared with the trial value used (block 8); if they are not the same, the new value of heat flux becomes the trial value, and the loop is repeated until convergence occurs.

The maximum material temperature is now calculated (block 9) as the temperature at the outside diameter of the single-tube model used (see fig. 8 and appendix C for details). The assumption is made that the convective heat transfer across the fluid film is the controlling heat-transfer mechanism and therefore a steady-state conduction equation can be used to calculate the radial temperature distribution in the single-tube model. This implies that the heat transferred to the hydrogen at each station is assumed to be generated uniformly within the single-tube model.

The outlet conditions from station I become the inlet conditions to station $I + 1$ (fig. 7), and the analysis is repeated for the next station. After each station in the first passage has been analyzed (block 10), the core exit conditions and pressure drop across the passage are determined (block 11). The program then goes to the first station of the second passage (blocks 12 to 16 to 4), and the station calculations are repeated (blocks 4 to 11). Thus, each passage in the core is considered.

On completion of the passage calculations, the pressure drops across each passage are compared (block 13); they must all be equal (core pressure drop is a constant). If they are not, the flow rates are adjusted in each passage (block 14) and the passage calculations repeated (blocks 4 to 13). The process is repeated until the pressure drop across each passage is the same. Results for time τ are listed at this point (block 17).

Finally, wall temperatures at time $\tau + \Delta\tau$ are calculated by using either a TQSS program (see ref. 3) or the single-tube model approximate method (block 18). The single-tube approximate method assumes that the rate of change of the coolant wall temperature with time is the same as the rate of change of the mean material temperature with time. An analysis of the entire core is then performed by using the new wall temperatures for time $\tau + \Delta\tau$ (block 19), and the entire process is repeated until time equals τ_{fin} .

Heat-transfer correlations. - As pointed out in appendix B, the Miller-Taylor correlation was used in the comparison presented herein for the turbulent flow regime:

$$\left. \begin{aligned} Nu_b &= 0.021 Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b} \right)^{-B} \\ B &= 0.29 + 0.0019 \frac{L}{D} \end{aligned} \right\} \quad (1)$$

Similarly, the correlation used for laminar flow is

$$Nu_{b,l} = 4.36 + \frac{0.036 \left(\frac{Pe_b}{\frac{L}{D}} \right)}{1 + 0.0011 \left(\frac{Pe_b}{\frac{L}{D}} \right)} \quad (2)$$

Pressure-drop equations. - The static pressure drop is a combination of both momentum and friction pressure drop:

$$\Delta P_{mom} = \frac{G^2}{g} \left(\frac{1}{\rho_{out}} - \frac{1}{\rho_{in}} \right) \quad (3)$$

$$\Delta P_{fr} = \frac{G^2}{g} \left[4f \frac{\Delta L}{D} \frac{1}{(\rho_{in} + \rho_{out})} \right] \quad (4)$$

Friction-factor correlation. - The relative roughness of the core coolant passages was approximately 0.0004 (see appendix B). The following equation was developed for friction factor as a function of Reynolds number for a relative roughness of 0.0004:

$$4f = 0.1552 - 0.04412 Y + 0.005318 Y^2 - 0.0002881 Y^3 + 0.000005903 Y^4 \quad (5)$$

where $Y = \ln(Re_b \times 10^{-6}) + 10$.

For laminar flow, the friction factor is obtained from

$$4f = \frac{64}{Re_b} \quad (6)$$

Simplifying Assumptions

Several assumptions had to be made in order to analyze the modified KIWI B-1B reactor with CAC. The effect of the core support plate and module and fuel-element inlet plenums on the temperature and pressure of the fluid entering the coolant passages was neglected. In other words, the heat transferred to the

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hydrogen and the pressure drop across the core support plate were assumed to be negligible. Since the passages in the core support plate were of large diameter and were relatively short, the pressure drop across the core support plate was known to be very small.

Since there were no orifices in the reactor and all the coolant passages were the same diameter, only one passage was used. This implies that the flow rate should have been the same in each coolant passage and therefore no radial profiles of pressure or temperature were predicted. All the fluid was assumed to flow through the coolant passages; hydrogen leaks between elements were neglected.

Figure 3(b) is a schematic drawing of a regular module assembly showing the six full-length fuel elements and one shorter fuel element in position. For CAC it was assumed that fuel elements and modules were all 52 inches long. Thus, the attachment threads in the center element and the inlet and outlet plenums were ignored, and the core could be analyzed by using 26 equal 2-inch axial increments. The core void fraction was obtained by dividing the total core flow cross-sectional area by the total core cross-sectional area.

Runs Analyzed

Twenty-six experimental runs have been made in the facility, each with specific objectives. Runs 19, 20, and 24 were selected for comparison with CAC because more core measurements were recorded for these runs than the earlier runs. Table I is a summary of the important parameters of these runs. Run 24 resulted in the highest pressures and highest flow rates of any of the runs, while run 20 was a comparatively low-pressure low-flow-rate run. Intermediate values were obtained for run 19. Thus, a range of pressure and flow rate is covered by the three runs selected.

TABLE I. - MAJOR RUN PARAMETERS

Parameter	Run		
	19	20	24
Tank pressure, psia	35	25	35
Time of cooldown before bootstrapping, sec	10	10	0
Run time (considered for CAC comparison), sec	25	40	12
Flow rate at end of run time, lb/sec	13.07	9.35	26.8
Core inlet pressure at end of run time, psia	37.3	25.9	78
Core inlet fluid temperature at end of run time, °R	206	197	221

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RESULTS AND DISCUSSION

Experimental Input Data for Core Analytical Code

The CAC calculates core outlet conditions and conditions within the core, as a function of position, from given inlet conditions, heat-generation rates, and a known initial wall-temperature distribution. Therefore, to compare CAC results with the experimental data from the nuclear-rocket-simulator experiment, certain experimental data had to be used as input to CAC; they include: core inlet pressure, core-inlet gas temperature, total core flow rate, and core heat-generation rate, which for these experiments was zero.

Core-inlet pressure. - Two pressure transducer measurements, located in the plenum between the flow separator and the core support plate at radii of 16.0 and 5.38 inches were recorded for runs 19, 20, and 24. Figure 9 shows the results of these measurements as a function of time for the three runs. Slight differences can be noted between the two measurements, and the average of the two (solid line in the figure) is the input for CAC. The difference between the two readings for run 19 is about 0.5 pound per square inch at τ equal to 25 seconds and for run 20, about 0.3 pound per square inch at τ equal to 40 seconds. The estimated accuracy of each of these measurements for runs 19 and 20 is ± 0.5 pound per square inch. For run 24, the difference noted is 1.7 pounds per square inch at τ equal to 12 seconds; the estimated accuracy is ± 1.5 pounds per square inch for each reading. Thus, the readings are within the estimated accuracy.

Core-inlet gas temperature. - Several measurements of core-inlet gas temperature were recorded for the three runs considered. Figure 4 shows schematically the location of these thermocouples within the large plenum between the flow separator and the core support plate and within the core support-plate passages.

Figure 10(a) shows the temperature within the plenum between the flow separator and the core support plate as a function of distance from the core centerline, and figure 10(b) shows the temperature within the support-plate passages, also as a function of distance from the core centerline for run 19. Similar results were obtained for runs 20 and 24.

Figure 10 shows clearly the temperature maldistribution problem at the core inlet; the same problem existed at the core exit and will be discussed further in the following section. Comparisons were made between (1) the average of the four sensors in the plenum and (2) the average of the measurements within the core-support-plate passages. During most of each run, the plenum average temperatures were a few degrees colder than the average passage temperatures as expected. However, as the temperatures dropped below about 200° R, the passage temperatures averaged lower than the plenum temperatures; poor instrumentation accuracy and flow maldistribution are believed to account for this phenomenon. Thus, the average of the four thermocouples in the plenum between the flow separator and the core support plate was taken to be the core-inlet temperature for CAC.

[REDACTED]

Core flow rate. - The tank-exit turbine-type flowmeter measured the flow rate into the system; storage of liquid hydrogen within the system during the runs, however, prohibited the use of this flow rate as the flow rate through the core. The calculated exhaust nozzle flow rate was used as the core flow rate, therefore, since it was known that hydrogen storage between the core inlet and the nozzle throat would be extremely small until liquid hydrogen entered the core. The measured nozzle chamber pressure P_{ch} and the nozzle chamber temperature T_{ch} were used to find the density and specific heat ratio γ in the nozzle chamber. Next, the nozzle throat pressure was obtained by assuming choked flow at the nozzle throat and by using isentropic expansion laws:

$$P_{th} = P_{ch} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} \quad (7)$$

Finally, the nozzle flow rate was calculated from

$$\dot{w}_n = 40.08 \phi \sqrt{\rho \Delta P} \quad \text{lb/sec} \quad (8)$$

where

$$\phi = \sqrt{\frac{0.9965 \left(\frac{\gamma}{\gamma - 1} \right) \left(\frac{P_{th}}{P_{ch}} \right)^{\frac{2}{\gamma}} \left[1 - \left(\frac{P_{th}}{P_{ch}} \right)^{\frac{\gamma - 1}{\gamma}} \right]}{\left[1 - 0.0035 \left(\frac{P_{th}}{P_{ch}} \right)^{\frac{2}{\gamma}} \right] \left[1 - \left(\frac{P_{th}}{P_{ch}} \right) \right]}}$$

The problem of flow, and consequently, temperature maldistribution, also complicated matters. Figure 11(a) shows a schematic of the exhaust nozzle as viewed from the core exit. The approximate position of the 14 thermocouples are shown in relation to the physical geometry of the nozzle, that is, inlet ports, openings, etc. Figure 11(b) shows the experimental temperatures recorded for these thermocouples after 25 seconds of run 19. The maldistribution problem is apparent. Also, although the time shown represents the worst case considered for run 19, the problem exists throughout the earlier part of the run to a lesser degree. Similar results were obtained for runs 20 and 24. Figure 11 illustrates the temperature maldistribution problem in the nozzle chamber and gives an insight into some of the causes of this problem. First of all, it appears that the temperatures in the nozzle chamber in the area of the short inlet duct of the nozzle are colder than temperatures in the areas of the long inlet ducts (see figs. 5 and 11). As the fluid enters the nozzle-inlet spider from the 4-inch-inlet pipe (see fig. 1), it will take the path of least resistance. Since the short inlet duct has lower resistance to flow than the long inlet ducts, more flow enters the short inlet duct. As a result, the angular sector of the system corresponding to the short inlet duct cools down more rapidly than the rest of the system.

[REDACTED]

Other causes of the temperature maldistribution are the interruptions in the nozzle tubes caused by installing the turbine bleed port, camera port, and light window. After these openings were cut, the intersected tubes were manifolded around the ports; the flow was fed back into the tubes on the downstream side; approximately 10 tubes were affected for each opening. It can be seen in figure 11 that the area around the turbine bleed port and the camera port is definitely warmer than the other areas. In the area of the light window, the cooling effect of the short inlet duct appears to predominate.

The effect of the physical configuration of the particular nozzle used in the facility may be summarized as follows: (1) a "cold" spot is expected in the area around θ equal to 0° and (2) a "warmer" spot is expected on the opposite side of the nozzle at θ approximately equal to 180° .

Figure 11 also shows that the center of the nozzle is generally cooler than the surrounding areas. Figures 12(a) and (b), which show temperature as a function of radius for the nozzle instrumentation-rake and core-exit-module plenums, respectively, also illustrate this fact. This anomaly cannot be explained based on the nozzle geometry, but is believed to be partly a result of the flow separator geometry. Figure 12(c), the angular temperature distribution at a radius of 14 inches, shows the distribution with the warm spot around 180° and the cold spot around 0° .

Because of the nozzle chamber temperature maldistribution problem just discussed, the selection of the temperature to use to find the density and specific heat ratio for equation (8) was difficult. It was expected, however, that the rate of storage within the entire system should decrease (after a sharp increase in the first seconds of the run) as time increases since the system is filling with liquid hydrogen. Therefore, it was expected that the flow rate out of the system $\dot{w}_n$ should approach the flow rate into the system $\dot{w}_F$. Thus, it was found that, by using the average of the five thermocouples on the instrumentation rake as the "true" nozzle chamber temperature, the calculated nozzle flow rate approached the flowmeter flow rate. These results can be seen in figures 13(a), (b), and (c) for runs 19, 20, and 24, respectively. The difference between the two flow rates shown in figure 13 is assumed to be the rate of storage in the system. It is quite large during the early part of each run, but decreases as time increases. The calculated nozzle flow rates shown in figure 13 were used as the core flow rates for the CAC predictions.

Comparison of Experimental and Predicted Results

Nozzle chamber temperature. - Figures 14(a), (b), and (c) show a comparison of predicted nozzle chamber temperature with the average of the five rake temperatures for runs 19, 20, and 24, respectively. Agreement is seen to be excellent for all three runs. A 0.1-second time increment was used in the prediction code. The maximum difference between predicted and experimental temperature, at τ equal to 40 seconds for run 20, is about 27° or 8 percent.

Material temperatures. - Figure 15 compares predicted and experimental core-material temperatures as a function of distance from the core inlet for

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run 19. The predicted results shown are the material temperatures obtained from the single-tube model (see appendix C for details). The experimental temperatures shown are average temperatures at the approximate axial position shown. For example, the temperature shown at L equal to 3 inches is the average of RT-1, RT-16, RT-26, and RT-31 (see fig. 4). Likewise, the temperatures shown at each of the other stations are averages of four experimental values. Similar results were obtained for runs 20 and 24. Differences as high as 42° R are seen at τ equal to 25 seconds. It should be kept in mind, however, that all the material-temperature thermocouples are installed at θ equal to 75° . The temperature maldistribution, which has been shown to exist, may account for some of the differences between experimental and predicted results in figure 15.

Figure 16 compares predicted and experimental core-material temperatures as a function of time at approximately 33 inches from the core inlet for run 19. The results are good over most of the run; the maximum difference of about 30° R or approximately 12 percent is seen at τ equal to 25 seconds. The experimental temperatures shown are the average of RT-4, RT-19, RT-29, and RT-34.

Nozzle chamber pressure. - Figures 17(a), (b), and (c) compare predicted and experimental nozzle chamber pressure for runs 19, 20, and 24, respectively. The first few seconds of runs 19 and 20 were characterized by pressure oscillations throughout the system, and slight differences between experimental and predicted pressures are seen. However, only a few representative experimental points are shown in the figures; a plot of all the points shows a band around the predicted pressure line.

During the last few seconds of each run, small differences may also be noted between predicted and experimental nozzle chamber pressure. An explanation of these small differences, up to about 6 percent, may be that the calculation of nozzle flow rate is probably poorest during this part of the run; temperature maldistribution in the nozzle chamber is maximum, and temperature sensor accuracy is poorest. Any error in flow rate will be squared in the nozzle-pressure and core-pressure-drop calculations since pressure drop is proportional to flow rate squared. Since the agreement over the main portion of the runs is excellent, the overall prediction of nozzle chamber pressure is believed to be very adequate.

Core pressure drop. - Figures 18(a), (b), and (c) compare the predicted and experimental core pressure drop as a function of time for runs 19, 20, and 24, respectively. On these figures, RP-28/29 and RP-33/38 (see fig. 4) are measurements of the pressure differential from the core-inlet-module plenums to core-exit-module plenums. The other experimental data in the figure are the difference between the measured core-inlet pressure, RP-121 and RP-123 (see fig. 4), and the measured nozzle chamber pressure (NP-50 and NP-51, fig. 5).

The experimental points shown in figure 18 are seen to fall within a rather wide scatter band. For the most part, the predicted pressure drop falls within this band, however. Pressure oscillations in the first few seconds of the runs are again noted in the experimental data. Also, larger differences are noted between predicted and experimental values in the last few seconds of each run

[REDACTED]

[REDACTED]

where the flow rate used is less certain; the flowmeter was not calibrated above 14 pounds per second and the accuracy of the nozzle chamber thermocouples is poorest. The prediction of core pressure drop is believed to be quite adequate based on the results discussed.

An explanation of the widely scattered experimental data may be the flow maldistribution throughout the core coolant passages. The measured pressure drop, RP-33/38, at a radius of 13.1 inches indicates a higher pressure drop than RP-28/29 at a radius of 17.3 inches. Since pressure drop is proportional to the weight flow rate squared, it is indicated that the flow rate is greater in the center of the core than toward the periphery. Again, more measurements are required in order to establish a definite pattern. The accuracy of the measuring instruments also contributes to the data scatter shown in these figures.

For runs 19 and 20 the estimated accuracy of RP-28/29 is ± 0.1 pound per square inch, and for RP-33/38, ± 0.25 pound per square inch. For run 24, the estimated accuracies of the two measurements are ± 0.2 and ± 0.5 pound per square inch, respectively. The accuracy of the other data (core-inlet pressure minus nozzle-chamber pressure) is estimated at ± 1.0 and ± 2.5 pounds per square inch for runs 19 and 20, and run 24, respectively. The pressures, RP-28/29 and RP-33/38, do not include the pressure drop across the core support plate or the recovery from the core-exit-module plenums to the nozzle chamber (somewhat canceling effects).

Axial pressure distribution. - Measurements were obtained in one fuel-element passage for axial pressure distribution, RP-1, RP-2, RP-3, RP-4, and RP-5 (see fig. 4). Results of these measurements and a comparison with predicted pressure as a function of length are presented in figure 19 for run 19. The experimental core-inlet pressure (RP-121 and RP-123), the core-inlet pressure used in the prediction program, is also shown in the figure. A comparison between predicted and experimental nozzle-chamber pressure is also shown in the figure. The excellent agreement between RP-1 and the predicted pressure at that point substantiates the assumption that the pressure drop across the core support plate is negligible. Also, good agreement along the length of the fuel element indicates that the relative roughness used in the calculations is appropriate. Agreement on this figure is within the experimental accuracy of the measurements.

CONCLUDING REMARKS

Results obtained from the Core Analytical Code computer program showed excellent agreement with average experimental data for simulated startup conditions, although severe local maldistributions were observed. For example, agreement between the measured and predicted nozzle-chamber pressure is within about 6 percent; predicted core pressure drop and axial pressure distribution are, for the most part, within the accuracy of the experimental data. The accurate measurement of the relative roughness of the core coolant passages contributed to the good agreement between measured and predicted pressures.

The maldistribution of flow and, therefore, temperature throughout the core

[REDACTED]

has made the accurate prediction of individual local material temperatures difficult. However, the prediction of local material temperatures compared well with the average of several measurements. Similarly, the comparison of the predicted and average experimental core-exit gas temperatures agreed within 27° R maximum, about 8 percent, although quite different local experimental values were observed.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 2, 1965.

[REDACTED]

APPENDIX A

SYMBOLS

The following symbols with consistent units are used throughout this report:

A	correlation coefficient for heat transfer
B	exponent on wall to bulk temperature ratio in turbulent heat-transfer correlation
C	exponent on length to diameter ratio in turbulent heat-transfer correlation
C_1, C_2	integration constants
C_p	specific heat
D	coolant flow passage diameter
D_{core}	core outside diameter
F	power distribution factor
f	friction factor
G	mass flow rate per unit area
GEN	heat-generation rate per unit volume
g	gravitational constant
H	enthalpy
H ₂ Subr	hydrogen-properties subroutine
h	heat-transfer coefficient
I	axial increment number
J	number of radial groups
j	radial group number
K	proportionality constant
K_L	entrance loss coefficient
k	thermal conductivity

[REDACTED]

L length from core inlet

ΔL incremental length of single-tube model

M Mach number

N flow-balancing iteration number

Nu Nusselt number

OD calculated outside diameter of single-tube model

P pressure

ΔP pressure drop

Pe Peclet number ($Re \cdot Pr$)

Pr Prandtl number

Q rate of heat transferred to coolant, Btu/sec

ΔQ net heat gained in single-tube model (heat generated minus heat transferred to hydrogen) in specified time increment, Btu

Q' heat-generation rate in single-tube model, Btu/sec

QC heat conducted to an axial station, Btu

$\dot{q}$ heat transferred to hydrogen for single-tube model per unit volume and unit time

R gas constant

Re Reynolds number

r radius

T temperature

ΔT change in temperature

TOLER convergence tolerance used in pressure, heat-flux, and flow-balancing iterations

TØSS IBM 7090 code for computing transient or steady-state temperature distributions

V volume of single-tube model

$\dot{w}$ weight flow rate

[REDACTED]



X exponent on flow-balancing equation

x distance from top of nozzle

Z distance from top of module

α void fraction (flow cross-sectional area divided by total cross-sectional area)

γ specific heat ratio

ϵ rms roughness

θ angular position in core

μ viscosity

ρ density

τ time

$\Delta\tau$ time increment

ϕ compressibility factor

Subscripts:

a axial

av average

BE tube length minus first and last 1.5 in.

b bulk

ch nozzle chamber

e exit

F flowmeter

f film

fin final

fr friction

I initial

i axial increment number

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in inlet
j radial group number
l local
m material
mom momentum
max maximum
min minimum
N flow-balancing-iteration loop number
n nozzle
o orifice
old previous iteration
out outlet
r radial
T total
t turbulent
th throat
tr trial
w wall
l station inlet
 α, β first and second flow-balancing iterations

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APPENDIX B

HEAT-TRANSFER AND PRESSURE-DROP STATUS

Heat Transfer

Turbulent flow. - Investigators have studied heat transfer to hydrogen for several years; the NERVA (Nuclear Engine for Rocket Vehicle Application) program has encouraged much of this work in the turbulent flow regime. Several different correlations have been proposed that correlate experimental data with varying degrees of accuracy, for different parameter ranges. For example, Wolf and McCarthy (ref. 4) reported steady-state gaseous hydrogen tests for both nickel and 321 stainless-steel tubes with inside diameters of 0.326, and 0.305 and 0.430 inch, respectively. Wall to bulk temperature ratios ranged from 1.5 to 11.09, pressures ranged from 32 to 865 pounds per square inch absolute, bulk Reynolds numbers varied from 18 000 to 220 000, and inlet bulk temperatures from 135° to 546° R were obtained. In these tests, a minimum length of 30 diameters was provided as a hydraulic entrance region upstream of the test section in order to establish a fully developed velocity profile with a uniform temperature profile at the entrance to the electrically heated part of the test section. About 10 diameters were provided at the exit of the test section. Specially designed inlet and exit mixing chambers were used for determination of pressures and bulk temperatures. Average Nusselt numbers for the central part of the tubes were determined by use of

$$Nu_{b,av} = 0.045 Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b} \right)^{-0.55} \left(\frac{L_{BE}}{D} \right)^{-0.15} \quad (B1)$$

In this equation L_{BE} denotes the tube length minus the first and last 1.5 inches and was included to account for the different test-section lengths considered. Results of equation (B1), with property values based on the average bulk temperature, agreed to within ± 8 percent with data.

Local Nusselt numbers were also determined in reference 4 by use of equation (B2); these, however, were restricted to the latter part of the tube for the two test sections:

$$Nu_{w,l} = 0.023 Re_w^{0.8} Pr_w^{0.4} \left(\frac{T_w}{T_b} \right)^{0.8} \quad (B2)$$

In these local calculations, the average wall temperature and the average bulk temperature of the gas for the tube region under consideration were employed. Properties are evaluated at the wall temperature; good agreement resulted.

Taylor (ref. 5) reports steady-state results of gaseous hydrogen flowing through tungsten tubes under the following conditions: pressures from 40 to 100 pounds per square inch absolute, local surface temperatures up to 5600° R, bulk fluid temperatures about 570° R, local Reynolds numbers from 2000 to 30 000,

local ratios of wall to bulk temperatures from 1.5 to 5.9, and heat fluxes to 1 700 000 Btu per hour per square foot. Data correlated to within ± 10 percent by use of property values evaluated at film temperatures:

$$Nu_f = 0.021 Re_f^{0.8} Pr_f^{0.4} \quad (B3)$$

Miller and Taylor examined several correlations (ref. 6) in an attempt to obtain an improved correlation in regions far removed from the experimental data. As a result of the calculations performed for reference 6, it was found that a modification of the Dalle Donne correlation (see ref. 6) reduced the scatter of the experimental data considerably. The equation (herein referred to as the Miller-Taylor correlation) is

$$Nu_b = 0.021 Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b} \right)^{-B} \quad (1)$$

where

$$B = 0.29 + 0.0019 \frac{L}{D}$$

The experimental data correlated by equation (1) covered the following range of variables:

- (1) $10 \leq L/D \leq 240$
- (2) $200^\circ R \leq T \leq 2800^\circ R$
- (3) $1.1 \leq T_w/T_b \leq 8.0$
- (4) $30\,000 \leq Re \leq 400\,000$

The range of variables considered in the nuclear-rocket-simulator experiment core are about

- (1) $0 \leq L/D \leq 340$
- (2) $200^\circ R \leq T_b \leq 540^\circ R$
- (3) $1.0 \leq T_w/T_b \leq 1.2$
- (4) $0 \leq P \leq 80 \text{ psia}$
- (5) $2000 \leq Re \leq 150\,000$

Since the range of variables encountered in a nuclear-rocket-simulator experiment are, for the most part, within the range of variables of the Miller-Taylor correlation and since the use of bulk fluid properties eases the calculation procedure, equation (1) is used in this study to predict heat transfer in

the turbulent flow regime. Fluid properties in equation (B2) are based on wall temperature and in equation (B3) on film temperatures.

Laminar flow. - For laminar-flow heat transfer, the Graetz equation is often used (ref. 7):

$$Nu_F = 1.75 \left(\frac{\dot{w} C_p}{k \Delta L} \right)^{1/3} \quad (B4)$$

This equation assumes a fully developed velocity profile at the point where heating begins; for viscous fluids, this assumption is valid because the velocity profile develops more rapidly than the temperature profile. However, for Prandtl numbers near 1.0, which includes gaseous hydrogen, the velocity and temperature profiles develop at similar rates along the tube, and the assumption of a fully developed velocity profile at the tube entrance can lead to large errors in predictions.

Kays (ref. 8) presents numerical solutions, for a number of heating cases with velocity and temperature uniform at the tube entrance, that employ variable velocity profiles along the tube. Kays compares experimental data with the numerical solutions with good agreement. Comparisons of the same data with solutions obtained by use of the Graetz equation differed considerably.

Kays presents numerical solutions for the cases of (1) constant wall temperature, (2) constant temperature difference, and (3) constant heat flux input. It is believed that the assumption of constant heat flux input (considering an incremental length), most nearly approximates the conditions present in the cold-flow experiment discussed in this report. Therefore, the equation developed by Kays for these conditions is used for laminar-flow heat transfer in the analyses presented herein:

$$Nu_{b,l} = 4.36 + \frac{0.036 \left(\frac{Pe_b}{\frac{L}{D}} \right)}{1 + 0.0011 \left(\frac{Pe_b}{\frac{L}{D}} \right)} \quad (2)$$

Pressure Drop

The pressure drop across a test specimen is usually calculated in three parts: (1) entrance losses, (2) friction and momentum losses within the tube, and (3) exit losses. The entrance losses can be calculated from the following equation by the proper selection of the inlet loss coefficient K_L :

$$\Delta P_{in} = \frac{K_L G^2}{2 g \rho_{in}} \left(\frac{D}{D_o} \right)^4 \quad (B5)$$

[REDACTED]

If no orificing is used, as is the case in the experiment described herein, the tube inside diameter D and the orifice diameter D_o are the same, and a standard head loss coefficient of 0.5 may be used (ref. 9).

The nozzle chamber pressure may be obtained by subtracting from the total pressure at the coolant passage exit, the term

$$\frac{(1 - \alpha)^2 G^2}{2g\rho}$$

The pressure drop within the coolant passages is a combination of both momentum and friction pressure drop:

$$\Delta P = \Delta P_{fr} + \Delta P_{mom} \quad (B6)$$

The momentum pressure drop is calculated from equation (3). In the analyses presented, the coolant passage is divided into many incremental lengths; thus, the calculated outlet pressure from the first station becomes the inlet pressure to the second, etc.

The friction pressure drop is by far the most difficult to calculate accurately. Moynihan (ref. 10) shows that friction factor and, hence, pressure drop are strongly dependent on the orientation of the flow system. In isothermal, incompressible, turbulent flow, the Fanning friction factor for smooth pipes is well correlated by the Karman-Nikuradse equation:

$$\frac{1}{\sqrt{f}} = 4 \log(\text{Re} \sqrt{f}) - 0.4 \quad (B7)$$

Experimenters using horizontal test sections have calculated friction factors and have plotted these friction factors as a function of bulk Reynolds number. Their data fell below the Karman-Nikuradse line (eq. (B7)). However, for vertical upflow in the heat-transfer section, average experimental friction factors lie on or above this line. No pressure-drop data appear to be available for the case of downflow in the heat-transfer section.

Since the nuclear-rocket-simulator experiment was run in a downfiring attitude, the flow of gas through the core presented the condition of downflow. Further, since the flow in this case is nonisothermal and compressible, the Karman-Nikuradse relation is not applicable. It was decided to predict friction pressure drop from equation (4) where the friction factor as a function of Reynolds number is obtained from a Moody diagram (ref. 11) for various relative roughness values.

A fuel element from the group that was used to make up the core studied in this report was split, and surface roughness measurements were made. Two samples were taken with similar results; results of one of these measurements are shown in figure 20. The actual surface profile is shown at the top, while the variation in arithmetical average roughness is shown at the bottom. The variation in arithmetical average roughness is seen to be approximately 60 micro-inches, and the rms average roughness is obtained by increasing the arithmetical

[REDACTED]

average roughness by about 11 percent. Thus, the rms average roughness is approximately 66 microinches.

The relative roughness of the passage is then calculated by dividing the rms average roughness by the passage diameter:

$$\frac{\epsilon}{D} = \frac{0.000066}{0.153} = 0.00043$$

A Moody diagram (ref. 11) presents curves of friction factor as a function of Reynolds number for various relative roughness values. The following equation fits the curve presented on the Moody diagram for a relative roughness of 0.0004 and was used in CAC in the calculation of friction pressure drop

$$4f = 0.1552 - 0.04412 Y + 0.005318 Y^2 - 0.0002881 Y^3 + 0.000005903 Y^4 \quad (5)$$

where

$$Y = \ln(\text{Re}_b \times 10^{-6}) + 10$$

For laminar isothermal flow, the friction factor is independent of roughness and may be calculated from (ref. 12):

$$4f = \frac{64}{\text{Re}_b} \quad (6)$$

Knudsen and Katz (ref. 13) point out that a finite length is required for the local friction factor to equal the fully developed friction factor. Since this length is approximately 6 tube diameters and is only about one-half the first incremental length considered in this study, this effect is neglected.

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APPENDIX C

CORE ANALYTICAL CODE (CAC)

An analytical heat-transfer and fluid-flow program has been written to predict temperatures and pressures throughout an internally heated core with axial circular coolant passages. The program accepts a general core geometry and includes multipassage (orificing) effects and nonuniform power generation. The program is written in FORTRAN IV to be accepted by an IBM 7094 computer and is used with a hydrogen-properties subroutine and a linear-interpolation subprogram (DATA FUNCTION). Listings of the CAC program (p. 37) and the DATA FUNCTION subprogram (p. 47) are presented. A description and listing of the hydrogen-properties subroutine are presented in reference 14.

Input Data

The input data format for the CAC program and the DATA FUNCTION subprogram are presented (p. 49). A description of each of the FORTRAN names follows:

TOTAL	number of axial increments
D	inside diameter of coolant passages, in.
DELTA	length of axial increment, in.
COD	core outside diameter, in.
ALPHA	void fraction (flow cross-sectional area divided by total core cross-sectional area)
DELTAU	time increment, sec
FINAL	final time, sec
RUNNUM	run number
CONV	convergence tolerance for hydrogen-properties subroutine (usually 0.000001)
TAUIN	starting time, sec
TOT	number of radial groups (see fig. 21)
ETRMAL	maximum number of iterations for pressure-drop loop, heat-flux loop, and pressure-balancing loop (usually 15)
TOLER	convergence tolerance for pressure-drop loop, heat-flux loop, and pressure-balancing loop (usually 0.001)
RHO	density of core material, lb/cu in.

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TØSS (0) program uses a single-tube model to calculate wall temperatures
 (1) program stops to allow a TØSS calculation of wall temperatures (see section Transient-wall-temperature calculation)

V trial value of specific volume of hydrogen for hydrogen-properties subroutine (usually 3.0)

VFILM trial value of film specific volume of hydrogen for hydrogen-properties subroutine (usually 3.0)

TS trial value of gas temperature for hydrogen-properties subroutine (usually 300 for cooldown studies)

TAUPR time at which output begins listing (usually same as TAUIN), sec

NFLUID trial value for fluid region number for hydrogen-properties subroutine (always 2 for gas runs)

RAD(J) radial position of each group, in.; note: one number must be supplied for each radial group

ORFSIZ(J) orifice size for each group, in.

CAYL(J) head loss coefficient for each radial group

GRO(J) percent of total number of coolant passages in each group

TM(I,J) wall temperatures at time TAUIN for each axial increment and each group, °R; several cards may be required for these temperatures

ATURB }
 BTURB }
 CTURB }

turbulent heat-transfer-correlation coefficients: As discussed in appendix B, the Miller-Taylor correlation, equation (1), was used for this study. To use this correlation, the user of CAC must supply ATURB equal to 0.021, BTURB and CTURB equal to zero. A more general correlation may be used, however,

$$Nu_b = A Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_w}{T_b} \right)^B \left(\frac{L}{D} \right)^C \quad (C1)$$

The user must supply the constants A, B, and C in ATURB, BTURB, and CTURB, respectively.

M number of curves that follow (always 8)

K1 number of data points in curve K2

K2 identification number for curve

In the formats (p. 49), X represents a decimal digit and specifies the type of information in each field. Notice that in the fields that show a decimal point, a decimal point must be included somewhere in that field. In the fields that do not have a decimal point shown, however, a decimal point must not be used and these numbers must be right-oriented in their field.

Hydrogen-Properties Subroutine

The hydrogen-properties subroutine STATE(J) is coded in FORTRAN language and permits calculation of fluid-state relations, thermodynamic properties, and transport properties of molecular hydrogen in any fixed ortho-para combination. The subroutine covers the temperature range from melting to dissociation for pressures up to 340 atmospheres (~5000 psia).

Properties are obtained by combinations of analytical and empirical formulations with tabulations of published data. Any two state variables may be used as independent variables as follows:

Call letter	Independent variables
-3	Enthalpy, pressure
-1	Enthalpy, specific volume
1	Specific volume, temperature
2	Specific volume, pressure
3,4	Temperature, pressure

Iterative solutions are used in calculating variables normally specified as independent variables. Thus, trial values must be supplied for the dependent variables. Results are independent of the trial values, however, since only single-valued continuous formulations are used.

DATA FUNCTION Subprogram

The FUNCTION subprogram called DATA is set up to read and store several columns of data. Further, when the proper call is made by the calling program, the DATA FUNCTION subprogram will return to the calling program the dependent variable resulting from the independent variable and curve number specified in the call. For example, the call

FLOWIN = DATA(TAU,1)

causes the DATA FUNCTION subprogram to go to curve 1 (second argument) and find

[REDACTED]

(or calculate by linear interpolation, if necessary), the dependent variable corresponding to the independent variable TAU (first argument). On return to the calling program, FLOWIN contains the value of the dependent variable desired.

As used with the CAC program, the data for the DATA FUNCTION subprogram are set up as follows (see input format):

Curve	Independent variable	Dependent variable
1	Time	Total flow rate
2	Time	Inlet pressure
3	Time	Inlet temperature
4	Time	Maximum heat-generation rate
5	Temperature	Core-material specific heat
6	Temperature	Core-material thermal conductivity
7	Axial position	Axial power factor
8	Radial position	Radial power factor

Curves 1 to 4 (core flow rate, inlet pressure, inlet temperature, and heat-generation rate) contain the experimental inlet conditions. Curves 5 and 6 supply the material properties of the core, and curves 7 and 8 provide the axial and radial heating profiles. (These profiles can be obtained from nuclear heating studies.)

It should be noted that since DATA FUNCTION uses a linear interpolation routine to calculate values between the data points, accuracy generally will improve as the number of data points increases.

Computational Technique

In order to contain this program in the 7094 core storage area, the following assumptions had to be made:

- (1) Each radial group (see fig. 21) is thermally isolated.
- (2) Within each group, all orifices are the same diameter (the same head loss coefficient applies to each passage within a group).
- (3) The heat-generation rate does not vary radially within a group.

With these assumptions, a single-tube model can be chosen for analysis from each group.

Single-tube-model outside diameter. - As discussed previously, the nuclear-

reactor concept under consideration has circular coolant passages parallel to the longitudinal axis of the reactor. The single-tube model is determined by the following analysis. The total core flow cross-sectional area is obtained from

$$\text{Flow area} = \alpha \frac{\pi}{4} D_{\text{core}}^2$$

and the flow cross-sectional area for a single-coolant passage is

$$\text{Area for one hole} = \frac{\pi}{4} D^2$$

Then the number of coolant passages is

$$\text{Number of holes} = \text{Flow area} / \text{Area for one hole}$$

Now the core material cross-sectional area can be obtained from the relation

$$\text{Core material area} = (1 - \alpha) \frac{\pi}{4} D_{\text{core}}^2$$

and the material cross-sectional area per passage is

$$\frac{\text{Material area}}{\text{Hole}} = \frac{\text{Core material area}}{\text{Number of holes}}$$

Finally, the single-tube-model outside diameter is

$$OD = \sqrt{\frac{4}{\pi} \frac{\text{Material area}}{\text{Hole}} + D^2} \quad (C2)$$

This approximation requires that the single-tube cross-sectional area times the total number of holes be equal to the reactor cross-sectional area.

A detailed flow diagram of CAC is shown in figure 22. As the present discussion of CAC progresses, the reader may find it helpful to follow the development of the program in the flow diagram.

Inlet conditions. - For time τ_1 CAC obtains the total weight flow rate through the core $\dot{w}_{\text{in}}$, the core-inlet pressure P_{in} , the core-inlet temperature T_{in} , and the maximum heat-generation rate GEN_{max} , from curves 1, 2, 3, and 4, respectively, of the DATA FUNCTION subprogram. Then, for the first iteration of the pressure-balancing loop, the flow rate is assumed to be the same in each passage in the core. Thus,

$$\dot{w} = \dot{w}_{\text{in}} / \text{Number of flow passages}$$

The hydrogen density is obtained from the hydrogen-properties subroutine, and

the program is ready to begin analyzing each group separately. The pressure on the downstream side of the orifice on the first passage is obtained from

$$P_{1,j} = P_{in} - \frac{(K_L)_j (G_j)^2}{2g\rho_{in}} \left(\frac{D}{D_o}\right)^4 \quad (C3)$$

This pressure and the core-inlet temperature define the state of the fluid at the inlet to the first axial station.

Trial value for heat flux. - The determination of heat flux over an axial station must be an iterative procedure since it is a function of the average bulk fluid temperature in the increment, which in turn is a function of heat flux. Thus, for the first iteration in the heat-flux loop

$$Q = h_{tr} \pi D (\Delta L) (T_w - T_{b,1}) \quad (C4)$$

where h_{tr} is calculated based on the fluid properties of the inlet.

Pressure-drop loop. - The pressure drop across each station is also an iterative procedure since pressure drop is a function of outlet density, which in turn is a function of outlet pressure. The fluid enthalpy at the station inlet is obtained from the hydrogen-properties subroutine with temperature and pressure used at the independent variables. The fluid enthalpy at the station outlet is approximated by using the trial value of heat flux and a simplified form of the energy equation:

$$H_{out} = H_1 + \frac{Q}{\dot{w}} \quad (C5)$$

Also, the outlet pressure is assumed equal to the station inlet pressure on the first iteration. The hydrogen-properties subroutine is called with enthalpy and pressure as the independent variables. Thus, the station-outlet fluid properties are defined, and the pressure drop across the station can be calculated.

The average temperature, average pressure, and average Reynolds number are obtained, and the friction factor is calculated from equation (3) or (4), depending on the Reynolds number.

The calculated pressure drop is then obtained from equations (3) and (4), and the calculated outlet pressure is then determined from

$$P_{out} = P_1 - \Delta P$$

A comparison is made at this point to see if the calculated outlet pressure is equal to the trial value of outlet pressure used. If not, the calculated outlet pressure becomes the trial value, and the loop is repeated until convergence occurs.

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Heat-flux loop. - The outlet pressure and the trial value of outlet enthalpy have been obtained and define the fluid temperature at the station outlet. Thus, average bulk fluid temperature and average station pressure can be determined, from which a bulk Reynolds number can be calculated. If the flow is laminar ($Re < 2300$) a convective heat-transfer coefficient is determined from equation (2).

For turbulent flow, the convective heat-transfer coefficient is obtained from equation (C1) or the Miller-Taylor equation (eq. (1)). The station heat flux is determined from

$$Q = h\pi D \Delta L(T_w - T_{b,av}) \quad (C6)$$

A check is made at this point to be sure that the Mach number in the passage is less than 1:

$$M = \frac{2G}{(\rho_{in} + \rho_{out}) \sqrt{\gamma g R T_{b,av}}} \quad (C7)$$

The new value of heat flux is compared with the trial value used. If these two values are not the same, the calculated value is used as a new trial value, and the loop is repeated until convergence results. Notice that the pressure-drop loop lies inside the heat-flux loop and must be satisfied on each heat-flux iteration.

Maximum material temperature. - In calculating the maximum material temperature, the assumption is made that the convective heat transfer across the fluid film is the controlling heat-transfer mechanism. Therefore, a steady-state conduction calculation of material temperature as a function of radius should yield results sufficiently accurate for a qualitative estimate of the temperatures present within the fuel element. The basic equation (ref. 13) is

$$\frac{d}{dr} \left(r \frac{dT}{dr} \right) = - \frac{\dot{q}}{k} r$$

Integrating yields

$$r \frac{dT}{dr} = - \frac{\dot{q} r^2}{2k} + C_1$$

but

$$\frac{dT}{dr} = 0 \quad \text{at } r = r_{max}$$

$$C_1 = \frac{\dot{q} r_{max}^2}{2k}$$

Then,

$$dT = \left(-\frac{\dot{q}r}{2k} + \frac{\dot{q}r_{\max}^2}{2kr} \right) dr$$

Integrating again gives

$$T = -\frac{\dot{q}r^2}{4k} + \frac{\dot{q}r_{\max}^2}{2k} \ln r + C_2$$

but

$$T = T_{m,\max} \quad \text{at} \quad r = r_{\max}$$

Thus,

$$C_2 = T_{m,\max} + \frac{\dot{q}r_{\max}^2}{4k} - \frac{\dot{q}r_{\max}^2}{2k} \ln r_{\max}$$

At the coolant wall, $r = r_w$ and $T = T_w$,

$$T_w = -\frac{\dot{q}r_w^2}{4k} + \frac{\dot{q}r_{\max}^2}{2k} \ln \left(\frac{r_w}{r_{\max}} \right) + \frac{\dot{q}r_{\max}^2}{4k} + T_{m,\max}$$

Rearranging in terms of diameters, $OD = 2r_{\max}$, $D = 2r_w$

$$T_{m,\max} = T_w + \frac{\dot{q}}{16k} \left[OD^2 \ln \left(\frac{OD}{D} \right)^2 - (OD^2 - D^2) \right] \quad (C8)$$

Notice that $\dot{q}$ represents the heat transferred to the hydrogen for the single-tube model per unit volume and unit time. As a result of the assumptions made, this analysis is at best an approximation of the transient conditions present at startup or cooldown of a power run or a cooldown (no internal heat generation) study.

Outlet conditions. - The preceding analyses are applied to each axial increment; the outlet fluid properties of increment I become the inlet fluid properties of increment I + 1. The entire analysis is then repeated for each passage.

Next, the total pressure at the exit of each passage is calculated,

$$P_{T,j} = P_{out} \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma}{\gamma - 1}} \quad (C9)$$

from which a nozzle chamber pressure is calculated for each passage

$$P_{ch,j} = P_{T,j} - \frac{(1 - \alpha)^2 G_j^2}{2g\rho_j} \quad (C10)$$

A pressure drop from core inlet to nozzle chamber is calculated for each passage

$$\Delta P_j = P_{in} - P_{out}$$

and these pressure drops should be the same (the core pressure drop is fixed) for each passage. If they are not, the flow rates through each passage must be adjusted until this condition is satisfied.

Pressure balancing. - With the coolant passage diameter constant throughout the core, the flow rates are assumed the same in each passage for the first iteration. This is usually not the case, however, and adjusting the flow rates in the various passages is usually required.

In adjusting the flow rates on the second iteration, the momentum pressure drop is neglected for simplicity. The friction pressure drop is approximately proportional to the weight flow rate squared; that is

$$\left. \begin{aligned} \Delta P &\sim \dot{w}^2 \\ \dot{w} &= K\sqrt{\Delta P} \end{aligned} \right\} \quad (C11)$$

or

Therefore, for the second flow-balancing iteration

$$\left. \begin{aligned} \frac{\dot{w}_\beta}{\dot{w}_\alpha} &= \frac{\sqrt{\Delta P_\beta}}{\sqrt{\Delta P_\alpha}} \\ \dot{w}_\beta &= \dot{w}_\alpha \sqrt{\frac{\Delta P_\beta}{\Delta P_\alpha}} \end{aligned} \right\} \quad (C12)$$

or

But ΔP_β must be the same for all passages, so a mean pressure drop must be calculated from the ΔP 's obtained on the first iteration. At the same time, the total flow rate through the core remains the same:

$$\dot{w}_{in} = \sum_{j=1}^J \dot{w}_j$$

It therefore follows that

$$\frac{\dot{w}_{in}}{\sqrt{\Delta P_{\beta,av}}} = \sum_{j=1}^J \frac{(\dot{w}_{\alpha})_j}{(\sqrt{\Delta P_{\alpha}})_j} \quad (C13)$$

and the desired mean pressure drop can be calculated from:

$$\Delta P_{\beta,av} = \left[\frac{\dot{w}_{in}}{\sum_{j=1}^J \left(\frac{\dot{w}_{\alpha}}{\sqrt{\Delta P_{\alpha}}} \right)_j} \right]^2 \quad (C14)$$

Now, the weight flow rate in each passage can be calculated from equation (C12). Another analysis is performed on each passage by using the corrected flow rates, and the resulting pressure drops for each passage are again compared. They are not likely to be equal, however, since the previous adjustment on flow rates was made by neglecting the momentum pressure drop.

Since the heat added to the coolant in a reactor does significantly affect the momentum pressure drop, its effect should now be included. Therefore, it is now assumed that the passage coolant flow rate is proportional to the core pressure drop, not to the 1/2 power as in equation (C11), but to some other power that includes the momentum pressure drop effect:

$$\dot{w} = K(\Delta P)^X \quad (C15)$$

The exponent can be calculated from the results of the first and second passage iteration

$$\left(\frac{\dot{w}_{\beta}}{\dot{w}_{\alpha}} \right)_j = \left(\frac{\Delta P_{\beta}}{\Delta P_{\alpha}} \right)_j^{X_j} \quad (C16)$$

and

$$X_j = \frac{\ln \left(\frac{\dot{w}_{\beta}}{\dot{w}_{\alpha}} \right)_j}{\ln \left(\frac{\Delta P_{\beta}}{\Delta P_{\alpha}} \right)_j} \quad (C17)$$

The average core pressure drop is again calculated as outlined by using equation (C14), and the new weight flow rate is obtained for each passage by using equation (C16) with the new exponent X_j . This iterative procedure is repeated until the pressure drop across each passage is the same. At this point, CAC writes the output listing for time τ ; a sample is presented at the end of this appendix (p. 52).

Transient-wall-temperature calculation. - The operator using CAC is allowed two methods of calculating wall temperatures at time $\tau + \Delta\tau$. The first uses another program, TØSS, to obtain accurate transient results (see ref. 3), and the second uses a single-tube approximate method to calculate new wall temperatures.

TØSS method: The TØSS program solves the heat-transfer equations for the transient temperature distribution of a three-dimensional irregular body by using a first-forward difference method. If the operator of CAC makes the TØSS specification (TØSS = 1 in the input data), CAC will provide a listing of the output data at time τ and will stop. The operator must then set up the TØSS deck with fluid temperatures, heat-transfer coefficients, wall temperatures at time τ , and heat-generation rates, all as a function of axial position (these parameters are provided by the CAC output listing). Geometry data are also required as input to TØSS.

TØSS then calculates the transient temperature distribution from time τ to time $\tau + \Delta\tau$ by using the boundary conditions (fluid temperature and heat-transfer coefficient) supplied. At time $\tau + \Delta\tau$, TØSS stops, and its output listing contains the temperature distribution (including the required wall temperatures) desired. Now, the operator must set up the CAC deck with the new wall temperatures and resubmit the program for the flow analysis at time $\tau + \Delta\tau$.

Since the accuracy of this method improves with a smaller $\Delta\tau$, it is obvious that much time would be required to obtain results for even a few seconds of data. As a result, the single-tube approximate method was developed.

Single tube approximate method: If the operator makes no TØSS specification (TØSS = 0 in the CAC input data), CAC will calculate wall temperatures for time $\tau + \Delta\tau$ as follows: The DATA FUNCTION subprogram is called on for the power factor as a function of axial and radial position. Then the single-tube-model heat-generation rate (Btu/sec) can be obtained for each axial station and each radial passage:

$$Q'_{i,j} = \text{GEN}_{\max}(F_{a,i})(F_{r,j})(V)$$

The rate of heat transfer to the hydrogen $Q_{i,j}$ is subtracted from the heating rate, and the difference multiplied by the time increment:

$$\Delta Q_{i,j} = (Q'_{i,j} - Q_{i,j})\Delta\tau$$

The DATA FUNCTION subprogram is called on again for values of thermal conductivity and specific heat of the core material (as a function of wall temperature) for each axial station in each radial group. Now the net heat conducted to an axial station may be calculated:

$$QC_{i,j} = k_{m,i,j} \frac{\pi}{4} \frac{(OD^2 - D^2)\Delta\tau}{\Delta L} (T_{w,i+1,j} + T_{w,i-1,j} - 2T_{w,i,j}) \quad (C18)$$

At the last axial increment in each passage

$$QC_{fin,j} = k_{m,i,j} \frac{\pi}{4} \frac{(OD^2 - D^2)\Delta\tau}{\Delta L} (T_{w,i-1,j} - T_{w,i,j})$$

The heat conducted to the first station in each passage is assumed to be lost by convection on the inlet end of the passage; thus

$$QC_{i=1,j} = 0$$

Also, to ensure stable results as τ increases, the net heat gained by an axial increment by conduction is assumed to be always negative or zero; positive values of $QC_{i,j}$ are set equal to zero.

Now the change in temperature of each axial station in each radial passage from time τ to $\tau + \Delta\tau$ is calculated

$$\Delta T_{i,j} = \frac{\Delta Q_{i,j} + QC_{i,j}}{V \rho_m C_{p_{m,i,j}}} \quad (C19)$$

and wall temperatures at time $\tau + \Delta\tau$ are obtained by assuming that the rate of change of the wall temperature with time is equal to the rate of change of the mean material temperature with time:

$$T_{w,i,j,\tau+\Delta\tau} = T_{w,i,j,\tau} + \Delta T_{i,j} \quad (C20)$$

Next, time is increased incrementally

$$\tau = \tau + \Delta\tau$$

and the entire analysis is repeated. The analysis is complete when the time reaches τ_{fin} .

The advantage of the single-tube-model calculation of wall temperature is apparent when it is realized that, with the single-tube model method, a run can be calculated in a matter of minutes while the TQSS method could require many hours.

[REDACTED]

Program Listing of CORE ANALYTICAL CODE

C		0001
C		0002
C		0003
C	CAC - CORE ANALYTICAL CODE - AN ANALYTICAL PREDICTION	0004
C	PROGRAM TO STUDY THE HEAT TRANSFER AND FLUID FLOW	0005
C	CHARACTERISTICS OF A CIRCULAR HEATING ELEMENT WITH	0006
C	CIRCULAR COOLANT PASSAGES. HYDROGEN IS USED AS THE	0007
C	WORKING FLUID AND A HYDROGEN PROPERTIES SUBROUTINE	0008
C	MUST BE USED (STATE AND STATE S) WITH THIS PROGRAM	0009
C		0010
C		0011
	DIMENSION SIGMA(10),AMOCK(10)	0012
	1,G(10),GSQ(10),GRO(10),RHOE(10),TE(10),PE(10),PT(10),PCHAM(10),	0013
	2PDAV(15),X(10),CAYL(10),RAD(10),ORFSIZ(10),AA(10),BB(10),PIN(10)	0014
	DIMENSION TWALL(52,10),TM(52,10),FLOW(10,15),PDROP(10,15),	0015
	1QL(52,10),PAVG(52,10),TBAVG(52,10),HCEE(52,10),RE(52,10),	0016
	2RHOBUL(52,10),QT(52,10),QQ(52,10),DQ(52,10),DUCT(52,10),	0017
	3CEEP(52,10),DELTAT(52,10),DT(52,10),QN(52,10),TMAX(52,10)	0018
C		0019
	COMMON /STATE1/STORE(50)/STATE2/UNITS,COMP,CONV/STATE3/CS(215)	0020
	1/STATE4/JUNK(50)	0021
C		0022
C	ASSIGNMENT OF INPUT - OUTPUT DATA STORAGE INTO -STORE-	0023
C	INDIRECT ASSIGNMENTS ARE C(9), CP(10), CV(11), H(12), (DP/DT)V(13)	0024
C		0025
	EQUIVALENCE (N FLUID,STORE(5)), (P,STORE(6)), (TS,STORE(7)),	0026
	1 (V,STORE(8)), (XQ,STORE(14)), (VL,STORE(15)), (VG,STORE(16)),	0027
	2 (HL,STORE(17)), (HG,STORE(18)), (V FILM,STORE(19))	0028
	EQUIVALENCE (T FILM,STORE(26)), (VISCOS,STORE(27)),	0029
	1 (VIS L,STORE(28)), (VIS G,STORE(29)), (THERM K,STORE(30)),	0030
	2 (CP FILM,STORE(31)),(H,STORE(12)),(CV,STORE(11)),(CP,STORE(10)),	0031
	3(C,STORE(9))	0032
C		0033
C		0034
	5 READ (5,12)TOTALL,D,DELTAL,COD,ALPHA,DELTAU,FINAL,RUNNUM	0035
	READ (5,12)CONV,TAUIN,TOT,ETRMAT,TOLER,RHO	0036
	READ (5,12)TOSS,V,VFILM,TS,TAUPR	0037
	READ (5,14)NFLUID	0038
	JTOTAL=TOT	0039
	ITOTAL = TOTALL	0040
	ITOTM1=ITOTAL-1	0041
	READ (5,10)(RAD(J),J=1,JTOTAL)	0042
	READ (5,10)(ORFSIZ(J),J=1,JTOTAL)	0043
	READ (5,10)(CAYL(J),J=1,JTOTAL)	0044

	READ (5,10)(GRO(J),J=1,JTOTAL)	0045
	READ (5,4)((TM(I,J),I=1,ITOTAL),J=1,JTOTAL)	0046
	READ (5,10) ATURB,BTURB,CTURB	0047
C		0048
C		0049
	WRITE (6,300)RUNNUM	0050
	WRITE (6,302)DELTAU	0051
	WRITE (6,303)TAUIN	0052
	WRITE (6,304)FINAL	0053
	WRITE (6,305)DELTAL	0054
	WRITE (6,306)D	0055
	WRITE (6,309)TALL	0056
	WRITE (6,310)COD	0057
	WRITE (6,311)RHO	0058
	WRITE (6,415)ALPHA	0059
	WRITE (6,425)TOT	0060
	WRITE (6,312)TOLER	0061
	WRITE (6,313)ETRMAL	0062
	WRITE (6,428)	0063
	WRITE (6,430)((TM(I,J),I=1,ITOTAL),J=1,JTOTAL)	0064
	WRITE (6,447)	0065
	IF(BTURB.EQ.0.)GO TO 470	0066
	WRITE (6,448)ATURB,BTURB,CTURB	0067
	WRITE (6,449)	0068
	GO TO 471	0069
C		0070
C	MILLER-TAYLOR CORRELATION	0071
C	H=0.021(K/D)(RE**0.8)(PR**0.4)(TWALL/TBULK)** -(0.29+0.0019L/D)	0072
C		0073
470	WRITE(6,472)	0074
472	FORMAT(1HJ,48HTURBULENT - MILLER-TAYLOR CORRELATION-BULK PROP.)	0075
	WRITE(6,451)	0076
451	FORMAT (1HJ,61HH=0.021(K/D)(RE**0.8)(PR**0.4)(TWALL/TBULK)** -(0.29	0077
	1+0.0019L/D) //)	0078
	WRITE (6,449)	0079
C		0080
471	DO 6 J=1,JTOTAL	0081
	DO 6 I=1,ITOTAL	0082
6	TWALL(I,J)=TM(I,J)	0083
	MAXITR = ETRMAL	0084
	PY = 3.1415926	0085
	PYOV4=PY/4.0	0086
	GEE = 32.2	0087
	EJAY=778.	0088
	AKON=2.*GEE*EJAY	0089
	R=767.0	0090
	DSQ = D*D	0091
	CODSQ=COD**2	0092
	FLAR=ALPHA*PYOV4*CODSQ	0093
	AR=PYOV4*DSQ	0094
	ENUM=FLAR/AR	0095
	II=ENUM	0096
	ENUM=II	0097
	IF(ENUM)652,651,652	0098
651	ENUM=1.0	0099
652	DO 11 J=1,JTOTAL	0100
11	GRO (J) = GRO(J)*ENUM	0101
	SAR=(1.0-ALPHA)*PYOV4*CODSQ	0102
	PAR = SAR/ENUM	0103
	OD=SQRT(4.0*PAR/PY+DSQ)	0104
	ODSQ=OD**2	0105
	CAY1 = 576.0/(PY*DSQ)	0106

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CAY3 = PY*D*DELTA
CAY4 = 1.0/CAY3
CAY5 = PY*(ODSQ-DSQ)*DELTA/4.0
W = CAY5*RHO
TAU = TAUIN
AL=CAY5/(DELTA*DELTA)
XOVRD = DELTA / D
EYE=1.
C
C
C INITIALIZE TRIAL VALUES FOR STATE(J)
C
VL=.25
VG=7.0
V IN=V
VL IN=VL
VG IN=VG
VFLM IN =VFILM
NFLU IN=NFLUID
C
UNITS=0.
CALL STATES
C
DUMMY = DATA(1.0,0)
C
C
C BEGIN CALCULATIONS WITH NEW TIME INCREMENT
C
1 FLOWIN = DATA(TAU,1)
475 PEE=DATA(TAU,2)
TIN = DATA(TAU,3)
QGIN = DATA(TAU,4)
N=1
NFINAL=N
DO 3 J=1,JTOTAL
3 FLOW(J,N)=FLOWIN/ENUM
C
C BEGIN CALCULATIONS WITH NEW FLOW-RATES
C
7 DO 9 J=1,JTOTAL
G(J)=CAY1*FLOW(J,N)
9 GSQ(J)=G(J)*G(J)
J=1
P=PEE*144.0
TS = TIN
C
C RE-INITIALIZE TRIAL VALUES FOR STATE(J)
C
V=V IN
VL=VL IN
VG=VG IN
VFILM=VFILM IN
NFLUID=NFLU IN
C
CALL STATE (3)
H1=H/778.0
HIHOLD=H1
DENSIN = 1.0/V
C
C BEGIN PASSAGE CALCULATIONS
C
8 PIN(J)=PEE-((CAYL(J)*GSQ(J))/(288.0*GEE*DENSIN))*(D/DRFSIZ(J))**.4.

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10		0169
I = 1		0170
P1=PIN(J)		0171
T1 = TIN		0172
C		0173
C	RE-INITIALIZE TRIAL VALUES FOR STATE(J)	0174
C		0175
	V=W IN	0176
	VL=VL IN	0177
	VG=VG IN	0178
	VFILM=VFLM IN	0179
	NFLUID=NFLU IN	0180
C		0181
C	BEGIN STATION CALCULATIONS	0182
C		0183
2	TFILM=T1	0184
	P = P1*144.0	0185
	CALL STATE(4)	0186
	DENS1=1./VFILM	0187
	VISCIN = VISCOS	0188
C		0189
C		0190
C	HEAT TRANSFER AND FLOW CALCULATIONS	0191
C		0192
C		0193
1008	DUMY1=(G(J)*D)/(VISCOS*12.)	0194
	TERM1= DUMY1**.8	0195
	DUMY2 = CPFILM*VISCOS/THERMK	0196
	TERM2 = DUMY2**.4	0197
	IF(CTURB)3939,3940,3939	0198
3940	TERM3 = ATURB	0199
	GO TO 203	0200
C	FIRST STATION MAYBE	0201
3939	IF (I-2)201,202,202	0202
201	DUMY4 = ATURB	0203
	GO TO 206	0204
202	DUMY4 = ATURB*(DELTA*(EYE-1.)/D)**(CTURB)	0205
206	DUMY5 = ATURB*(DELTA*EYE/D)**CTURB	0206
	TERM3 =(DUMY4 + DUMY5)/2.	0207
203	ELL=DELTA*0.5*(2.*EYE-1.)	0208
	BTURB1= -(0.29+.0019*ELL/D)	0209
	IF(BTURB.EQ.0.)BTURB=BTURB1	0210
	TERM4=(TWALL(I,J)/T1)**(BTURB)	0211
	TERM = THERMK/(D*12.*778.)	0212
	HC=TERM*TERM1*TERM2*TERM3*TERM4	0213
	Q=HC*CAY3*(TWALL(I,J)-T1)	0214
	IF (Q) 204,204,205	0215
204	Q=1.E-20	0216
205	ITER=0	0217
	KLMN=0	0218
	QOLD=Q	0219
C		0220
C		0221
C	BEGIN Q LOOP ITERATION	0222
C		0223
40	ITER = ITER+1	0224
	Q = (QOLD+Q)/2.	0225
	QOLD = Q	0226
	ITR = 0	0227
	H2=H1+Q/FLOW(J,N)	0228
	P2=P1	0229
C		0230

C	BEGIN PRESSURE LOOP ITERATION	0231
C		0232
45	ITR = ITR+1	0233
	POLD=P2	0234
	P=P2*144.0	0235
	H=H2*778.0	0236
	CALL STATE(-3)	0237
	DENS2=1.0/V	0238
	TFILM=TS	0239
	P=P2*144.	0240
	CALL STATE(4)	0241
	TERM=2.*(G(J)*D)/(12.*(VISCIN+VISCOS))	0242
	IF(TERM-2300.0)46,46,47	0243
C		0244
C		0245
C		0246
C	LAMINAR ISOTHERMAL FRICTION FACTOR	0247
C		0248
C		0249
C		0250
46	F = 16.0/TERM	0251
	GO TO 51	0252
C		0253
C		0254
C	RELATIVE ROUGHNESS = 0.0004	0255
C		0256
47	REVRE = TERM*(1.0E-6)	0257
	REVRE1 = ALOG(REVRE) + 10.	0258
	F =(0.1552 - 0.04412*REVRE1 + 0.005318*(REVRE1)**2. - 0.0002881*	0259
	1*(REVRE1)**3. + 0.000005903*(REVRE1)**4.0)/4.0	0260
C		0261
51	SPVOL1 = 1.0/DENS1	0262
	SPVOL2=1.0/DENS2	0263
	FRICT=F	0264
	TERM1=(GSQ(J)/GEE)*(SPVOL2-SPVOL1)	0265
	DLTPM=TERM1	0266
	DPLUSD = DENS1+DENS2	0267
	TERM2=(4.0*F*DELTAL*GSQ(J))/(D*GEE*DPLUSD)	0268
	DLTPF=TERM2	0269
	DELTAP = TERM1+TERM2	0270
	P2 = P1-DELTAP/144.0	0271
	IF(P2)54,55,55	0272
54	WRITE (6,200)	0273
	WRITE (6,250)P1,P2,TERM1,TERM2,DELTAP,I	0274
	GO TO 5	0275
55	ERROR=ABS(1.0-POLD/P2)	0276
	IF(ERROR-TOLER)50,50,48	0277
48	IF(ITR-MAXITR)45,49,49	0278
49	WRITE (6,100)	0279
	GO TO 5	0280
50	P=P2*144.0	0281
	H=H2*778.0	0282
	CALL STATE(-3)	0283
	T2=TS	0284
1012	TBAVG(I,J)=(T1+T2)/2.0	0285
	IF(TWALL(I,J)-TBAVG(I,J))520,520,521	0286
520	TBAVG(I,J)=TWALL(I,J) - .00001	0287
	T2=(2.0*TBAVG(I,J)) - T1	0288
521	PAVG(I,J)=(P1+P2)/2.0	0289
	P=PAVG(I,J)*144.0	0290
	TFILM=TBAVG(I,J)	0291
	CALL STATE(4)	0292

	REPREV=REAVG	0293
	TERM=(G(J)*D)/(VISCOS*12.)	0294
5432	REAVG=TERM	0295
	IF(TERM-2300.)501,502,502	0296
501	DUMY2=CPFILM*VISCOS/THERMK	0297
	PECLET=TERM*DUMY2	0298
	ELL = 0.5*DELTA*(2.*EYE - 1.)	0299
	CHILVP=4.36+(0.036*PECLET/(ELL/D))/(1.+0.0011*(PECLET/(ELL/D)))	0300
	HC=(THERMK/(D*12.*778.))*CHILVP	0301
C		0302
C		0303
	GO TO 503	0304
502	TERM1=TERM*.8	0305
	DUMY2 = CPFILM*VISCOS/THERMK	0306
	TERM2 = DUMY2*.4	0307
	TERM3=THERMK/(D*12.*778.)	0308
	IF(CTURB)3938,3937,3938	0309
3937	TERM4 = ATURB	0310
	GO TO 507	0311
C	FIRST SECTION MAYBE	0312
3938	IF(I-2)504,505,505	0313
504	DUMY4= ATURB	0314
	GO TO 506	0315
505	XIN=(EYE-1.)*DELTA	0316
	DUMY4=ATURB*(XIN/D)**(CTURB)	0317
506	XOUT=EYE*DELTA	0318
	DUMY5=ATURB*(XOUT/D)**(CTURB)	0319
	TERM4=(DUMY4 + DUMY5)/2.	0320
507	ELL=DELTA*0.5*(2.*EYE-1.)	0321
	BTURB1= -(0.29+.0019*ELL/D)	0322
	IF(BTURB.EQ.0.)BTURB=BTURB1	0323
	TERM5=(TWALL(I,J)/TBAVG(I,J))*(BTURB)	0324
	HC=TERM1*TERM2*TERM3*TERM4*TERM5	0325
503	Q=HC*CAY3*(TWALL(I,J)-TBAVG(I,J))	0326
	GAMMA=CP/CV	0327
	TERM1=SQRT(GAMMA*GEE*R*TBAVG(I,J))	0328
	AMACH=(2.0*G(J))/(DPLUSD*TERM1)	0329
	AMOCK(J) = AMACH	0330
	IF(AMACH-1.0) 57,56,56	0331
56	WRITE (6,350)	0332
	WRITE (6,355)AMACH	0333
	GO TO 5	0334
57	IF (Q) 9177,9177,9178	0335
9177	Q=1.E-20	0336
9178	ERROR = ABS(1.0-QOLD/Q)	0337
	IF(Q.LE.0.0000000499) GO TO 60	0338
	IF(KLMN.GE.1)GO TO 60	0339
	IF (ERROR-TOLER) 60,60,58	0340
58	IF (ITER-MAXITER)40,59,59	0341
59	WRITE (6,120)	0342
	WRITE (6,125)ERROR,Q,TOLER,QOLD,I	0343
	TERM=(REPREV+TERM)/2.	0344
	ITER=1	0345
	KLMN=KLMN+1	0346
	IF(KLMN.GE.2) GO TO 5	0347
	GO TO 5432	0348
C		0349
C		0350
60	RE(I,J)=TERM	0351
	RHOBUL(I,J)=DPLUSD/2.0	0352
	HCEE(I,J)=HC	0353
	QT(I,J)=Q	0354

```

C      QQ(I,J)=Q*CAY4                                0355
C      CALCULATE MAX MATERIAL TEMPERATURE BASED ON STEADY STATE MODEL 0356
C      QDOT = Q/CAY5                                0357
C      DOVRDI=ODSQ/DSQ                                0358
C      DCONST = (ODSQ*(ALOG(DOVRDI)) - (ODSQ-DSQ))/16. 0359
C      DUMB = TWALL(I,J)                              0360
C      DUCT(I,J) = DATA(DUMB,6)                      0361
C      TMAX(I,J) = TWALL(I,J)+QDOT*DCONST/DUCT(I,J)    0362
C      IF (1-ITOTAL)70,75,75                          0363
70  I = I+1                                           0364
    EYE=I                                           0365
    T1 = T2                                           0366
    P1 = P2                                           0367
    H1=H2                                           0368
    GO TO 2                                           0369
C      PASSAGE EXIT CONDITIONS                        0370
C      75 RHOE(J)=DENS2                                0371
C      TE(J)=T2                                        0372
C      PE(J)=P2                                        0373
C      IF(J-JTOTAL) 76,77,77                          0374
76  J=J+1                                           0375
    H1=H1HOLD                                       0376
    GO TO 8                                           0377
77  DO 775 J=1,JTOTAL                               0378
    AKONST=288.0*GEE*RHOE(J)                        0379
    GOVRG1 = GAMMA/(GAMMA-1.)                        0380
    PT(J)=PE(J)*((1.+(GAMMA-1.)/2.)*AMOCK(J)*AMOCK(J))*GOVRG1 0381
    PCHAM(J)=PT(J)-(1.0-ALPHA)**2*GSQ(J)/AKONST      0382
775 PDROP(J,N)=PEE-PCHAM(J)                         0383
776 CONTINUE                                         0384
C      BEGIN FLOW BALANCING LOOP                      0385
C      PMX=0.0                                         0386
C      PMN=1.E20                                       0387
C      DO 777 J=1,JTOTAL                             0388
C      PMX=AMAX1(PDROP(J,N),PMX)                     0389
777 PMN=AMIN1(PDROP(J,N),PMN)                       0390
778 CONTINUE                                         0391
    ERROR=ABS(1.0-PMX/PMN)                           0392
    IF(ERROR-TOLER) 101,101,79                       0393
79  IF(N-MAXITR) 82,81,81                           0394
81  WRITE (6,360)ERROR,PMX,PMN,TOLER                 0395
    GO TO 5                                           0396
82  N=N+1                                           0397
    NFINAL=N                                           0398
    DO 825 J=1,JTOTAL                               0399
825 SIGMA(J)=(GRO(J)*FLOW(J,N-1))/(SQRT(PDROP(J,N-1))) 0400
    SUM=0.0                                           0401
    DO 826 J=1,JTOTAL                               0402
826 SUM=SUM+SIGMA(J)                                0403
    PDAV(N)=(FLOWIN/SUM)**2                          0404
    IF(N-2) 83,83,88                                 0405
83  DO 835 J=1,JTOTAL                               0406
835 X(J)=.5                                           0407
    GO TO 89                                           0408

```

88	DO 885 J=1,JTOTAL	0417
	AA(J)=ALOG(FLOW(J,N-1)/FLOW(J,N-2))	0418
	BB(J)=ALOG(PDROP(J,N-1)/PDROP(J,N-2))	0419
885	X(J)=AA(J)/BB(J)	0420
89	DO 602 J=1,JTOTAL	0421
602	FLOW(J,N)=FLOW(J,N-1)*(PDAV(N)/PDROP(J,N-1))*X(J)	0422
	GO TO 7	0423
C		0424
C	CONVERGED RESULTS AT TIME = TAU	0425
C		0426
101	IF(TAU-TAUPR)93,102,102	0427
102	WRITE (6,325)RUNNUM	0428
	WRITE (6,326)TAU	0429
	WRITE (6,328)PEE	0430
	WRITE (6,329)TIN	0431
	WRITE (6,330)DENSIN	0432
	WRITE (6,331)FLOWIN	0433
	WRITE (6,450)PDROP(1,NFINAL)	0434
	WRITE (6,400)PCHAM(1)	0435
	DO 92 J=1,JTOTAL	0436
	EJ = J	0437
	WRITE (6,332)EJ,ORFSIZ(J)	0438
	WRITE (6,335)	0439
	WRITE(6,336)	0440
	WRITE (6,337)	0441
	WRITE (6,338)	0442
	DO 90 I=1,ITOTAL	0443
90	WRITE (6,340)I,TBAVG(I,J),TMAX(I,J),TWALL(I,J),PAVG(I,J),RHOBL(I,	0444
	1J),QQ(I,J),RE(I,J),HCEE(I,J)	0445
	WRITE (6,345)	0446
	WRITE (6,346)TE(J)	0447
	WRITE (6,347)PE(J)	0448
	WRITE (6,348)RHOE(J)	0449
	WRITE (6,435)CAYL(J)	0450
	WRITE (6,440)RAD(J)	0451
	WRITE (6,445)GRO(J)	0452
	WRITE (6,446)AMOCK(J)	0453
92	WRITE (6,410)FLOW(J,NFINAL)	0454
C		0455
C	(1) TOSS(STOP) OR (0) SINGLE TUBE MODEL CALCULATION OF WALL	0456
C	TEMPERATURE AT TIME TAU + DELTA TAU	0457
C		0458
93	IF(TOSS-1.0) 781,5,5	0459
781	IF(TAU-FINAL) 80,5,5	0460
C		0461
C	SINGLE TUBE MODEL	0462
C		0463
80	DO 85 J=1,JTOTAL	0464
	DO 85 I=1,ITOTAL	0465
	APR = I	0466
	DUM = APR*DELTAL	0467
	EMULT = DATA(DUM,7)	0468
	DUMM = RAD(J)	0469
	EMULTI = DATA(DUMM,8)	0470
	QN(I,J) = QGIN+EMULT*EMULTI*CAY5	0471
85	DQ(I,J) = (QN(I,J)-QT(I,J))*DELTAU	0472
	DO 86 J=1,JTOTAL	0473
	DO 86 I=1,ITOTAL	0474
	DUMB=TM(I,J)	0475
	DUCT(I,J)=DATA(DUMB,6)	0476
86	CEEP(I,J)=DATA(DUMB,5)	0477
	DO 865 J=1,JTOTAL	0478

```

      QL(I,J)=0.0
865  QL(ITOTAL,J)=DUCT(ITOTAL,J)*AL*(TM(ITOTAL-1,J)-TM(ITOTAL,J))*DELTA
      1U
      DO 866 J=1,JTOTAL
      DO 866 I=2,ITOTM1
      QL(I,J)=DUCT(I,J)*AL*(TM(I+1,J)+TM(I-1,J)-2.0*TM(I,J))*DELTAU
      IF(QL(I,J))866,866,8866
8866  QL(I,J)=0.
866  CONTINUE
      DO 87 J=1,JTOTAL
      DO 87 I=1,ITOTAL
      DELTAT(I,J)=(DQ(I,J)+QL(I,J))/(W*CEEP(I,J))
      TM(I,J)=TM(I,J)+DELTAT(I,J)
      IF(TM(I,J)-TBAVG(I,J))871,87,87
871  TM(I,J) = TBAVG(I,J)
      87  TWALL(I,J)=TM(I,J)
      TAU = TAU+DELTAU
      GO TO 1

C
C
C
C
      4  FORMAT(12F6.0)
      10 FORMAT(12F6.4)
      12 FORMAT(8F9.4)
      14 FORMAT(11I)
100  FORMAT(33X,66HMAXIMUM NUMBER OF ITERATIONS WAS REACHED BEFORE PRES
      1SURE CONVERGED)
120  FORMAT(2X,59HMAXIMUM NUMBER OF ITERATIONS WAS REACHED BEFORE Q CON
      1VERGED)
125  FORMAT(2X,          8HERROR = ,F7.5,5X,9HQ USED = ,F10.8,5X,12HTOL
      1ERANCE = ,F7.5,5X,8HOLD Q = ,F10.8,10H STATION = ,I3)
200  FORMAT(2X,22HPRESSURE WENT NEGATIVE)
250  FORMAT(2X,4HP1 = ,F11.3,4HP2 = ,F11.3,7HTERM1 = ,F11.3,7HTERM2 = ,F11.
      13,8HDELTAP = ,F11.3,11H STATION = ,I2)
300  FORMAT(2H1 ,10HRUN NUMBER,F8.0,36X,23HPRINT OUT OF INPUT DATA //)
302  FORMAT(2X,23HTIME INCREMENT (SEC) = ,F6.2)
303  FORMAT(2X,21HINITIAL TIME (SEC) = ,F6.2)
304  FORMAT(2X,44HFINAL TIME IN SECONDS (CALCULATIONS STOP) = ,F7.2)
305  FORMAT(2X,26HLENGTH OF CELL (INCHES) = ,F6.2)
306  FORMAT(2X,27HINSIDE DIAMETER (INCHES) = ,F7.4)
307  FORMAT(2X,28HOUTSIDE DIAMETER (INCHES) = ,F7.4)
308  FORMAT(2X,34HINLET PRESSURE LOSS COEFFICIENT = ,F6.3)
309  FORMAT(2X,33HNUMBER OF STATIONS PER PASSAGE = ,F5.0)
310  FORMAT(2X,15HCORE DIAMETER = ,F9.4)
311  FORMAT(2X,41HDENSITY OF CORE MATERIAL (LB/CU. INCH) = ,F8.5)
312  FORMAT(2X,24HCONVERGENCE TOLERANCE = ,F7.5)
313  FORMAT(2X,47HMAXIMUM NUMBER OF ITERATIONS FOR CONVERGENCE = ,F5.0)
325  FORMAT(2H1 ,10HRUN NUMBER,F8.0,39X,14HPROGRAM OUTPUT //)
326  FORMAT(2X,7HTIME = ,F6.2)
328  FORMAT(2X,16HPRESSURE (IN) = ,F10.3)
329  FORMAT(2X,19HTEMPERATURE (IN) = ,F9.3)
330  FORMAT(2X,15HDENSITY (IN) = ,F10.6)
331  FORMAT(2X,9HFLOWIN = ,F10.6)
332  FORMAT(2HJ ,43X,14HPASSAGE NUMBER,F4.0,5X,19HORIFICE DIAMETER = ,F
      16.4)
335  FORMAT(52X,29H(AVERAGE VALUES IN EACH CELL)//)
336  FORMAT(13X,10HBULK FLUID,3X,12HMAX MATERIAL,6X,4HWALL,20X,4HBULK,
      140X,13HHEAT TRANSFER)
337  FORMAT(2X,7HSTATION,3X,11HTEMPERATURE,3X,11HTEMPERATURE,3X,11HTEMP
      1ERATURE,3X,8HPRESSURE,4X,7HDENSITY,9X,9HHEAT FLUX,7X,8HREYNOLDS,5X
      2,15HCOEF. (BTU/SEC-)

```

338 FORMAT(13X,9H(RANKINE),5X,9H(RANKINE),5X,9H(RANKINE),6X,5H(PSI),4X
 1,10H(LB/CU FT),3X,17H(BTU/SEC-SQ.INCH),6X,3HNO.,5X,19HINCH SQ - DE
 2GREE R)//) 0541
 340 FORMAT(5X,I2,F15.3,F14.3,F14.3,F11.3,F12.5,F18.8,F15.2,F15.6) 0544
 345 FORMAT(2HJ ,54X,23HPASSAGE EXIT CONDITIONS) 0545
 346 FORMAT(54X,14HTEMPERATURE = ,F10.4) 0546
 347 FORMAT(54X,11HPRESSURE = ,F13.4) 0547
 348 FORMAT(54X,10HDENSITY = ,F14.6) 0548
 350 FORMAT(2X,30HMACH NUMBER HAS EXCEEDED UNITY) 0549
 355 FORMAT(2X,14HMACH NUMBER = ,F10.2) 0550
 360 FORMAT (2X,8HERROR = ,E15.8,4X,7HPMAX = ,E15.8,4X,7HPMIN = ,E15.8
 1,4X,8HTOLER = ,E15.8) 0551
 400 FORMAT(2X,25HNOZZLE CHAMBER PRESSURE =,F8.2) 0552
 410 FORMAT(49X,28HFLOW-RATE IN EACH PASSAGE = ,F9.6//) 0553
 415 FORMAT(2X,15HVOID FRACTION =,F7.4) 0554
 420 FORMAT(2X,20HRADIUS OF GYRATION =,F7.4) 0555
 425 FORMAT(2X,27HNUMBER OF PASSAGE GROUPS = ,F5.1) 0556
 428 FORMAT(56X,21HMATERIAL TEMPERATURES) 0557
 430 FORMAT(21F6.0) 0558
 435 FORMAT(2HJ ,44X,33HINLET PRESSURE LOSS COEFFICIENT =,F7.4) 0559
 440 FORMAT(54X,17HRADIAL POSITION = ,F7.2) 0560
 445 FORMAT(46X,33HNUMBER OF PASSAGES WITHIN GROUP =,F7.0) 0561
 446 FORMAT(50X,23HPASSAGE EXIT MACH NO. =, F7.5) 0562
 447 FORMAT(2HJ ,5X, 26HHEAT TRANSFER CORRELATIONS) 0563
 448 FORMAT(2HJ ,15HTURBULENT- H=,F6.4,49H (K/D) * (RE**0.8) * (PR**0
 1.40)* (TWALL/TBULK)**(,F6.3,12H) * (L/D)**(,F6.3,28H) (BU 0564
 2LK PROPERTIES)) 0565
 449 FORMAT (2HJ ,73HLAMINAR- H=(K/D){4.36+ (0.036REPR/(X/D))/ (1+0.0 0566
 1011REPR/(X/D)), (BULK)) 0567
 450 FORMAT(2X,15HPRESSURE DROP =,F11.6) 0568
 END 0569
 0570
 0571

[REDACTED]

Listing of DATA FUNCTION Subprogram

```
C      DATA FUNCTION
C      DATA FUNCTION IS A SUBPROGRAM WHICH READS TWO-
C      DIMENSIONAL DATA INTO CORE STORAGE AND LINEARLY
C      INTERPOLATES OR EXTRAPOLATES FOR DATA POINTS AS
C      THE USER DESIRES.
C
C      FUNCTION DATA (XBAR,L)
C
C      DIMENSION   X(125,8), NUM(8), Y(125,8)
C
101    FORMAT(2I3)
102    FORMAT(12F6.2)
      IF(L)10,10,11
10     READ  (5,101)M
      WRITE  (6,80)M
      DO 12 I=1,M
      READ  (5,101)K1,K2
      NUM(K2)=K1
      READ  (5,102)(X(J,K2),J=1,K1)
      READ  (5,102)(Y(J,K2),J=1,K1)
      IF (M-8)75,75,70
70     WRITE (6,59)
      GO TO 12
75     GO TO (1,2,3,4,5,6,7,8),I
1      WRITE (6,90)K1,K2
      WRITE  (6,51)
      WRITE  (6,60) (X(J,K2),Y(J,K2), J=1,K1)
      GO TO 12
2      WRITE (6,90)K1,K2
      WRITE  (6,52)
      WRITE  (6,60) (X(J,K2),Y(J,K2), J=1,K1)
      GO TO 12
3      WRITE (6,90)K1,K2
      WRITE  (6,53)
      WRITE  (6,60) (X(J,K2),Y(J,K2), J=1,K1)
      GO TO 12
4      WRITE (6,90)K1,K2
      WRITE  (6,54)
      WRITE  (6,60) (X(J,K2),Y(J,K2), J=1,K1)
      GO TO 12
5      WRITE (6,90)K1,K2
      WRITE  (6,55)
      WRITE  (6,60) (X(J,K2),Y(J,K2), J=1,K1)
      GO TO 12
6      WRITE (6,90)K1,K2
      WRITE  (6,56)
      WRITE  (6,60) (X(J,K2),Y(J,K2), J=1,K1)
      GO TO 12
7      WRITE (6,90)K1,K2
      WRITE  (6,57)
      WRITE  (6,60) (X(J,K2),Y(J,K2), J=1,K1)
      GO TO 12
8      WRITE (6,90)K1,K2
      WRITE  (6,58)
      WRITE  (6,60) (X(J,K2),Y(J,K2), J=1,K1)
12     CONTINUE
      DATA=0.0
      GO TO 13
11     N=NUM(L)
      IF(XBAR-X(1,L)) 14,14,15
```

CONFIDENTIAL

```

14      I=1
      GO TO 21
15      IF(X(N,L)-XBAR)17,17,18
17      I=N-1
      GO TO 21
18      I=1
19      IF(XBAR-X(I+1,L))21,21,2
20      I=I+1
      GO TO 19
21      IF(Y(I,L)-Y(I+1,L))22,23,22
22      F=(XBAR-X(I,L))/(X(I+1,L)-X(I,L))
      DATA=Y(I,L)*(1.0-F)+Y(I+1,L)*F
      GO TO 13
23      DATA = Y(I,L)
13      RETURN
C
C
51      FORMAT      (52X,4HTIME,14X,9HFLOW-RATE //)
52      FORMAT      (52X,4HTIME,12X, 14HINLET PRESSURE //)
53      FORMAT      (52X,4HTIME,10X,17HINLET TEMPERATURE //)
54      FORMAT      (52X,4HTIME,12X,13HMAXIMUM POWER //)
55      FORMAT      (48X,11HTEMPERATURE,9X,13HSPECIFIC HEAT //)
56      FORMAT      (48X,11HTEMPERATURE,6X,20HTHERMAL CONDUCTIVITY //)
57      FORMAT      (47X,14HAXIAL POSITION,5X,18HAXIAL POWER FACTOR //)
58      FORMAT      (46X,15HRADIAL POSITION,5X,19HRADIAL POWER FACTOR //)
59      FORMAT(2X,59HNUMBER OF INPUT VECTORS EXCEEDS NUMBER OF WRITE OUT F
10FORMATS //)
60      FORMAT      (49X,F8.2,14X,F11.5)
80      FORMAT(1H1,5X,39HNUMBER OF INPUT VECTORS IN THE ARRAY IS,I3 //)
90      FORMAT      (1HJ,25X,
1      49HNUMBER OF ELEMENTS IN FOLLOWING VECTORS SHOULD BE,I4,2X
2,27HAND THE ASSOCIATED INDEX IS,I4)
      END

```

Core Analytical Code Input Format

Card

1	1	9	10	18	19	27	28	36	37	45	46	54	55	63	64	72	
	TOTALL		D		DELTAL		COD		ALPHA		DELTAU		FINAL		RUNNUM		
	XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX		

2	1	9	10	18	19	27	28	36	37	45	46	54					
	CONV		TAUIN		TOT		ETRMAL		TOLER		RHO						
	XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX						

3	1	9	10	18	19	27	28	36	37	45							
	TSS		V		VFILM		TS		TAUPR								
	XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX		XX.XXXX								

4	1																
	NFLUID																
	X																

5	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	RAD(I)																								
	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX

6	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	ORFSIZ(I)																								
	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX

7	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	CAYL(I)																								
	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX

8	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	GRO(I)																								
	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX	X.XXXX

9	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	TM(I,J)																								
	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X	XXXX.X

10	1	6	7	12	13	18																			
	ATURB		BTURB		CTURB																				
	X.XXXX		X.XXXX		X.XXXX																				

11	1	3																							
	M																								
	8																								

12	1	3	4	6																					
	K1		K2																						
	XX		1																						

Card

13	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	TIME (sec)→				XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX		

14	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72
	FLOW RATE (lb/sec)→																							
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

15	1	3	4	6																					
	K1		K2																						
	XX		2																						

16	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72
	TIME (sec)→				XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

17	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72		
	INLET PRESSURE (psia)→																									
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX			

18	1	3	4	6																					
	K1		K2																						
	XX		3																						

19	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	TIME (sec)→				XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX		

20	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	INLET TEMPERATURE (°R)→								XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX			
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX		

21	1	3	4	6																					
	K1		K2																						
	XX		4																						

22	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	TIME (sec)→				XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX		

23	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	MAXIMUM HEAT GENERATION RATE (Btu/(sec)(in. ³))→																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX		

24	1	3	4	6																					
	K1		K2																						
	XX		5																						

Card

25	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	TEMPERATURE ($^{\circ}$ R) $\rightarrow$																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

26	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	SPECIFIC HEAT OF CORE MATERIAL (Btu/(lb)($^{\circ}$ R)) $\rightarrow$																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

27	1	3	4	6																				
	K1		K2																					
	XX			6																				

28	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	TEMPERATURE ($^{\circ}$ R) $\rightarrow$																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

29	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	THERMAL CONDUCTIVITY OF CORE MATERIAL (Btu/(in.)(sec)($^{\circ}$ R)) $\rightarrow$																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

30	1	3	4	6																				
	K1		K2																					
	XX			7																				

31	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	AXIAL POSITION (in.) $\rightarrow$																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

32	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	AXIAL POWER FACTOR ($P_i/P_{\max}$) $\rightarrow$																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

33	1	3	4	6																				
	K1		K2																					
	XX			8																				

34	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	RADIAL POSITION (in.) $\rightarrow$																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

35	1	6	7	12	13	18	19	24	25	30	31	36	37	42	43	48	49	54	55	60	61	66	67	72	
	RADIAL POWER FACTOR ($P_j/P_{\max}$) $\rightarrow$																								
	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	XXX.XX	

Sample Output

RUN NUMBER 24.

TIME = 6.00
 PRESSURE (IN) = 25.400
 TEMPERATURE (IN) = 468.510
 DENSITY (IN) = 0.010172
 FLOWIN = 7.199998
 PRESSURE DROP = 6.746917
 NOZZLE CHAMBER PRESSURE = 18.65

PASSAGE NUMBER 1. ORIFICE DIAMETER = 0.1530
 (AVERAGE VALUES IN EACH CELL)

STATION	BULK FLUID TEMPERATURE (RANKINE)	MAX MATERIAL TEMPERATURE (RANKINE)	WALL TEMPERATURE (RANKINE)	PRESSJRE (PSIA)	BULK DENSITY (LB/CJ FT)	HEAT FLUX (BTU/SEC-SQ. INCH)	REYNOLDS NO.	HEAT TRANSFER COEF. (BTU/SFC- INCH SQ - DEGREE R)
1	472.100	509.383	508.833	25.041	0.00995	0.02355303	15973.97	0.000641
2	478.849	511.603	511.117	24.826	0.00973	0.02075262	15821.93	0.000643
3	484.783	513.507	513.079	24.607	0.00953	0.01824613	15691.19	0.000645
4	489.991	515.126	514.749	24.384	0.00934	0.01600230	15578.68	0.000646
5	494.549	516.499	516.169	24.159	0.00917	0.01400185	15481.83	0.000648
6	498.531	517.663	517.375	23.930	0.00901	0.01222529	15398.45	0.000649
7	502.003	518.650	518.398	23.698	0.00886	0.01065312	15326.67	0.000650
8	505.025	519.486	519.266	23.462	0.00872	0.00926623	15264.88	0.000651
9	507.650	520.193	520.002	23.224	0.00859	0.00804625	15211.71	0.000652
10	509.927	520.790	520.625	22.982	0.00846	0.00697590	15165.97	0.000653
11	511.899	521.296	521.152	22.737	0.00834	0.00603905	15126.63	0.000654
12	513.605	521.723	521.598	22.489	0.00822	0.00522082	15092.81	0.000655
13	515.079	522.083	521.975	22.237	0.00810	0.00450762	15063.75	0.000656
14	516.350	522.387	522.295	21.982	0.00799	0.00388712	15038.80	0.000657
15	517.446	522.643	522.554	21.723	0.00788	0.00334819	15017.38	0.000658
16	518.390	522.860	522.791	21.461	0.00777	0.00288083	14999.01	0.000659
17	519.201	523.042	522.983	21.195	0.00766	0.00247616	14983.26	0.000660
18	519.898	523.195	523.145	20.925	0.00756	0.00212622	14969.77	0.000661
19	520.497	523.324	523.281	20.650	0.00745	0.00182401	14958.22	0.000662
20	521.010	523.433	523.395	20.372	0.00734	0.00156335	14948.34	0.000663
21	521.450	523.524	523.493	20.088	0.00723	0.00133877	14939.89	0.000664
22	521.827	523.601	523.574	19.799	0.00712	0.00114547	14932.67	0.000665
23	522.149	523.666	523.643	19.505	0.00701	0.00097927	14926.51	0.000666
24	522.425	523.720	523.700	19.205	0.00690	0.00083652	14921.26	0.000667
25	522.660	523.766	523.749	18.900	0.00679	0.00071398	14916.78	0.000668
26	522.861	523.803	523.788	18.588	0.00667	0.00060835	14912.96	0.000669

PASSAGE EXIT CONDITIONS

TEMPERATURE = 522.9534

PRESSURE = 18.4314

DENSITY = 0.006616

INLET PRESSURE LOSS COEFFICIENT = 0.5000

RADIAL POSITION = 0.

NUMBER OF PASSAGES WITHIN GROUP = 8184.

PASSAGE EXIT MACH NO. = 0.24448

FLOW-RATE IN EACH PASSAGE = 0.000880

[REDACTED]

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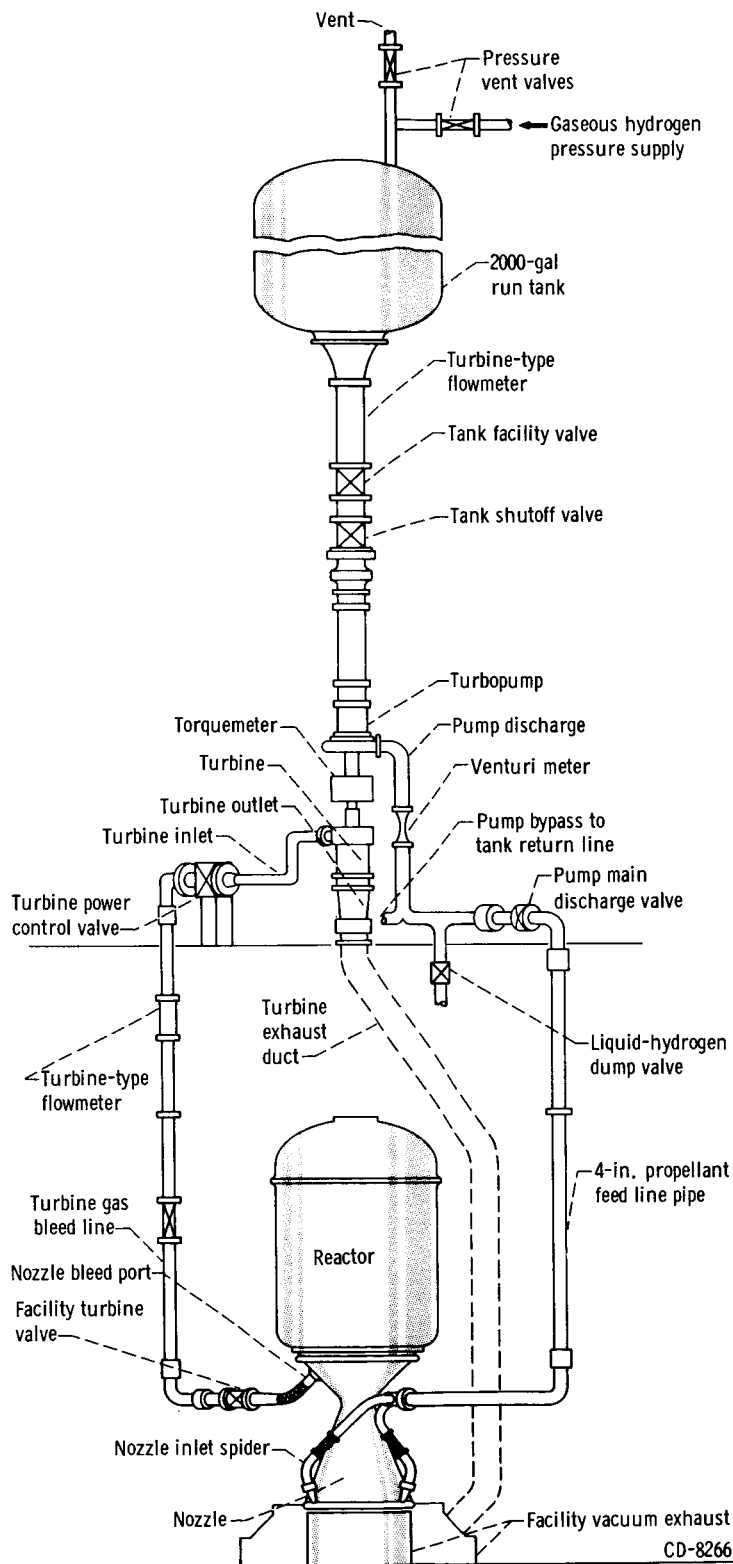


Figure 1. - Schematic drawing of nuclear-rocket cold-flow experiment.

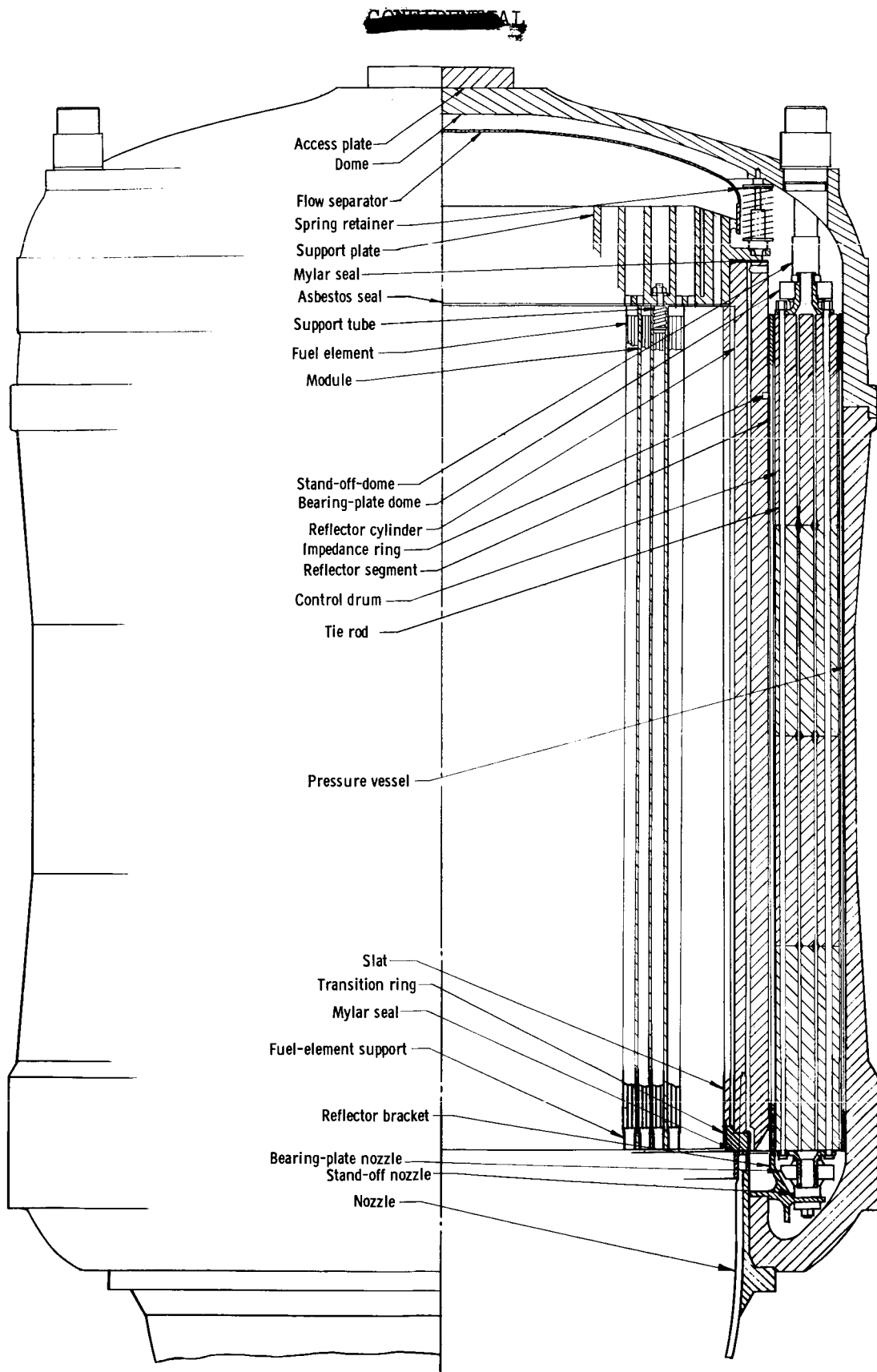
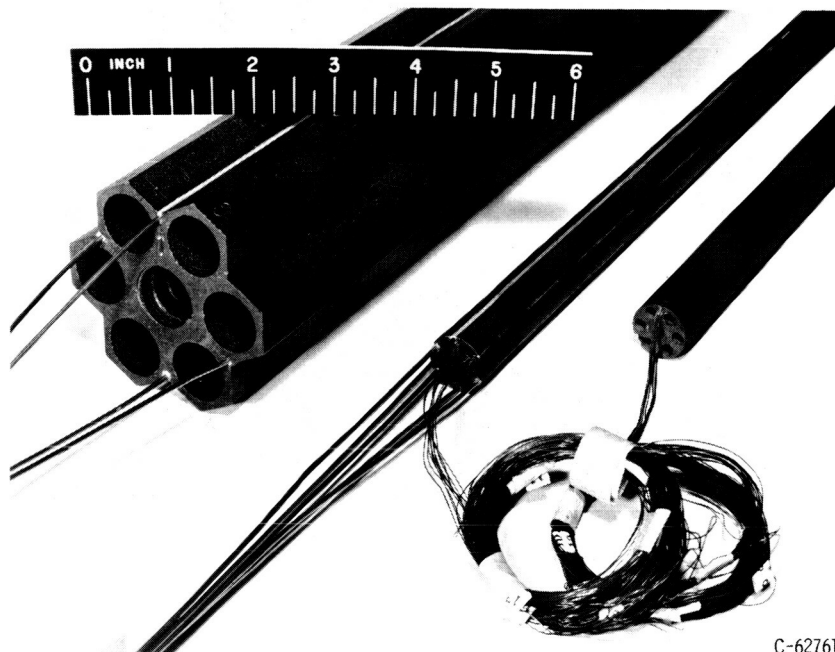
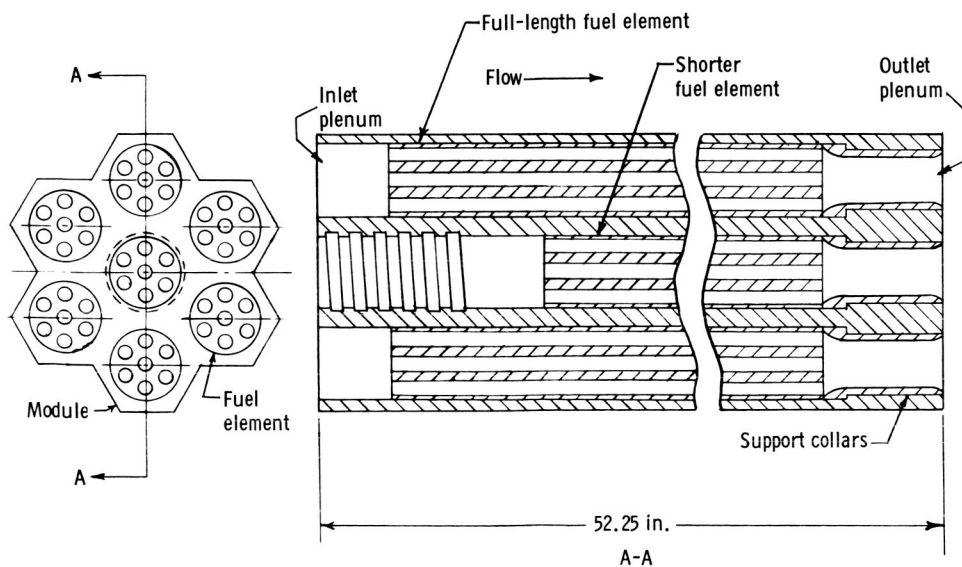


Figure 2. - Schematic drawing of reactor.



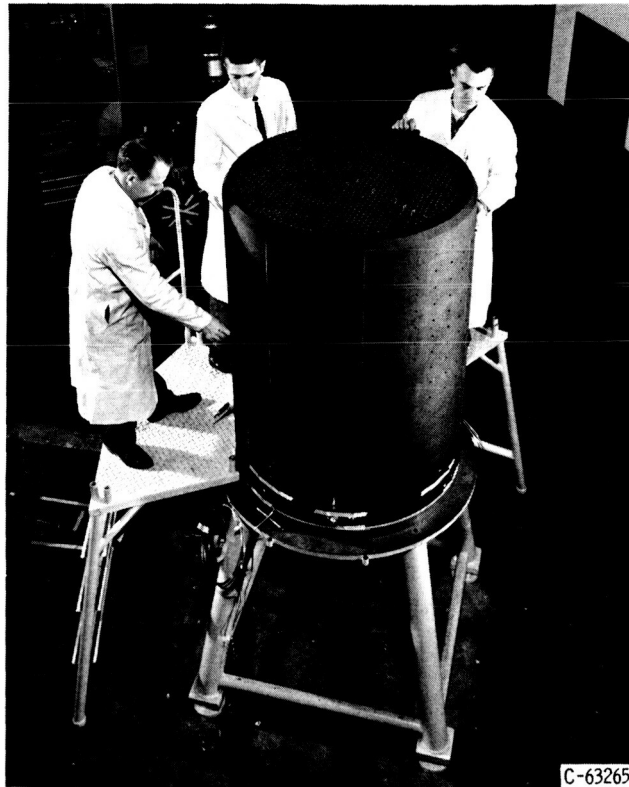
(a) Instrumented fuel elements and module.

C-62761



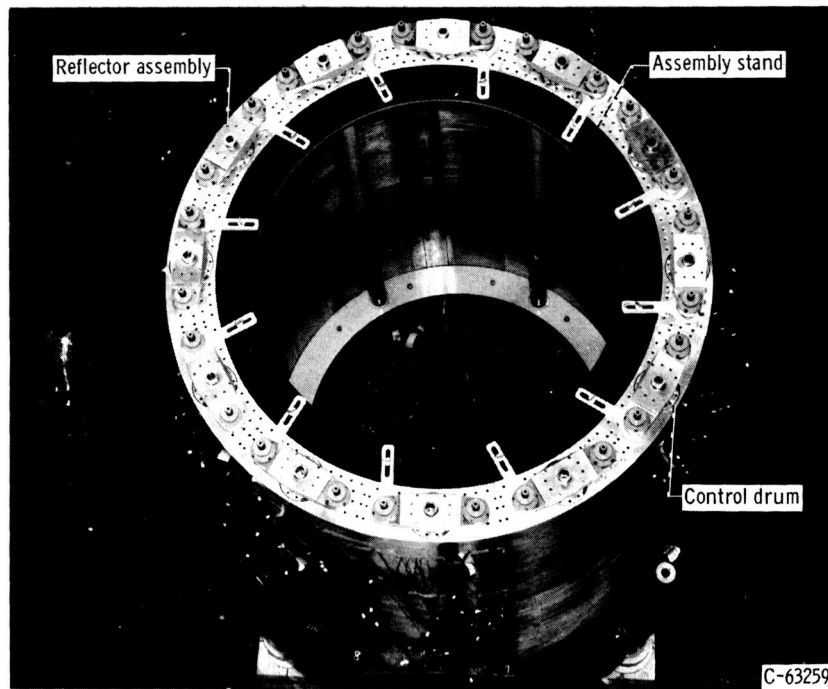
(b) Core regular module assembly.

Figure 3. - Reactor components.



C-63265

(c) Installation of plunger, spring, and plug assembly.



Reflector assembly

Assembly stand

Control drum

C-63259

(d) Outer aluminum reflector in assembly stand.

Figure 3. - Concluded.

CORE INLET			
Item designation	Radius, r, in.	Angular position in core, θ , deg	Distance from top of module, Z, in.
Fluid temperature			
RT-343	5.3	16	-3.12
RT-344	9.7	22	-3.12
RT-345	11.3	18	-3.12
RT-349	17	342	-6.75
RT-350	17	162	-6.75
RT-353	5.5	354	-8.25
RT-354	5.5	174	-8.25
RT-392	17.1	19	-3.12
Pressure			
RP-121	16	180	-10
RP-123	5.38	180	-7.75
FUEL ELEMENT			
Item designation	Radius, r, in.	Angular position in core, θ , deg	Distance from top of module, Z, in.
Material temperature			
RT-1	0.17	75	1.0
RT-2			8.8
RT-3			16.6
RT-4			32.3
RT-5			47.9
RT-15	9.6		49.5
RT-16	12.5		2.6
RT-17			10.4
RT-18			18.2
RT-19			33.9
RT-20			49.5
RT-25	14.4		49.5
RT-26	17.0		2.6
RT-27			10.4
RT-28			18.2
RT-29			33.9
RT-30	0.62		49.5
RT-31			3.1
RT-32			10.9
RT-33			18.7
RT-34			34.4
RT-35			50.
Fluid temperature			
RT-56	1.7	75	52.25
RT-58	8.8		
RT-59	12.9		
RT-60	13.9		
RT-61	17.0		
Pressure			
RP-1	9.5	75	2.6
RP-2			10.4
RP-3			18.2
RP-4			33.9
RP-5			49.5
RP-28	17.3	15	.25
RP-29	17.3	15	51.6
RP-33	13.1	15	.25
RP-38	13.1	15	51.6

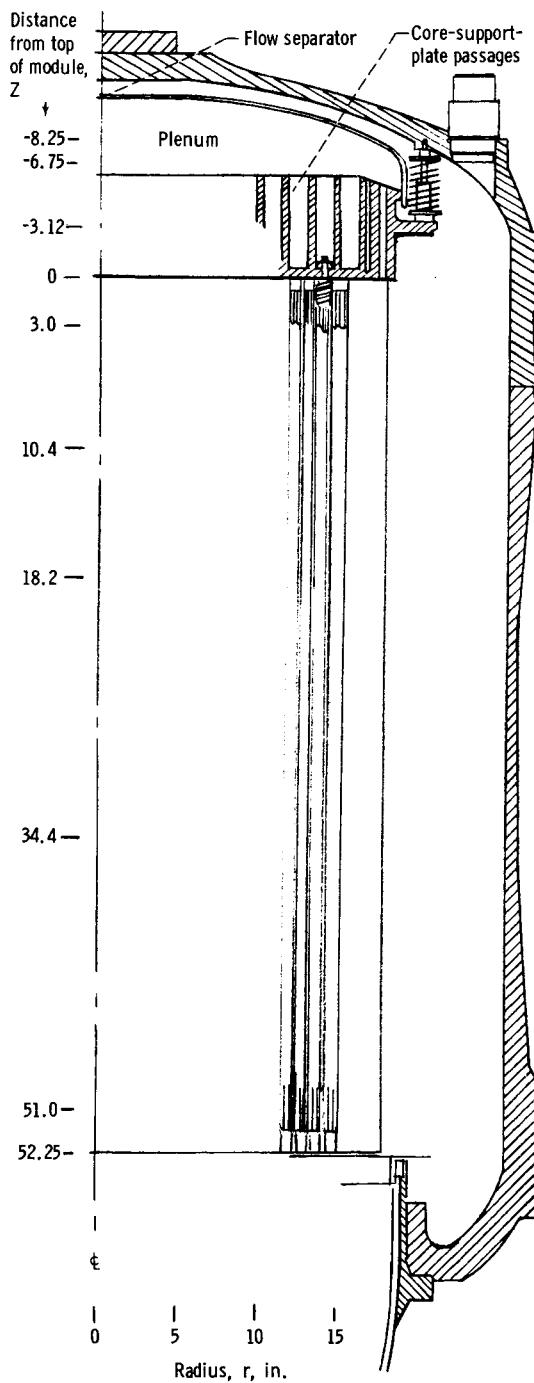


Figure 4. - Core instrumentation locations.

RAKE			
Item designation	Radius, r, in.	Angular position in core, θ , deg	Distance from top of nozzle, x, in.
Fluid temperature			
NT-60	11.5	22	4.0 ↓
NT-61	5.5	22	
NT-62	.5	202	
NT-63	5.5	202	
NT-64	11.5	202	
NOZZLE CHAMBER			
Item designation	Radius, r, in.	Angular position in core, θ , deg	Distance from top of nozzle, x, in.
Fluid temperature			
NT-65	15.5	234	4.0 ↓
NT-66	↓	324	
NT-67		34	
NT-68		142	
Pressure			
NP-20	19.5	234	4.0
NP-50	19.5	140	12.5
NP-51	19.5	320	12.5

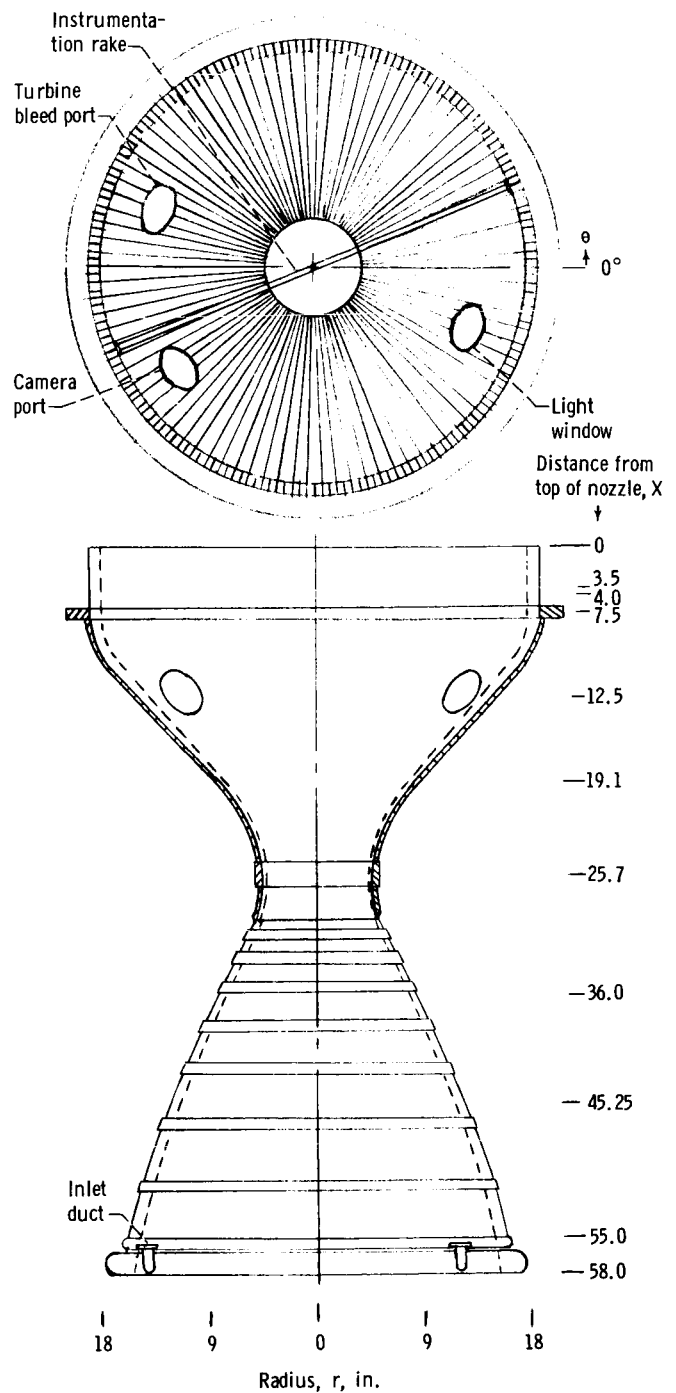
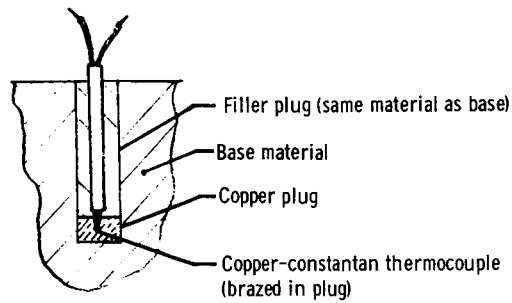
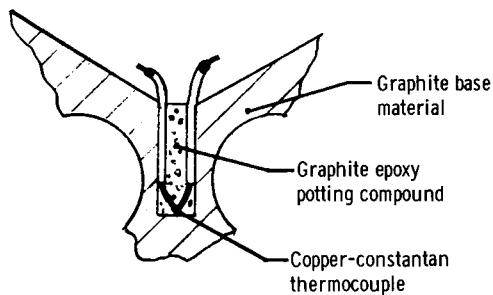


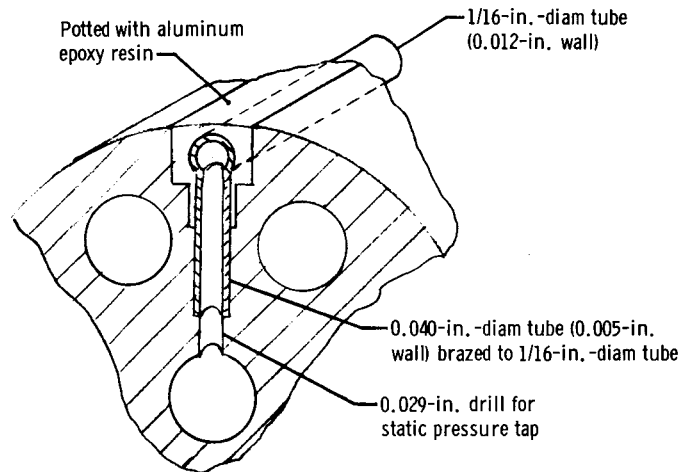
Figure 5. - Nozzle-chamber instrumentation.



(a) Thermocouple installation for material temperature measurements in metal parts.



(b) Thermocouple installation in graphite parts.



(c) Static-pressure-tap installation in reactor components.

Figure 6. - Details of typical pressure and thermocouple installations.

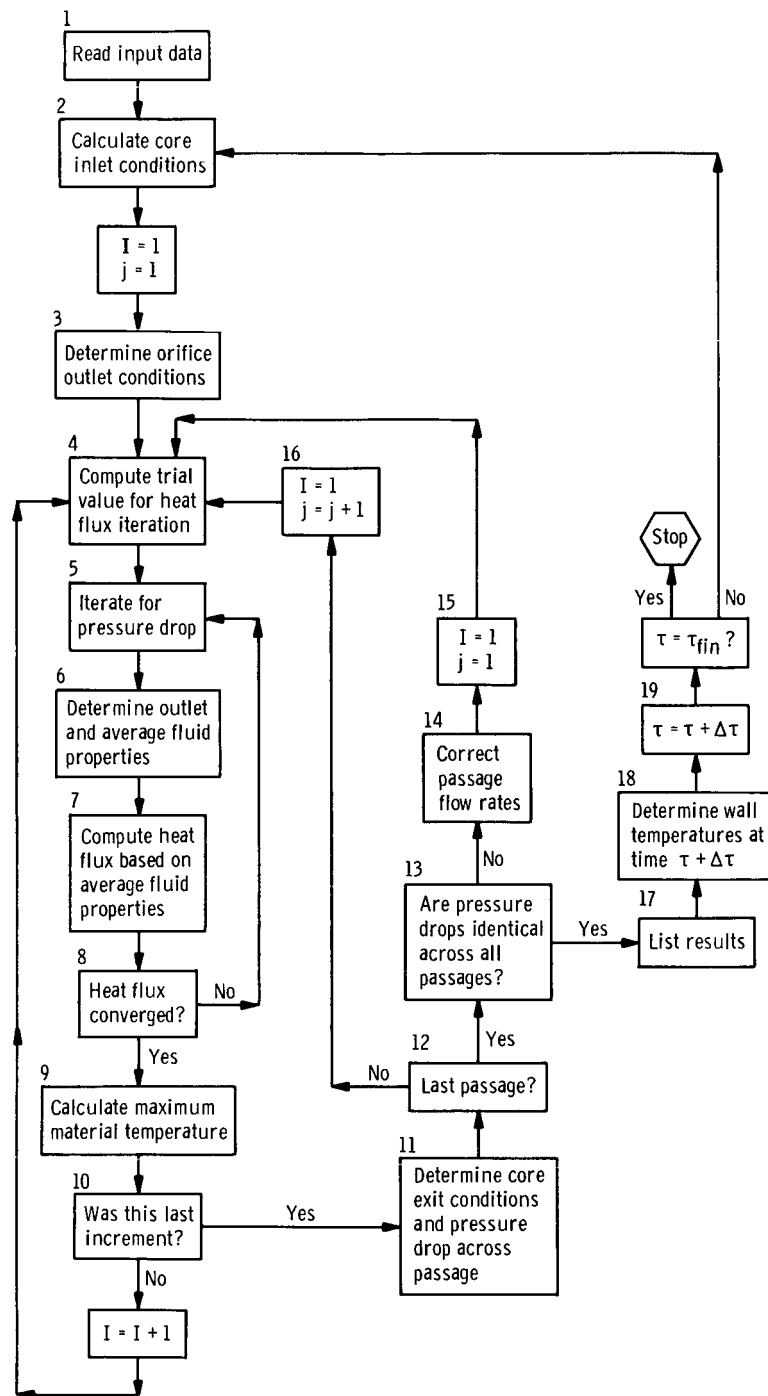


Figure 7. - Simplified flow diagram for Core Analytical Code (CAC).

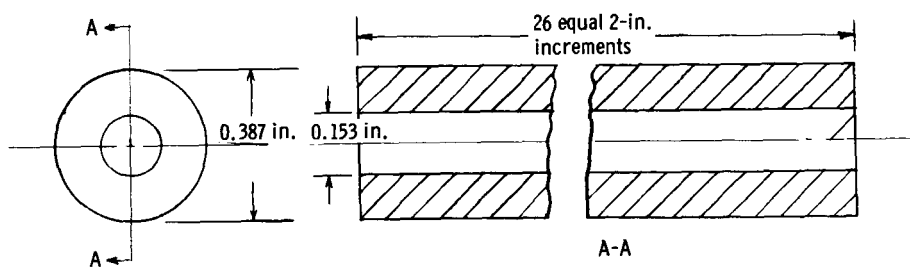
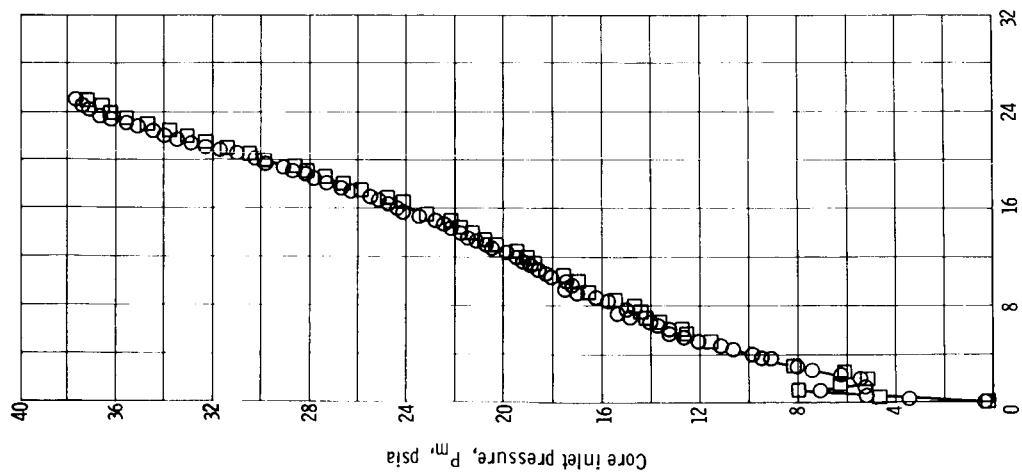
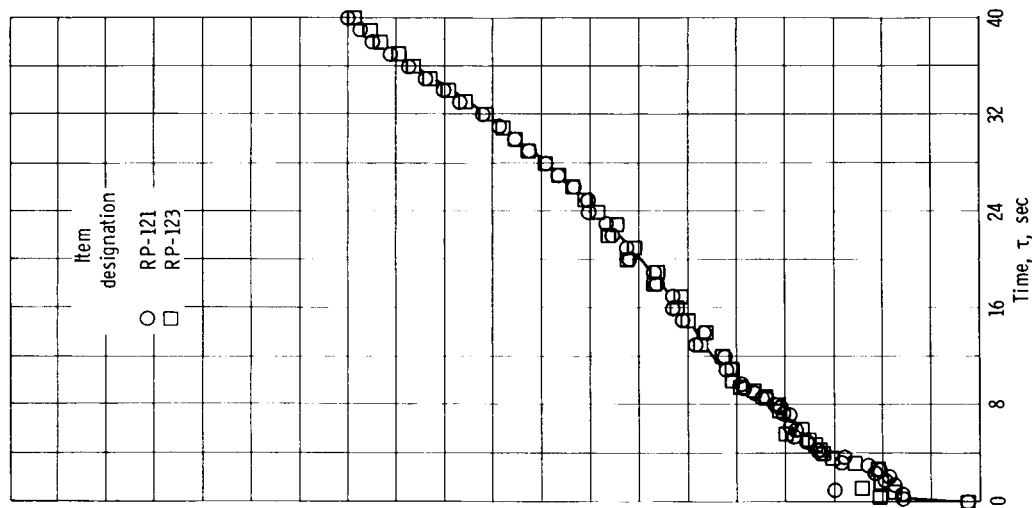


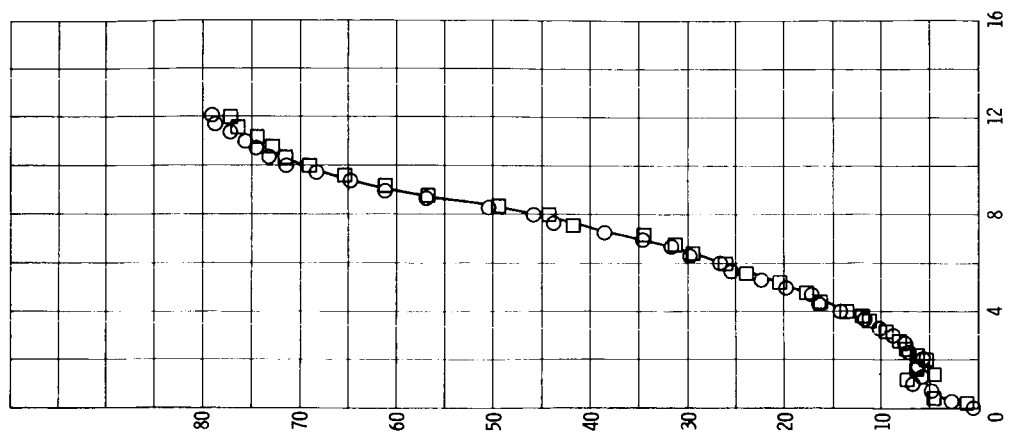
Figure 8. - Single-tube-model geometry.



(a) Run 19.



(b) Run 20.



(c) Run 24.

Figure 9. - Core inlet pressure as function of time.

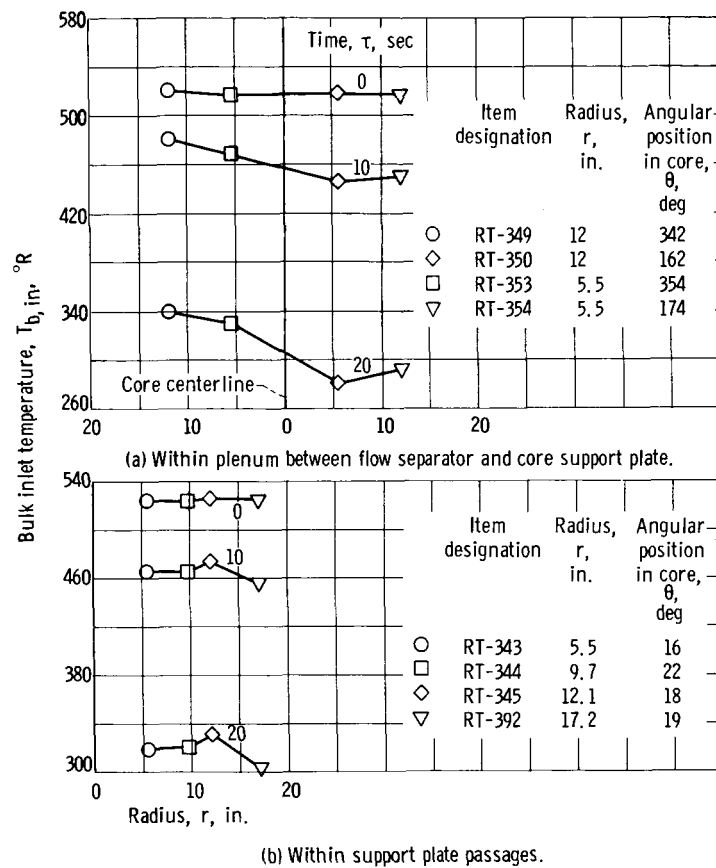
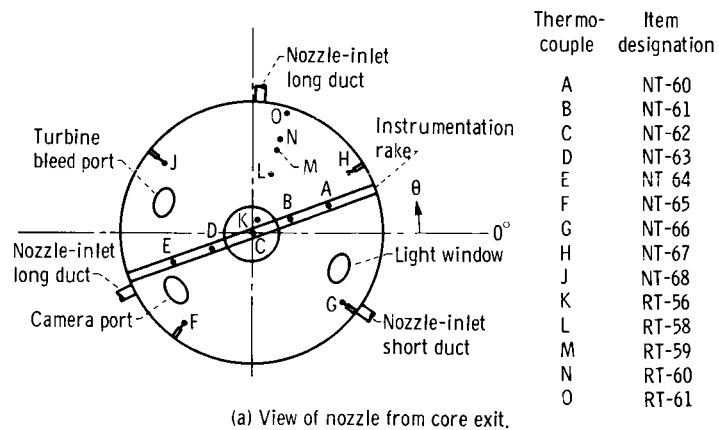
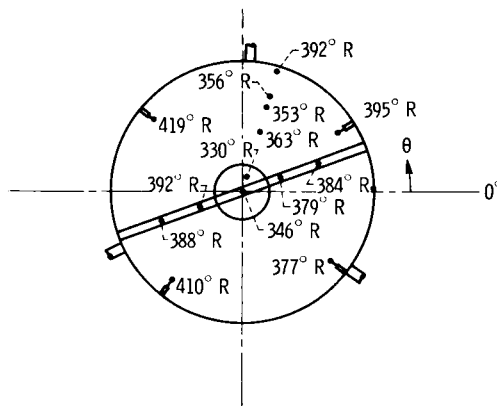


Figure 10. - Core inlet gas radial temperature profiles as function of radius. Run 19.

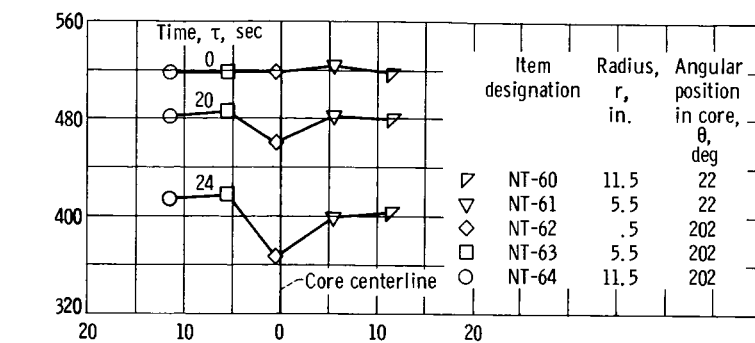


(a) View of nozzle from core exit.

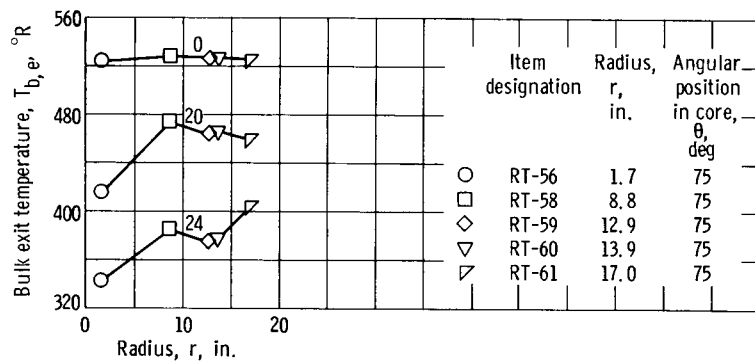


(b) Temperature distribution.

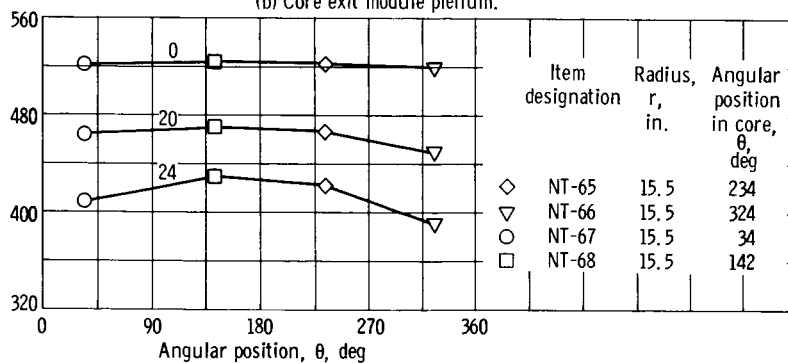
Figure 11. - Nozzle chamber instrumentation schematic drawing and temperature distribution after 25 seconds of run 19.



(a) Nozzle instrumentation rake.

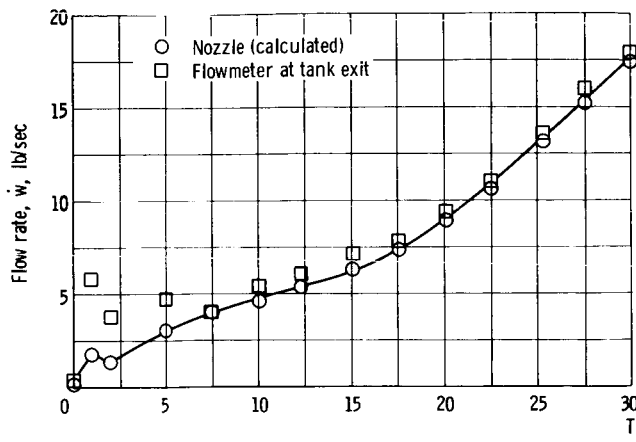


(b) Core exit module plenum.

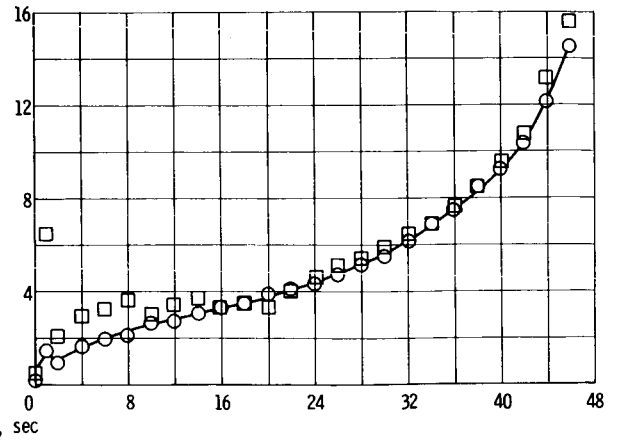


(c) Angular distribution at radius of 14 inches in nozzle chamber.

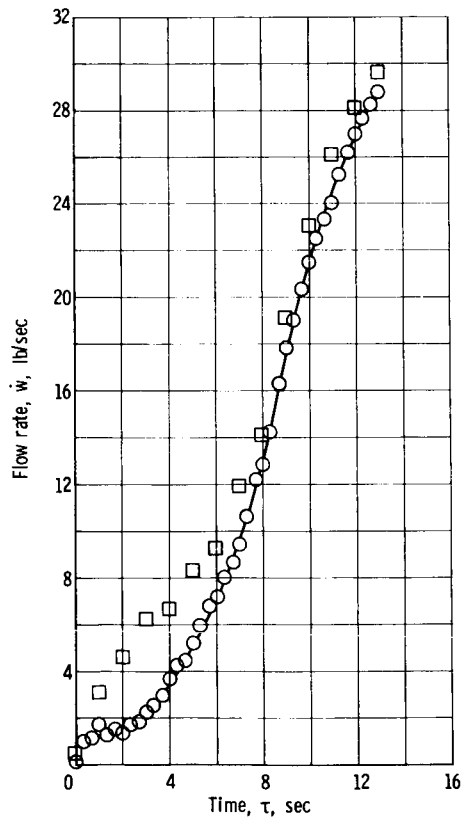
Figure 12. - Core exit gas temperature profiles for run 19.



(a) Run 19.



(b) Run 20.



(c) Run 24.

Figure 13. - Flow rate as function of time.

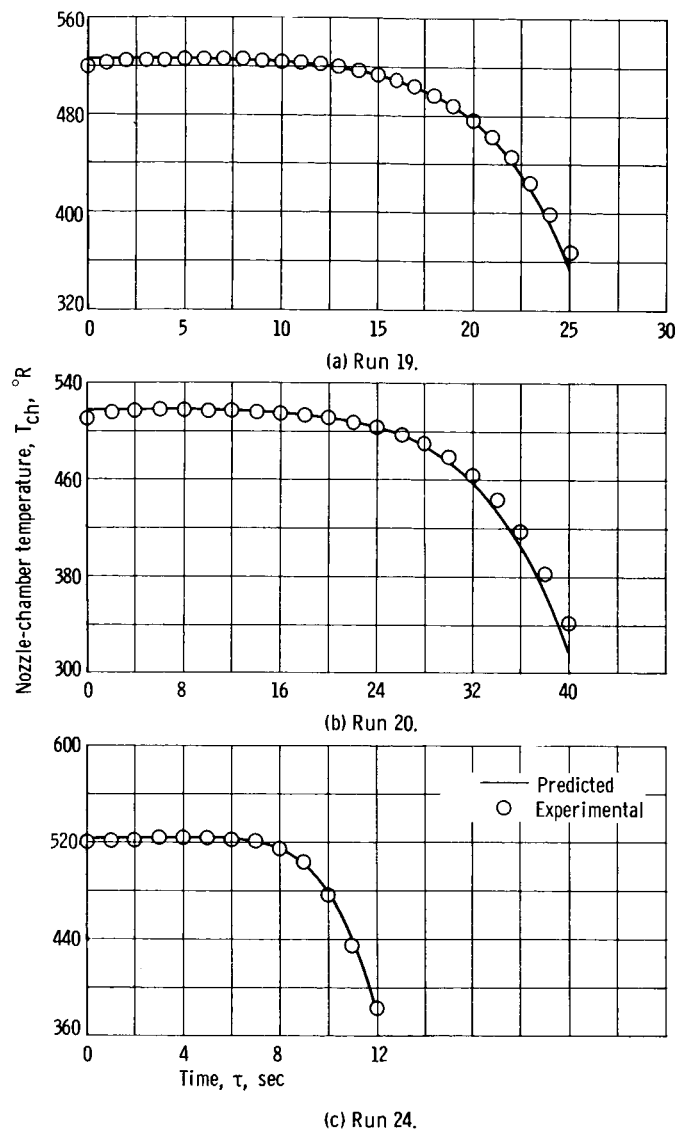


Figure 14. - Nozzle-chamber temperature as function of time.

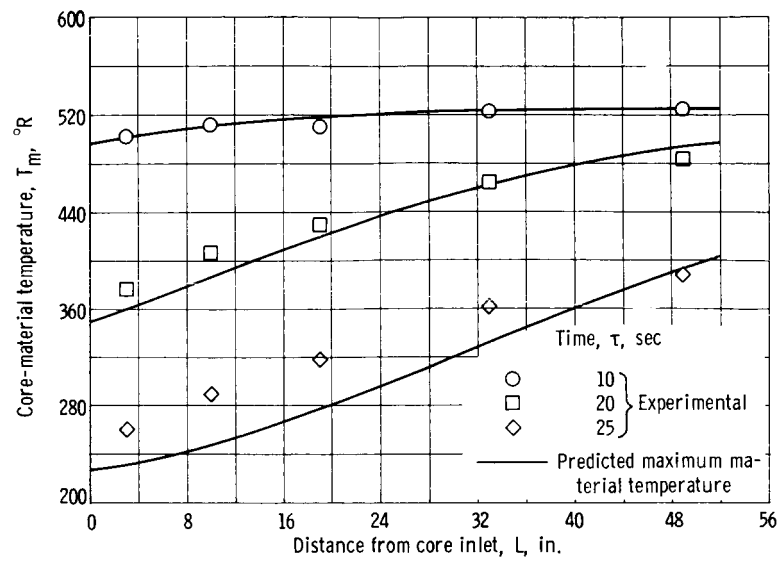


Figure 15. - Core-material temperature as function of distance from core inlet for run 19.

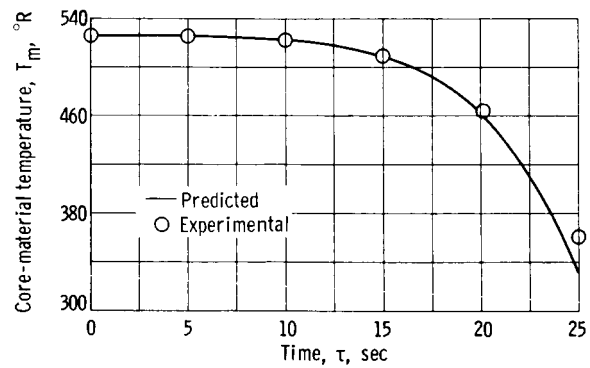
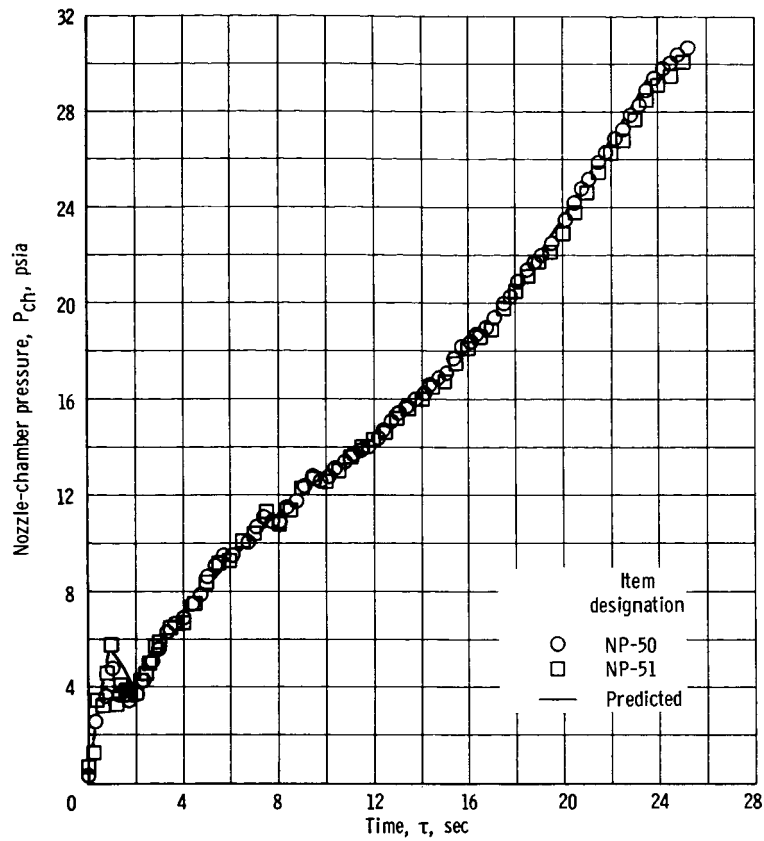
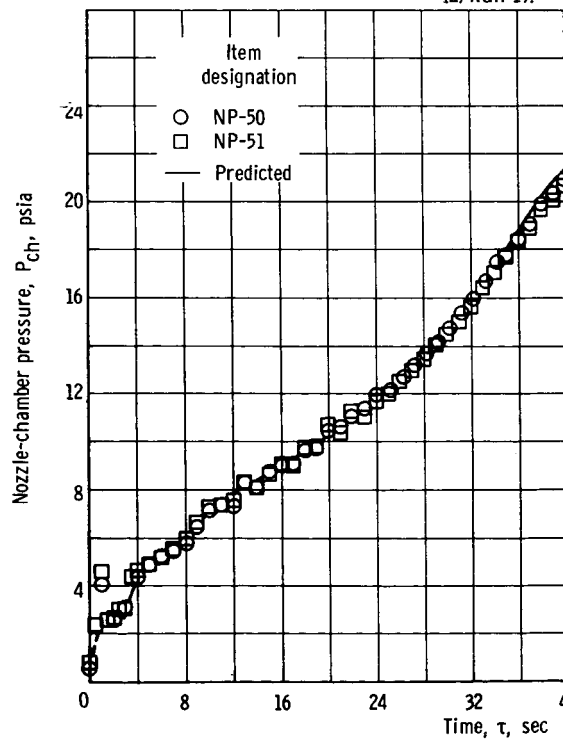


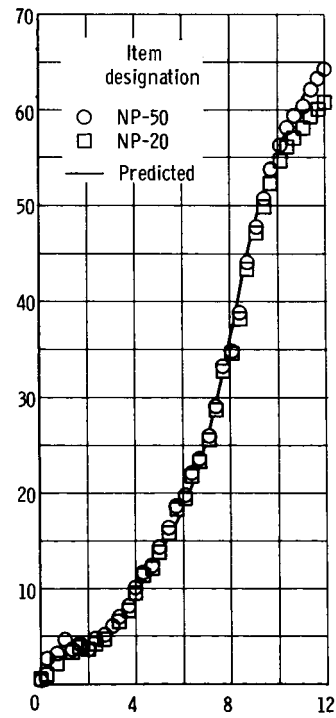
Figure 16. - Core-material temperature as function of time at $L \approx 33$ inches for run 19.



(a) Run 19.

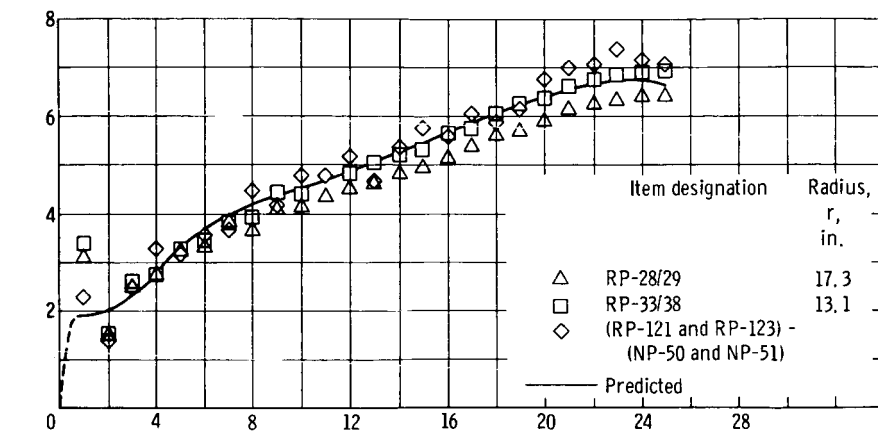


(b) Run 20.

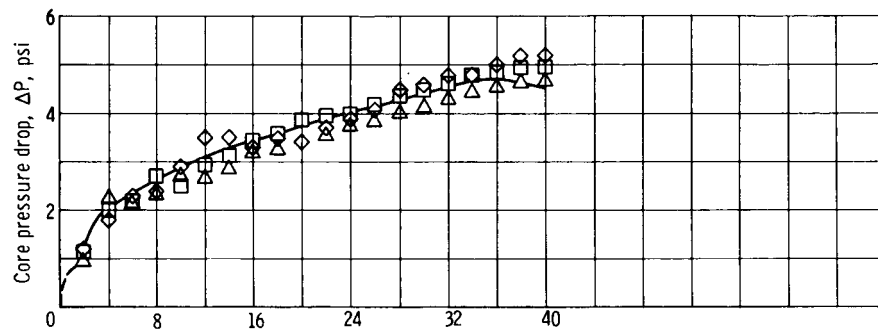


(c) Run 24.

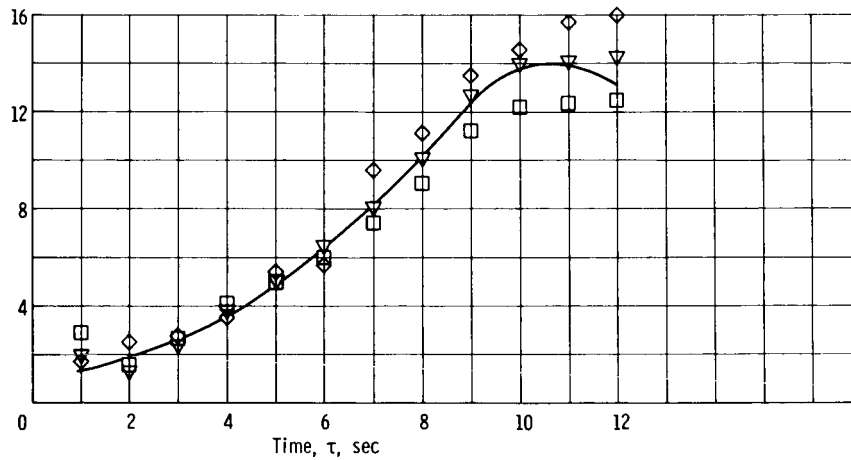
Figure 17. - Nozzle-chamber pressure as function of time.



(a) Run 19.



(b) Run 20.



(c) Run 24.

Figure 18. - Core pressure drop as function of time.

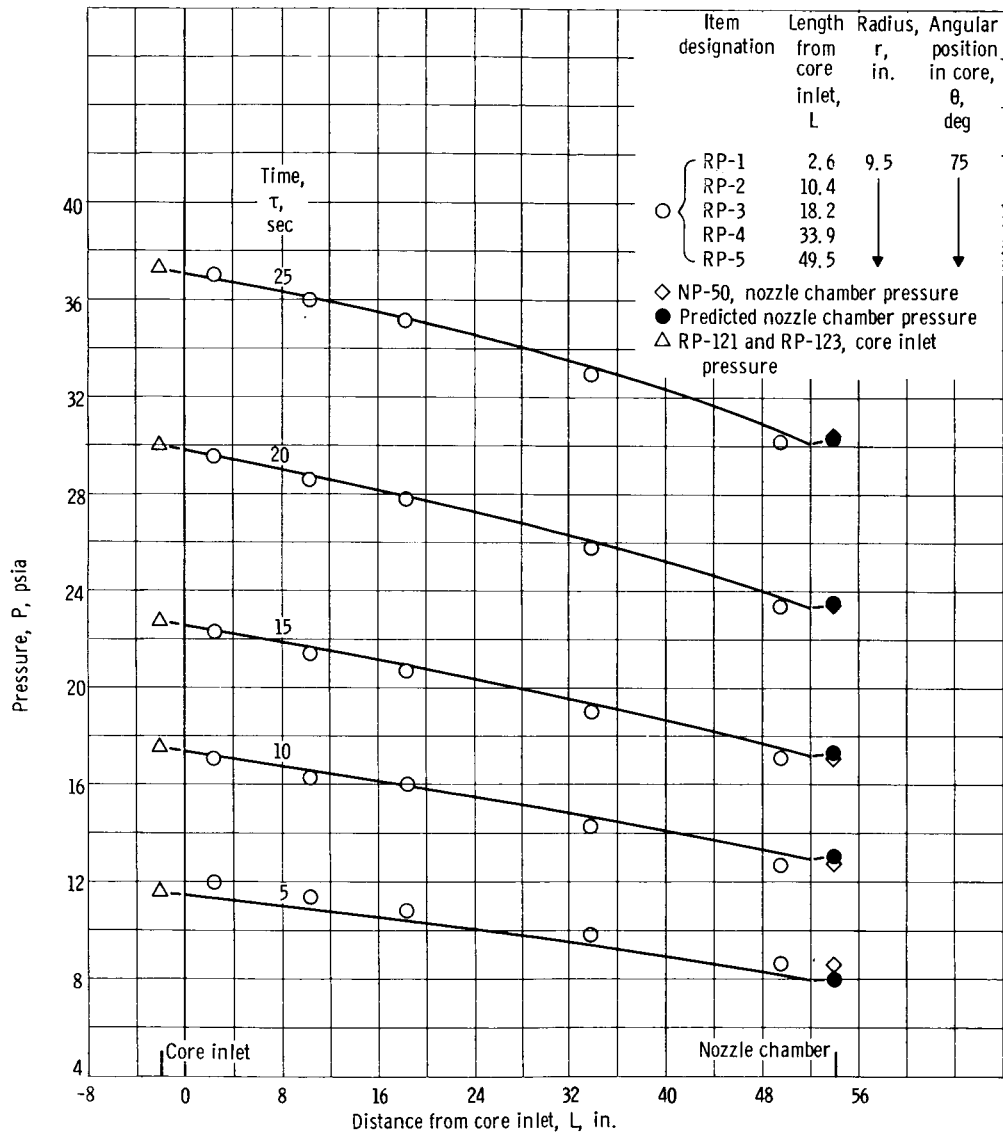
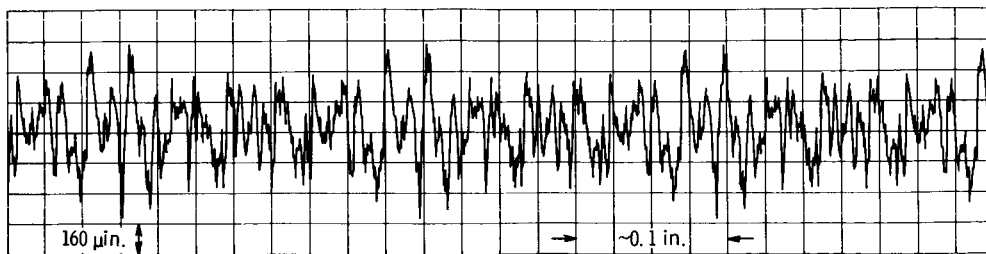
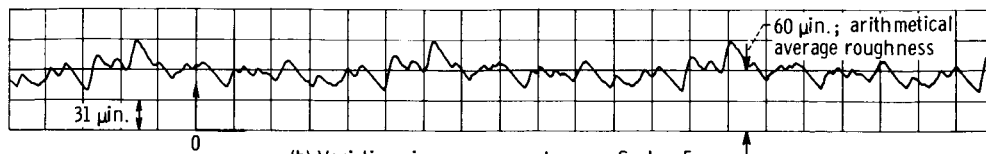


Figure 19. - Coolant pressure as function of distance from core inlet for run 19.

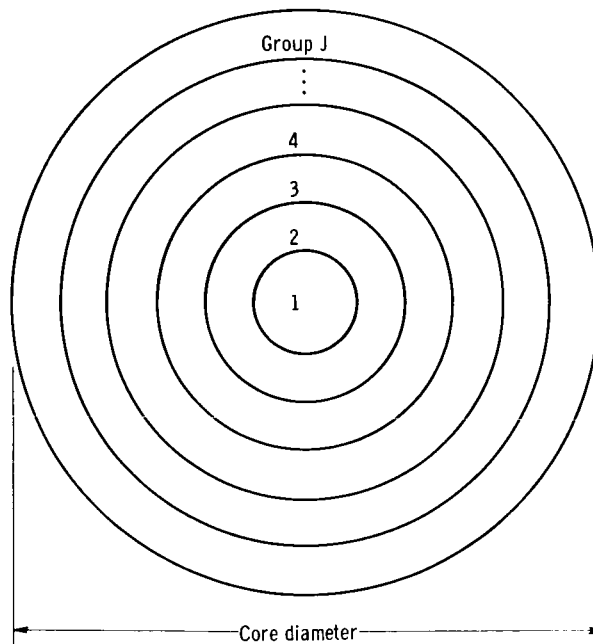


(a) Surface profile. Scale = 100.



(b) Variations in average roughness. Scale = 5.

Figure 20. - Surface profile and variations in average roughness of core fuel elements.



Assumptions:

- (1) All orifices in each group are the same diameter.
- (2) Conduction between groups is negligible.
- (3) Radial heat generation does not vary within each group.

Figure 21. - Core radial geometry model.

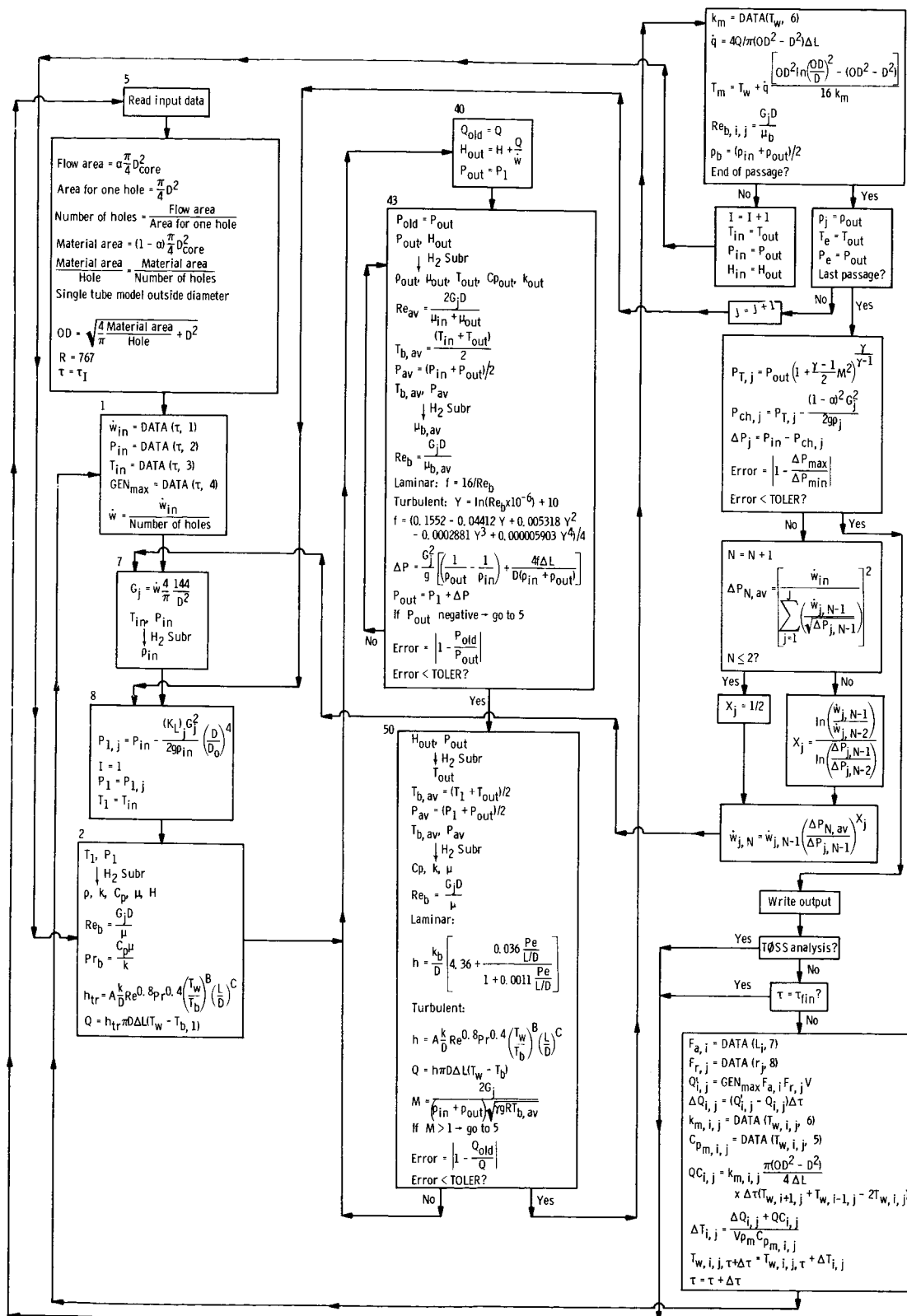


Figure 22. - Detailed flow diagram for Core Analytical Code (CAC).

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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