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SUMMARY

Design of nonuniform axial flux heaters, and equipment and piping design for simultaneous sampling of three subchannels in the nine-rod test section was completed and procurement initiated.

Several one-rod transient flow tests were performed and results recorded with magnetic tape. This method is expected to result in more accurate and expeditious collection of transient data than the methods previously reported. The latter depends on processing data recorded on Sanborn charts and are considerably more laborious. Analog data are first reduced to a digital binary tape, and a computer program (GE635) written for converting the binary tape to engineering units. Procedural corrections are in progress.

Two runs were made with the nine-rod test section in which flow and enthalpy were measured in the side subchannel. Typical reactor grid spacers were used with 18-inch spacing with the last spacer 4 inches from the flow exit where samples were taken. Flows were set at 0.5 and 1.0×10^6 lb/h ft² and system pressure at 1000 psia. Comparison of this preliminary data, with previous data taken without spacers on Project Agreement 44, indicates the effect of the spacer is to increase flow in the corner and side subchannels and decrease flow in the center subchannel. This trend is in agreement with the distribution of spacer flow resistance in the three typical subchannels.

1. INTRODUCTION

1.1 GENERAL

The work on the Deficient Cooling Program is directed toward extension of out-of-pile heat transfer data in support of current nuclear-powered, water-cooled plants. A brief review of current technology reveals that the large bulk of data is of the steady- or quasi-steady-state class. Thus, a need exists for data taken under transient conditions of power, flow and pressure in combination with different geometries. Analysis and study of such data are expected to contribute to the following overall objectives:

- a. A firmer understanding and establishment of heat transfer safety limitations, and
- b. Extension of safe operating limits to higher power densities.

Deficient cooling conditions are considered to be those which result in inadequate cooling of the fuel. They may result in potentially excessive cladding temperature which, in combination with the internal gas pressure of the fuel, may cause some type of fuel disruption. Resultant temperatures depend on the mode or modes of heat transfer that arise during deficient cooling conditions. A brief description of these modes of heat transfer follows.

Three different modes of heat transfer can generally occur when heat is removed, during high quality conditions, from a surface such as a fuel rod: nucleate boiling, with a liquid film on the heated surface; transition boiling; and the liquid deficient region. Nucleate boiling occurs at very high surface heat transfer coefficients, usually in excess of 10,000 Btu/h-ft², with steady surface temperatures. Increase of heat flux eventually results in "film dryout"

and a change of mode to transition boiling, which is usually characterized by temperature oscillations of varying amplitude on the heated surface. The transition mode of heat transfer exhibits relatively low heat transfer coefficients, on the order of 1000 Btu/h-ft² or less. Continued increase of heat flux eventually results in the liquid deficient regions, with some liquid droplets impinging on the heated surface which is mostly steam cooled.

The heat flux at which transition is made from the nucleate to transition mode of boiling, as evidenced by onset of surface temperature oscillations, is usually termed the critical heat flux (CHF). For low qualities, it is also known as the departure from nucleate boiling (DNB), or burnout point. Considerable effort has been made on parametric definition of the CHF with pressure, coolant flow, vapor quality, and the geometry of the system. These parametric studies serve as design data and indicate the operating conditions beyond which fuel surface temperatures increase substantially, with greater risk to fuel cladding integrity.

Most of the work defining limits of CHF has been done with small incremental heat flux increases which would allow it to be classified as steady- or quasi-state data. However, the actual modes of heat transfer become more complex in some cases involving transients, when the dynamic characteristics of the fuel-coolant system come into play. Therefore, practical cases of transient conditions which are considered worthwhile for study and test under this Deficient Cooling Program are those involving:

- a. Transient reduction of flow,
- b. Transient increase of power,
- c. Oscillation of power into and out of the transition boiling region to determine effects of prolonged operation at CHF, and
- d. Transient decrease of pressure which causes flashing and potentially deficient cooling conditions due to increased void content.

Furthermore, it is proposed to study under transient conditions typical geometry changes such as those due to fuel spacer components and those caused by rod bowing and swelling. Such studies are expected to define more clearly heat transfer safety limitations, and will eventually result in extension of safe operation to higher limits.

1.2 PROGRAM OBJECTIVES

The objectives expected to be accomplished under this program are as follows:

- a. Determine experimentally the CHF and temperature regimes which may occur in water reactor fuel assemblies due to nonstandard cooling conditions that result from power, flow, or pressure transients, and determine these values relative to steady-state data.
- b. Evaluate temperature regimes likely to be experienced by water reactor fuel assemblies in loss-of-coolant accidents, and determine areas of similarity or relationships between these regimes and those found in transient critical conditions.

- c. Evaluate consequences of fuel rod geometry changes on heat transfer performance from simulated tests on single, electrically-heated rods.
- d. Provide a plan for further in- and out-of-pile work necessary for more complete performance and definition of the performance of water reactor fuel under deficient cooling conditions.

1.3 ORGANIZATION OF PROGRAM

The outline of tasks, as originally proposed for the entire program, is shown in Table 1, with brief reference to the equipment and type of tests. It is intended to preserve these task reference designations in this and subsequent reports so that documenting of work and progress can be made in a systematic manner.

Tasks 3, 4, 5, and 8 involve test work. Chronological sequence of testing will probably proceed in the numerical task order.

1.4 ACTIVITIES COVERED BY THIS REPORT

Activities reviewed in this report are: Task 2—Design of nonuniform axial flux heaters for one-rod tests, and equipment and piping design for simultaneous sampling of three subchannels in the nine-rod test section; Tasks 3 and 8—Preliminary one-rod transient test data, and nine-rod subchannel data with typical fuel spacers; and Task 6—Transient data processing by use of magnetic tape recording.

Table 1
TASK DESIGNATION AND CONTENT

No.	Title	Content
1	Planning and Analysis	<ul style="list-style-type: none"> a. Review current technology and plan appropriate tests to integrate with required safety programs b. Analysis as necessary to determine test parameters
2a	Design	<ul style="list-style-type: none"> a. Design new equipment or modifications of existing equipment to carry out test plans
2b	Manufacture	<ul style="list-style-type: none"> a. Manufacture or purchase new equipment required
3	One-Rod Exploratory Transient CHF Tests	<p>Exploratory tests involving</p> <ul style="list-style-type: none"> a. Steady-state and transient flow, power, and pressure

Table 1 (Continued)

No.	Title	Content
		b. Cycling of power and flow into the region of CHF transition boiling c. Prolonged exposure to CHF conditions d. Modifications of heaters for non-uniform axial heat flux
4	Multirod Transient Tests	Tests involving: a. Steady state and transient conditions b. Power and flow cycling c. Combinations of intra-bundle clearance, power distribution, and spacer components with a. and b.
5	One-Rod Tests with Geometry Changes	a. Effects of temperature and internal pressure on heater swelling b. Steady-state simulated swelling at constant coolant pressure drop
6.	Data Reduction and Analysis	a. As required for test Tasks 1, 3, 4, 5, and 8
7.	Project Administration, Reporting, and Recommendations	a. Administration of entire program b. Regular and topical reporting c. Future recommendations for continued efforts
8.	Multirod Geometry Changes	a. Steady-state CHF data with spacer components and simulated fuel rod bowing and swelling

2. PLANNING AND ANALYSIS (TASK 1)

2.1 PLANNING

An average of 2½ to 3 engineers have been employed on the program. Design, procurement, and analysis have continued to escalate and will be at the originally planned level in the next quarter.

During technical discussions at AEC Headquarters, it was recommended that multirod tests be expanded to include 16-rod bundles with heated lengths up to 12 feet. Such bundles would better simulate actual fuel bundles

compared to nine-rod bundles with 6 foot heated lengths in the present plans. This updating of the test program is made possible by the construction of a new 8600 kW heat transfer test facility (ATLAS) at the General Electric Company site in San Jose, California. The facility will be much better equipped than the present one for transient type work with operations expected to start in the latter part of 1970. The inclusion of 16-rod bundle tests in the test program, while not changing the overall scope, would

necessitate realignment and revision of the test schedule. The major change would occur in Task 4 where the bulk of work would become 16-rod transient work.

2.2 ANALYSIS

Analysis, this quarter, was in the area of transient data reduction and is covered in Section 5 below.

3. DESIGN AND MANUFACTURE (TASKS 2a, 2b)

3.1 DESIGN

3.1.1 General Design of Nonuniform Axial Power Shapes

The effect of nonuniform axial heat flux on the occurrence of CHF is to be investigated in both one-rod and nine-rod tests as part of the Deficient Cooling Program. The high cost of instrumented heater rods and the technician man-hours required to change rods in a test section limit the number of different axial power shapes which can be tested. This requires that careful consideration be given their selection.

The following primary factors were considered in selecting heater rod axial power shapes:

- a. The heater rod axial power shapes should be similar to actual power shapes experienced in a BWR during reactor operation,
- b. Present methods of construction used by heater rod vendors to reproduce desired power shapes place limitations on the selection of power shapes,
- c. The axial power shape should provide the capability of obtaining CHF data over a large part of the operating range experienced in a BWR and should have power requirements within the limits of existing test facilities,
- d. The power shape should give approximately the same boiling length as experienced in a BWR core, and
- e. The power shape should be designed so that CHF will be most likely to occur at the outlet end of the heated length to enable CHF detection with a limited number of thermocouples.

The application of these factors to axial power shape design for the nine-rod and one-rod tests is discussed in the following two paragraphs.

3.1.2 Axial Power Shape and Design for Nine-Rod Test

One axial power shape was chosen for use in the nine-rod tests and two shapes for the single rod exploratory tests described below. More than one power shape was not chosen for the nine-rod tests because rod to rod peaking differences within the test bundle can be obtained by applying different amounts of power to individual rods. In addition, the use of only one power shape provides maximum interchangeability between test section rods and spare rods in case of rod failure.

The nine-rod tests will be started with a 6-foot heated length which is half of the 12 foot heated length in present BWR cores. It was decided to use an axial power shape representative of the power shape in the bottom (flow inlet side) half of a reactor core, primarily to simplify instrumentation.

A typical normalized power or flux distribution in an average reactor channel is shown in Figure 3-1. A considerable amount of local fluctuation in power occurs due to fuel rod spacers and other real causes. Figure 3-2 shows a smoothed power shape which is used for core sizing, design, and core transient calculations in which the power shape is assumed to remain constant. The latter was chosen as a starting point, for test heater design, because

- a. A smooth shape is more economical to manufacture with assurance of reproducibility,
- b. The choice of a smooth shape such as the 0 to 0.5 axial portion of Figure 3-2, over one with local disturbances as Figure 3-1, is not expected to cause a large effect on the CHF conditions at the midpoint, and
- c. The gradual axial increase of flux up to the midpoint will allow a design in which CHF can be predicted in the last few inches of the test section and thereby reduce the number of thermocouples required for CHF detection (compare the peaked axial flux design for one-rod testing in the following section where three times as many thermocouples (12) are necessary to give adequate CHF detection).

The three power shapes shown on Figure 3-3 were investigated for compatibility with the characteristics of the power supply and the range of flow conditions and heat flux on which test data was desired. The curve chosen is shown on Figure 3-4. It is essentially the same as the flat curve three on Figure 3-3. The Figure 3-4 curve was chosen primarily for the purpose of attaining the highest steam quality, at a given power which causes CHF, with other conditions constant. The characteristics of the heater profile shown in Figure 3-4 are summarized below and a typical condition for the nine-rod tests shown.

Variations of flow and subcooling will allow testing through different steam quality ranges.

Figure 3-1. Typical Power Distribution—Average Powered Channel

Figure 3-2. Core Sizing Power Distribution

Figure 3-3. Power Distributions Investigated for Nine-Rod Test

Figure 3-4. Axial Power Profile for Nine-Rod Heater

Heater Data

kW	— 186
Volts	— 334
Amperes	— 557
Ohms	— 0.600
Average Heat Flux	— 715,000 Btu/h-ft ²
Maximum Heat Flux	— 1×10^6 Btu/h-ft ²

Typical Nine-Rod Test Condition

Power Input	— 941 kW
Pressure	— 1000 psia
Mass Flux	— 1×10^6 lb/h-ft ² (5.65 lb/sec)
Average Heat Flux	— 403,000 Btu/h-ft ²
Maximum Heat Flux (CHF)	— 565,000 Btu/h-ft ²
Subcooling	— 15 Btu/lb
Steam Quality (at CHF)	— 0.22

As stated above, the heat flux of individual heaters, in the nine-rod bundle can be varied, relative to the others, by means of special transformers connected into the heater current cables. Figure 3-5a shows a conventional three-phase "Y" connected heater load which will result in equal heat flux from all rods for a balanced line voltage and heaters of equal resistance. Part (b) of the figure shows a transformer connected to depress the voltage and resultant heat flux from heater A. To boost the heat flux from heater A, the polarity of either coil of the transformer is reversed. This arrangement provides relative increase or decrease of individual heater flux by stages up to a total of about $\pm 40\%$. The net power loss in the transformer coil connected across the phase has been found to be negligible, on the order of 0.1%.

Figure 3-5c shows a transformer connected in both the A and D heater circuits so, that by the balanced ampere-turns in the two transformer coils, the current power and heat flux in the A heater are increased and proportionately decreased in the D heater. Taps on the transformer provide relative peaking, and depression, of power up to $\pm 30\%$.

The transformers shown in Figures 3-5b and c, can be used singly or in combinations in all three phases to produce flux patterns found in reactor fuel bundles. Present plans include a peaked heat flux on a selected rod, such as a corner rod, to cause CHF at the selected location. This procedure provides protection, from actual inadvertent burnout, to the balance of the rods in the assembly.

The circumferential distribution of thermocouples shown on Figure 3-6, is for CHF detection on the nonuniform axial flux of Figure 3-4. The staggered

arrangement provides essentially full protection. This is considered feasible due to the relatively high cost of the heaters and assembly. The axial arrangement of the thermocouples is shown at the bottom of Figure 3-7. CHF is expected in the last 1/2 inch of the heated length at flow exit. The thermocouples emerge from sealed grooves in the heater sheath; pass through an 1/8 X 2 inch section sealed in a high pressure gland; and then to a connector where wire sizes increase to 30 gage for ease of connection to terminal strips.

3.1.3 Axial Power Shape and Design for One-Rod Tests

Two axial power shapes were chosen for the initial exploratory tests to be done in the one-rod test section. The first is the same as Figure 3-4, for the nine-rod tests, for purposes of proof-testing instrumentation and comparison to nine-rod results. The second shape chosen is shown in Figure 3-8. This 6 foot length is arbitrarily shaped to incorporate the effects of an increasing axial flux in the direction of flow, and a decreasing flux gradient in the region of expected CHF.

In a boiling water reactor CHF is usually expected along the axial portion of the length where heat flux has a negative gradient as shown in Figures 3-2 and 3-8. Thus, in the peaked profile of Figure 3-8, CHF instrumentation will be provided over the last 12 inches of the peaked flux to determine its origin and extent. Figure 3-9 shows the axial and circumferential location of CHF thermocouples.

Typical operating conditions for the power profile of Figures 3-4 and 3-8, in a one-rod test section with a 0.136-inch flow annulus, are shown in Figure 3-10. Curves 1 and 2 show terminal conditions short of the CHF condition. Curves 1' and 2' show a condition at increased power, sufficient to cause the exit end of the profiles to be at CHF conditions. The illustration shows the possibility that a longer length of profile 2' can be at critical, than that of profile 1', particularly when power is such that the CHF zone has just been entered. The thermocouple arrangement of Figure 3-9 is expected to be sufficient to determine the axial extent of CHF on the negative power gradient section of Figures 3-8 and 3-10.

3.1.4 Nine-Rod Subchannel Sampling System

The purpose of this sampling system is to determine the flow and enthalpy in specific cross-sectional areas of the flow. The single sampling system, shown schematically in Figure 3-11, was designed and used on Project Agreement 44. A single sample was removed, from either of the typical subchannels 1, 2, or 3 shown in Figure 3-12; required measurements taken to determine flow and enthalpy; and the condensed sample returned to the main

a) CONVENTIONAL ELECTRICAL CONNECTIONS FOR 3-ROD ARRANGEMENT

h) BUCK (OR BOOST) TRANSFORMER ON HEATER A TO DECREASE VOLTAGE AND HEAT FLUX ON A RELATIVE TO D AND E

c) TRANSFORMER CONNECTED TO BOOST FLUX ON A AND DEPRESS FLUX ON D BOTH RELATIVE TO E

Figure 3-5. Transformer Connections to Vary Heat Flux Among Heater Rods

Figure 3-6. Typical Thermocouple Arrangement (Plan View at Flow Exit)

Figure 3-7. Thermocouple Details for Nine-Rod Heater

Figure 3-8. Axial Power Variation Proposed for One-Rod Tests

inches

Figure 3.9. CHF Thermocouple Locations for Profile of Figure 3-8

Figure 3-10. Operating Conditions for One-Rod Nonuniform Axial Flux

Figure 3-11. Schematic of Loop Showing Sampling Circuit

Figure 3-12. Cross Section of Nine-Rod Test Section Exit Showing Sample Subchannels

Figure 3-13. Flow Diagram for 3-Subchannel Simultaneous Sampling System (Nine-Rod Test Section)

Figure 3-14. Grid Type Spacer Details

Figure 3-15. Iso-Kinetic Interpolation

circulating pump. Change of sample subchannel was accomplished by reassembly of the sample tube which required considerable time and care in resetting test conditions in the new assembly. In the new sampling system, important economic and test advantages are gained by simultaneous sampling of all three subchannels. This redesign was accomplished and is schematically shown in Figure 3-13.

The redesign of the system for three-sample capacity was accomplished by the addition of heat exchangers, piping, orifice and vane type flow meters for the cooling water and samples respectively, and calibrated resistance temperature detectors (RTD's) for accurate temperature difference measurements.

A unique feature included in the first sample system, using heat exchangers HEI and HEI', is that the sample is

sufficiently subcooled in the HEI' so it can be used in HEI to condense the incoming sample flow. Since the sample and cooling water flows in HEI are equal they cancel in the heat balance. This eliminates two sources of error, sample and cooling water measurements, in the calculation for steam quality. The accuracy of the latter then is improved appreciably and depends simply on temperature measurements which are made with resistance temperature detectors calibrated to 0.2°F. All sample flows are measured downstream of the heat exchangers by vane type flowmeters.

The sampling system is piped so any one of the three subchannels can be led into exchangers HEI and HEI' when improved accuracy in enthalpy measurements is desired.

4. EXPERIMENTAL WORK

4.1 ONE-ROD TEST SECTION (TASK 3)

Seven transient flow runs were made, with a 0.540-inch o.d. heater in a 1.25-inch i.d. vessel, to ascertain performance characteristics of the 2-inch flow control valve and recording of data with an Ampex Tape Recorder. Recording of transient conditions on Sanborn charts has been found to be laborious and not as accurate as desired. Thus data recording by magnetic tape is being tried and is discussed in more detail in the following paragraph.

Work in analog-digital conversion and computer programming for reduction of data to engineering units was started and is in progress.

4.2 NINE-ROD TEST SECTION (PRELIMINARY SUBCHANNEL DATA)

Some preliminary subchannel sampling data were taken in the side subchannel of a nine-rod bundle with grid type spacers. This is in anticipation of more such data to be taken under this program using a more sophisticated and accurate sampling method as described above. The details of the nine-rod bundle and the isokinetic sampling method have been given in previous Project Agreement 44 GEAP reports (e.g., Nos. 13049, 10009, 10055, 10067).

Figure 3-12 shows the details of the geometry of the test section and the three typical subchannels. Details of the grid spacer used are shown in Figure 3-14. This nine-rod spacer simulates the corner, side, and center rods of an actual 49-rod fuel bundle.

Briefly, the sampling procedure consists of obtaining isokinetic conditions by adjusting the valve in the sample

line (Figure 3-11) until the static pressure is balanced in the subchannel being sampled and a diagonally opposite region of the rod bundle. The sample flow is then measured and the quality determined by calorimetry.

In some cases where the exact isokinetic conditions were not obtained during the test, the isokinetic quantities are determined by interpolation as shown in Figure 3-15.

Subchannel data for two test conditions were taken in the side subchannel at the exit end of the heated length which was 4 inches beyond the last of the five grid type spacers. The spacers were placed on 18-inch centers. *Clean* data, without spacers, had been taken earlier for all three subchannels under Project Agreement 44, as well as corner subchannel data with the same grid spacers. From this latter data, and the present side subchannel tests, it is possible to estimate the center subchannel spacer data from continuity. The results are presented in Table 2.

The trend seen in the data, with and without spacers, is in general agreement with the distribution of spacer resistance coefficients in the three typical subchannels. Comparison of data in Table 1a and 1b shows that the flow in the corner and side subchannels is increased. Flow in the center subchannel is reduced since the center subchannel has a higher spacer resistance coefficient than the other subchannels.

The grid spacer apparently has the effect of increasing the quality in the center subchannel. A small corresponding decrease might be expected in the quality of the other two subchannels, but this is masked by the error limits ($\pm 2\%$) of the measurements.

Table 2

SUBCHANNEL DATA WITH AND WITHOUT GRID SPACER
1000 psia, 0.570 in. o.d. heaters

a. With Spacers

Run	Total Bundle Average		No. 1 Corner		Subchannel No. 2 Side		No. 3 Center	
	$\bar{G}/10^6$	$\bar{X}$	$G_1/10^6$	X_1	$G_2/10^6$	X_2	$G_3/10^6$ *	X_3 *
2B2	0.530	0.029	0.469	-0.099	0.524	0.025	0.554	0.063
2E2	1.080	0.106	1.057	0.053	1.179	0.096	0.961	0.137

* From continuity

b. Clean Data (without spacers)

Run	Total Bundle Average		No. 1 Corner		Subchannel No. 2 Side		No. 3 Center	
	$\bar{G}/10^6$	$\bar{X}$	$G_1/10^6$	X_1	$G_2/10^6$	X_2	$G_3/10^6$	X_3
2B2	0.530	0.029	0.372	0.003	0.521	0.014	0.540*	0.030
2E2	1.080	0.106	1.046	0.049	1.078	0.097	1.180	0.105

* Measured (0.582 calculated by continuity)

5. DATA REDUCTION PROCEDURES

A method of recording and reducing transient test data, which will improve accuracy and reduce the time required for data reduction over previous methods, has been developed. It is expected this method will be used on most of the transient test data obtained in this program. In previous CHF test work, data have been recorded with a Dymec digital recorder and Sanborn chart recorders. The sampling rate of the Dymec recorder was found to be too slow for recording the rapidly changing conditions of the transient tests and the Sanborn chart recordings were difficult to read accurately.

The new method developed for recording data during transient tests uses a fourteen track Ampex tape recorder to continuously record data directly input from the test section and loop instrumentation. The measured gain characteristics of each channel can then be used to obtain an accurate reproduction of the test data from a playback of the tape. Typical parameters normally recorded on separate channels include test bundle power, loop pressure,

flow rate, inlet water temperature, heater rod surface temperature, and temperature of water in the turbine flow meter. One additional channel is used to record a signal which indicates the location of test runs on the tape. The latter signal consists of a constant voltage applied to the channel input during recording of the initial conditions before the start of the transient. At the instant the transient is initiated, the voltage across this channel is stepped up a constant amount until the end of the run.

After test data have been recorded, the tape is sent to a vendor (Lockheed) for A/D (analog to digital) conversion. The conversion consists of sampling each channel on the Ampex tape with a delay of 25 microseconds between channel samples. After sampling all channels with recorded test data, the conversion system waits a specified time interval (usually 1/40 or 1/80 second) and again samples each channel. The time lapse of 25 microseconds between channel samplings is considered negligible, compared to rates of change in test parameters. Thus all channels are

assumed to be sampled at the same time. The sampled data are recorded on magnetic tape in a binary form compatible with the GE 635 computer.

A computer code for reading the binary tape on the GE 635 computer has been developed. This code searches the binary tape for each test run indicated by a voltage step recorded on one channel for this purpose. When a run is encountered, the code reads into computer memory the initial conditions recorded prior to start of the transient, and the test parameters recorded during the transient. Before continuing to search for the next test run, the code

reduces the test data recorded in millivolts into engineering units. Included in the data reduction part of the code is a correction for a first order electronic lag resulting from a low pass filter in the frequency converter of the turbine flow meter. The equation employed to correct for this lag in recorded flow data is based on sampled-data theory.

This method for recording and reducing transient test data has been used successfully on a single-rod data.

A few procedural corrections are presently in progress and it is expected full details can be reported in following quarterly reports.

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