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Modeling of Cladding and Fuel Motion
in a
Loss of Flow Situation
for
GCFR Safety Analysis
COO-2471-6

Progress Report 6

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Modeling of Cladding and Fuel Motion

in a Loss of Flow Situation for GCFR Safety Analysis

Contract No. E(11-1)-2471

Summary

The first experiments have been run using electrically heated "fuel elements" in an inert gas (argon) loop. The fuel elements have a chopped cosine power input and have a Pb/Sn alloy cladding. Single elements were used in the first two experiments with a step power pulse of about 1 kw/ft which was sufficient to melt the center of the clad within 8 to 10 sec. As the molten cladding entered the "blanket" (unheated) region, it froze within about 1 inch.

The apparatus for the stainless steel pouring experiment is progressing. Additional models for freezing of molten "cladding" in colder regions are being analyzed and tested against the single tube pouring tests previously reported. Analytical routines are under development.

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Task I

Molten Alloy Poured Into Lower Blanket Region
of a Simulated Assembly

A. Stainless Steel Pouring Experiment (T. Wehner)

The design and fabrication of the stainless steel (SS) pouring experiment apparatus is progressing. A ceramic crucible made of lava grade A has been machined and fired. This crucible will be used to test the induction furnace on its capability of melting SS. The crucible is approximately 2 in. OD x 5 in. height x 1/4 in thick walls.

The high frequency induction furnace to be used in the SS pouring experiments has been activated and seems to work satisfactorily. A small quantity of brass has been melted successfully.

An electronic circuit has been designed to accompany the velocity detectors to be implanted in the 37 rod test bundle. Six (6) fine insulated SS wires will extend horizontally through the test bundle at equidistant intervals. As the hot liquid SS is poured down into the test bundle the 6 wires should break in succession. The time at which each break occurs can be recorded so that an average velocity can be determined.

The 6 SS wires will be connected to a circuit which will control a Voltage Controlled Generator (VCG). The VCG supplies input to a Multi-channel Scaler (MCS) which electronically stores information. Data can then be typed or punched onto paper tape.

FIG 1 LOGIC SCHEMATIC

In the battery and resistor circuit, each of the 6 SS wires is connected with a resistor in series. The 6 resistors are in parallel. As the loops of the circuit open due to the breaking of the wire by the hot liquid SS, the voltage input to the VCG changes causing a change in the output frequency of the VCG which is recorded on the MCS. The circuit design is the following (Fig. 2).

If the values of the resistances are chosen properly, there will be a constant change in the voltage input to the VCG as the resistors are removed from the circuit as shown in the following table. This constant voltage change will give a constant change in frequency according to the VCG specifications.

Table I

<u>i</u>	<u>$R_i (\Omega)$</u>	<u>#open loops</u>	<u>$R_{Total} (\Omega)$</u>	<u>V_{ab}/V</u>	<u>$\Delta V_{ab}/V$</u>
1	0.6×10^4	0	0.250×10^4	.800	
2	1.2×10^4	1	0.427×10^4	.701	.099
3	2.0×10^4	2	0.664×10^4	.601	.100
4	3.0×10^4	3	0.994×10^4	.502	.099
5	4.2×10^4	4	1.49×10^4	.402	.100
6	2.3×10^4	5	2.30×10^4	.303	.099
		6	∞	0	

Six (6) toggle switches will be added to the circuit to enable the exact correlation of open loops to frequency immediately prior to each experiment.

The support mechanism for the 37 rod test bundle is being fabricated. This variable-height support (Fig. 3) will keep the test bundle in alignment inside its protective mullite crucible and will provide for argon gas flow through the bundle. Following is a diagram of the support.

FIG 3
SUPPORT
STRUCTURE

B. Plugging Model Refinement

The plugging model to predict penetration lengths discussed on page 3 of Progress Report 4 has been refined. The model determines the time it takes to stop a constant velocity flow in a pipe by calculating the time required to freeze an idealized cylindrical slug of thickness dz at the front of the flow.

The assumptions are: that at time zero, the flow enters the pipe; that the temperature of the pipe wall in contact with the slug is constant; that there is no axial heat transfer; and that the temperature of the slug is uniform, i.e., the temperature of the slug is a lumped parameter.

The refinement of the model is to let the temperature of the slug vary with time. A linear function is used to approximate the time-dependence of the slug temperature. At time zero, $\bar{T}_{\text{slug}}(0) = \bar{T}_{\text{pour}}$. At a later time, t_1 , the slug has lost all of its specific heat and is at the liquidus temperature, so that $\bar{T}_{\text{slug}}(t_1) = T_L$. After giving up part of its latent heat the slug temperature reaches the solidus temperature, so that at some time, t_2 after t_1 , $\bar{T}_{\text{slug}}(t_2) = T_S$. At some later time, t_3 , the slug has given up all the remaining latent heat and is completely solid. t_3 is the time of interest because it is the time to plugging. A plot of the slug temperature versus time might look like this (Fig. 6) with the refined model.

Now, a heat balance as in the previous model can be applied to each part of the freezing process.

$$\rho dV C_p [\bar{T}_{\text{pour}} - T_L] = h dA_s \int_0^{t_1} [\bar{T}_{\text{slug}}(t) - \bar{T}_{\text{wall}}] dt, \quad (1)$$

$$\rho dV \chi \lambda = h dA_s \int_{t_1}^{t_2} [\bar{T}_{\text{slug}}(t) - \bar{T}_{\text{wall}}] dt, \text{ and} \quad (2)$$

$$\rho dV (1-\chi) \lambda = h dA_s \int_{t_2}^{t_3} [\bar{T}_{\text{slug}}(t) - \bar{T}_{\text{wall}}] dt, \quad (3)$$

where χ is the fraction of the latent heat lost by the slug in going from T_L to T_S . The integrals are evaluated: solving for t_3 yields

$$t_3 = \frac{D \rho}{2h} \left\{ \frac{C_p (\bar{T}_{\text{pour}} - T_L)}{(\bar{T}_{\text{pour}} + T_L - 2\bar{T}_{\text{wall}})} + \frac{\chi \lambda}{(T_L + T_S - 2\bar{T}_{\text{wall}})} + \frac{(1-\chi) \lambda}{2(T_S - \bar{T}_{\text{wall}})} \right\}. \quad (4)$$

The expression for the time to plugging from the previous model is

$$t = \frac{D \rho}{2h} \left\{ \frac{C_p (\bar{T}_{\text{pour}} - T_L)}{2(T_S - \bar{T}_{\text{wall}})} + \frac{\lambda}{2(T_S - \bar{T}_{\text{wall}})} \right\}. \quad (5)$$

The data for 50/50 Pb/Sn solder and for our previous experiments are

$C_p = 0.05 \text{ cal/gm-}^\circ\text{C}$, $\lambda = 12.8 \text{ cal/gm}$, $\chi = 0.30$, $T_S = 183^\circ\text{C}$, $T_L = 216^\circ\text{C}$, $\bar{T}_{\text{wall}} = 23^\circ\text{C}$. With this data the ratio t_3/t is

$$\frac{t_3}{t} = \frac{12.8 + .05(\bar{T}_{\text{pour}} - 216)}{21.4 + (16) \frac{(\bar{T}_{\text{pour}} - 216)}{(\bar{T}_{\text{pour}} + 170)}} \quad (6)$$

A few values of this ratio are tabulated below for various $\bar{T}_{\text{pour}}$'s.

Table II

$\bar{T}_{\text{pour}}$ (C)	t_3/t
216	.598
265	.657
335	.745
370	.790
500	.958

So, the refined model predicts a shorter time to plugging than the previous model. Therefore, at an assumed constant velocity, the penetration distance will be shorter in the refined model.

C. Lead-Tin Solder Pouring Experiment with Pyrex Glass "Fuel"

Another lead-tin solder pouring experiment has been performed. The purpose of the experiment was to determine the effect of the alumina ceramic "fuel" on the previous experimental results. In place of the alumina rods, Pyrex 7760 glass tubes were used. It was hypothesized that since the thermal properties of the glass are different from those of the alumina, the performance of the glass tubes as heat sinks would be different from the performance of the alumina rods, thus producing different experimental results. One of the possible different results is freezing of the solder pour at a different elevation in the test bundle.

The experimental set up was as identical to the last pouring experiment as possible. 590 grams of liquid solder at 335 C was poured from a diffuser cup onto the center 7 rods of a 37 rod assembly at room temperature. The only

major differences were the material and fit of the "fuel" rods. The solder cladding had been drawn onto the ceramic rods giving a very tight fit, while the glass tubing was simply inserted into preexisting cut lengths of solder tubing providing a loose fit. Following are some comparative data on the "fuel" rods for the two experiments.

Table III

Comparative Data on "Fuel" Rods

	<u>ceramic experiments</u>	<u>glass experiment</u>
"fuel" ID(cm)		
(hole in center of rod or tube)	.254	.389
"fuel" OD (cm)	.635	.600
solder cladding ID (cm)	.635	.640
	(same as "fuel" OD)	
solder cladding OD (cm)	.752	.775
<u>mass</u>		
cm of solder cladding (g/cm)	1.131	1.334
length of rod (cm)	61.0	61.0

Note that there is about 0.2 gram more of solder cladding per cm of cladding on a single rod in the glass experiment than in the ceramic experiments. Also, note the relatively large gap between the glass tube and the solder cladding.

The experimental results of the glass experiment were nearly identical to the results of the last ceramic experiment. The central area of the bundle directly beneath the 7 holes of the diffuser cup was completely stripped of cladding about 10 to 12 cms down from the tops of the rods. Gross penetration length was about 18 to 20 cms.

The ceramic rods used in the previous experiments were mullite (MV30) which is a lower density form of alumina. The properties are shown in the next table.

Table IV
Thermal Properties

	ρ $\left(\frac{\text{gm}}{\text{cm}^3}\right)$	C_p $\left(\frac{\text{cal}}{\text{gm}^\circ\text{C}}\right)$	T $(^\circ\text{C})$	K $\left(\frac{\text{cal}}{\text{sec cm}^\circ\text{C}}\right)$	α $\left(\frac{\text{cm}^2}{\text{sec}}\right)$
pure alumina	3.97 ¹	0.166 ⁴	25	0.06 ¹	0.091 ¹
(Al ₂ O ₃)		0.210 ⁴	400	0.02 ¹	0.024 ¹
		0.210 ⁴	800	0.015 ¹	0.018 ¹
998 alumina	3.85 ²	0.24 ⁵	24	0.079 ²	0.0855 ⁴
			800	0.021 ²	0.0227 ⁴
MV30 mullite	2.8 ²	0.23 ⁵	24	0.0062 ²	0.00963 ⁴
			up to 538	0.0050 ⁵	0.00776 ⁴
Pyrex 7760	2.23 ³	0.173 ³	25	0.00272 ³	0.00705 ³
glass		0.241 ³	300	0.00358 ³	0.00666 ³

References:

- 1) Plenum Press Handbook of High Temperature Materials, No. 1 Materials Index, Peter T. B. Shaffer, Plenum Press, N.Y., 1964, pp. 308-318.
- 2) McDaniel Refractory Porcelain Co. Catalogue FT 70, "Alumina and Mullite Tubes".
- 3) Personal communication with S.M. Sutherland of Corning Glass Works, Corning, NY.
- 4) Calculated from $\alpha = \frac{K}{\rho C_p}$
- 5) CRC Handbook of Tables for Applied Engineering Science, The Chemical Rubber Co., 1970, p. 144.

The thermal diffusivity, α , is thought to be a controlling physical variable in the experiment. α for the glass is nearly the same as α for the mullite, so there should be little difference between the thermal performance of the two materials. In a given heat transfer situation the glass and the mullite are expected to act similarly. However, the gap between the glass "fuel" and the solder cladding can act as a thermal resistance to heat transfer to the glass "fuel" from the solder cladding. So, in the glass experiment probably an insignificant amount of heat was deposited in the glass "fuel" during the time to freezing of the pour. Therefore, this experiment shows that heat transfer to the "fuel", whether it be mullite or glass, is insignificant in the transient time of the experiment. Freezing and plugging in the pouring experiments are not affected by the presence of the mullite ceramic "fuel".

Under transient conditions the heat capacity of the "fuel" is insignificant. The rate of heat transfer in the "cladding" is long compared to the transient time of the passing molten material. However, in the glass experiments since there was no thermal contact the cladding was stripped at the entrance due to the superheated fluid.

Task II

Electrically Heated Fuel Element Cladding Experiments

A. Design and Fabrication of Heating Elements (T. J. Scale)

The LOF accident in the GCFR is such that cladding and fuel meltdown may occur. The cladding phase of this accident has been modeled using a 50/50 Lead-Tin alloy for Stainless Steel and Mullite (low density Al_2O_3) for UO_2 . Single pin tests have been performed using an electrical heater with a chopped cosine power shape. High speed films have been taken of the meltdown and freeze out of the Pb/Sn alloy cladding. The objective is to study the motion and the freeze out of the cladding.

The heating rods have been more thoroughly tested using a radiant flux meter and a radiant flux detector. The profile of the power in the rod is a chopped cosine with a slight deviation from the predicted power curve. A project report on the development and calibration of the electrical heaters is included as Appendix A.

B. Grid Spacers

The grid spacers for the closed loop experiments have been designed and the working drawings are being made for the correct hydraulic diameters needed for the rod size that is being used.

C. Fabrication and Operation of the Closed Loop

The closed loop for the heated rod experiments has been completed and there have been two single tube experiments run to date.

The LOF accident has been simulated in a closed loop under low flow of argon gas. Instead of decreasing the heat transfer coefficient as in the real accident, a specified heat transfer coefficient is maintained and a transient power increase is obtained in the heater rod. The closed loop consists of a five foot test section, a heat exchanger, a gas circulator, and a heated pipe section. There is also a differential manometer to record the gas velocity in the loop. The heater rods are powered from the top of the five foot test section using auto-transformers with 240 volt a.c. input. (See Figure 7.)

FIGURE -7.

The heater rods have a chopped cosine power distribution with a $P/A \approx 1.25$, and a blanket power rating $B/A \approx 1/25$. The heaters are double wound nichrome wire on a eighth-inch Mullite tube with a Mullite cover tube. The wire winding is held in place by Saureisen cement on the inner tube. The heater rods are four feet long with a one-meter section wound to represent the core and a nine inch section at the lower end to represent the blanket. The heaters are clad with a Pb/Sn alloy 0.025" thick to give an overall rod diameter of 0.304".

An experiment consists of a single clad heater located in the test section. There is a glass tube around the heater tube giving a hydraulic diameter of 0.3". Argon gas is circulated and heated to a predetermined temperature. The power is increased in a step to about 3300 watts (280 volts). The camera is started. The voltage is turned off after about forty-five seconds.

The experiments to date, with single elements and heat fluxes of ~ 1 kilowatt/ft, show that plugging occurs within 1 inch of the core blanket interface. The actual motion of the cladding is of interest as well. The cladding melts from the inside out and as soon as it is molten on the inside the internal pressure (caused by expansion) produces bulges in the clad which soon break. After the centre section is bare, the cladding above will fall off in segments of tubes as its inside layer is molten. This all adds up to give a liquid state of low superheat which freezes very quickly upon contact with the lower powered blanket cladding.

References

1. R. E. Henry, W. C. Jeans, D. J. Quinn, and E. A. Spleha, "Cladding Relocation Experiments", Trans. Am. Nucl. Soc., 18, 209 (1974).
2. G. Hoppner, W. L. Chen, F. E. Dunn, M. A. Gromes, "Treat R5 Loss of Flow Experiment in Comparison with SAS Pretest Analysis", Trans. Am. Nucl. Soc., 18, 213 (1974).

Task 5

Development of a Calculational Routine for the Motion, Freeze-out of
Molten Cladding (Narisa Chu)

Experiments involving the motion and freeze-out of liquid lead-tin alloy through single alloy tubes of various sizes have been described in the last two progress reports^{1,2}. Simple lump parameter analysis has been used to correlate the data. A more satisfactory theory is desirable and the literature has been searched to find earlier work relating freezing of moving fluids along solid cooler surfaces.

S. Stefan³ formulated a phase change model in 1891. Since that time several authors have improved on the theory involving different assumptions relating the energy transfer between the fluid and solid interfaces and through the solidified material^{4,5,6} and others^{7,8} have studied the freezing in horizontal flow for tubes and containers of various geometries. Only recently have there been articles on solidification of fluids falling under the influence of gravity by Stephan⁹ and Mullin and Renda¹⁰.

There still existed uncertainties about how the fluid behaves in the transient cases where it falls through a subcooled tube.

Several models have been explored in this study. The first is a quasi-steady state approach. The second is an integral method suggested by Professor Khan, and the third is a method due to Ozisik-Mulligan⁸. Work is continuing with improvements in the treatment of the energy distribution and flow field. The following describes the effort to date.

A. Quasi-steady State Approach

The basic energy balance equation states that the rate at which energy is lost from the fluid to cause solidification is equal to the heat flowing from the fluid into the solidification region less that which flow out of the solidified region. If the thermal diffusivity of the tubing wall is small, the time constant of the wall will be small compared with the transient time of the fluid front falling through the tube. One may then assume that the

temperature of the outside wall of the tube will be constant. Since in the case under study the fluid and wall are the same metal and the thermal contact resistance is small, the total thermal resistance between the fluid and the outside of the tube wall will be that due to conduction through a cylinder wall with outside radius $R + w$ and inside radius δ (see Figure 8). Additional assumptions made are that the liquid is maintained at zero superheat, i.e., the liquid temperature $T_l = T_f$; and the sensible heat in the solidified region (between R and δ) is negligible.

The heat balance equation may then be written for the system in Fig. 8 as

$$\frac{T_f - T_w}{\frac{1}{k_w} \ln\left(\frac{R+w}{R}\right)} + \left(\frac{R}{R+w}\right) \frac{1}{k} \ln\left(\frac{R}{\delta}\right) = -\rho \lambda \delta \frac{d\delta}{dt} \quad (1)$$

FIG. 8

where $k = k_w$ is the thermal conductivity of the solidified liquid and wall

λ is the latent heat of fusion

R is the inside radius of the tube

δ is the inside radius of the solidified fluid

T_f , T_w , are the temperatures of the fluid (zero superheat) and outer diameter of the tube.

The solidified region grows thicker progressively toward the center of the tube as the fluid loses heat to the wall. At a time τ , $\delta = 0$ and the channel is blocked. This blocking time is

$$\tau(\delta \rightarrow 0) = \frac{\rho \lambda R^2}{2k} \left[\frac{\ln\left(\frac{R+w}{R}\right) - \frac{1}{2} \left(\frac{R}{R+w}\right)}{(T_f - T_w)} \right]$$

Using the following data corresponding to a set of tests, calculations were made to compare with the results of the tests.

$$R = 0.3225 \text{ cm}$$

$$w = 0.07 \text{ cm}$$

$$T_f = 183 \text{ C}$$

$$T_w = 20 \text{ C}$$

$$k = 0.111 \text{ cal/cm sec C}$$

$$\rho = 8.89 \text{ g/cm}^3$$

$$h_{sf} = 12.8 \text{ cal/gm}$$

$$C = 0.046 \text{ cal/gm C}$$

$$\tau(\delta \rightarrow 0) = 0.199 \text{ sec}$$

The average velocity of the liquid alloy was measured to be about 70 cm/sec, this with measurements of the penetration distance for low superheated tests allow one to calculate a blocking time of about 0.2 sec.

The simplifying assumptions of the constancy of the tube wall temperature and negligible sensible heat in the solidified region seem justified.

B. Integral Method

The basic energy-balance equation to describe this system shown in Fig. 9 is

FIG. 9

$$\frac{d}{dt} \int_{\delta}^R 2\pi r C (T_f - T_s(r)) r dr = \frac{2\pi (T_w - T_R)}{\frac{1}{k} \ln \frac{R+w}{R}} - 2\pi h_{sf} \delta \frac{d\delta}{dt} \quad (3)$$

where $T_s(r)$ is the temperature distribution in the solidified region and T_R is the temperature at the inside wall of the tube. If it is assumed that (i) the

liquid is always at the melting temperature T_f and (ii) the temperature distribution in the solid is linear, we see

$$T_s(r) = T_f + \frac{\delta - r}{R - \delta} (T_f - T_R), \quad \delta < r < R \quad (4)$$

On substitution of eqn. (4) into eqn. (3) and integrating, we have:

$$\frac{d}{dt} \left[\frac{\rho C}{6} (T_f - T_R) (\delta^2 + R\delta - 2R^2) \right] - h\rho\delta \frac{d\delta}{dt} = \frac{k(T_w - T_R)}{\ln \frac{R+w}{R}} \quad (5)$$

on integration for δ from R to 0 and t from 0 to τ we get

$$\tau = \frac{\rho R^2}{k} \ln \frac{R+w}{R} \left[\frac{\frac{C}{3}(T_f - T_R) - \frac{h}{2}}{(T_R - T_w)} \right] \quad (6)$$

Using the data from the previous section we see that for τ to be equal to 0.2 sec T_R is equal to 43.9 C and the extrapolated temperature gradient gives the effective thickness of the wall to be 0.065 (actual thickness 0.97 cm)cm. Therefore the assumption that the outside wall remains at constant temperature is reasonable.

C. Özisik-Mulligan's Method

According to Özisik and Mulligan, the steady-state solution of the system shown in Fig. 10 is

$$\frac{\delta}{R} = \exp \left(-\frac{B}{A} \right) \quad (7)$$

where

$$B = \frac{k(T_f - T_w)}{k_1(T_{sup} - T_f)}$$

$$A(Z) = a \sum_{m=1}^{\infty} e^{-\gamma_m^2 Z}$$

$$Z = \frac{2z}{R \cdot \text{RePr}}$$

Re = Reynolds number   Pr = Prandtl number

γ_m 's are the positive roots of the Bessel function $J_0(\gamma_m) = 0$

FIG. 10

The reasons for adapting their formula to investigate the experimental results are envisaged in the following two terms:

(1) Ozisik and Mulligan made the assumption that the fluid had a slug-flow velocity profile. The same velocity profile can be postulated for a vertical tube and the same solution is applicable for the later case if it is horizontal fluid flow or not. Now the quantity of interest is rather the freezing length where the solidified material is just blocking the tube than the blocking time mentioned previously.

(2) If the dimensionless number $\frac{h}{c_s(T_f - T_\infty)}$ is larger than 1.5, the transient problem can be replaced by the stationary problem without losing too much accuracy. The number for Pb/Sn is 1.7. Therefore it is valid to use the steady-state solution to examine the transient result.

Figure 11 shows the experimental data together with the curve of Eq. (14). The fitting seems to be satisfactory except no more information on the freezing of stainless steel cladding can be drawn because the number of the S.S. is 0.8 in a GCFR condition. The steady-state solution cannot be extended to S.S. A transient solution is required. This is further investigated in the following section.

FIG. 11

Appendix A
Development of a Fabrication Technique
for a
Shaped Power Electric Heater
for
G.C.F.R. Cladding Melting Experiments^{*}

by
Tim Scale
Project Report
in
partial fulfillment
of
requirements for the
Master of Science Degree
in
Nuclear Engineering

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I Introduction

The accident that is being studied for the gas cooled fast reactor is the loss of flow accident. During loss of flow there is the possibility of stainless steel cladding meltdown which could cause plugging in the lower blanket region. This plugging could render subsequent removal of heat impossible. Therefore tests should be performed to see if this is the case. The actual tests would be extremely costly and rather dangerous; therefore it is better to simulate the tests using other similar materials with similar properties.

The simulation of the LOF accident can be done using lead-tin solder tubes to represent the stainless steel cladding and the alumina rods to simulate the fuel. In order to more closely approximate the transient heat transfer it is better to have the alumina tubes heated according to the power shape of the actual reactor fuel pins. One pulses a current to heat the rod very quickly, which will approximate the heat transfer to the lead-tin just as if the helium gas in the GCFR stopped flowing. The need is for a mullite heater rod which will reach a preset power level within a second or two, maintain the power level for about 15 to 20 seconds, and then be terminated. In the actual experiment the solder clad rods will be preheated to a normal operating temperature in a closed argon gas loop where the argon gas is heated to about the solder solidus temperature and circulated by a blower. The power will be switched on from the preheating stage to the accident condition stage by one relay for each heater rod and one autotransformer for each heater rod. By using the autotransformers the voltage per rod can be changed so that each rod will have the same current flowing through it depending on the resistance of the rod. A movie camera will take pictures of the rod's clad melting, flowing down the rod and subsequent events. The actual experiment should take less than a minute, but the preheating of the gas could take as much as an hour. This is the basic method for the experiment.

II Specifications of the Heater Rod

Power Level	2.5 to 4.0 Kilowatts (Transient)
	500 to 750 Watts (Preheating Stage)
Voltage	280 Volts maximum
	110 Volts steady state (Preheating Stage)
Current	16 Amperes maximum
Power Shape	Chopped Cosine With $P/A \approx 1.2$
Length	4 ft. overall
Active Length	100 cm.
Lower Blanket	20 cm.
Inner Ceramic Tube	0.125 in. OD x .062 in. ID.
Ceramic Sheath	0.253 in. OD x 0.188 in. ID.
Solder Clad	0.025 thick
Heater Wire	Nichrome wire, double wound, #26 gauge
Cement	Saureisen

III Design of the Heater Rod

A. The Active Core Region

The active core region of the heater rod is to be 100 cm. or 39.4 inches. The maximum amperage obtained is 16 amperes and 280 volts which gives a power rating of 4,480 watts. The resistance of the heater wire in the rod must then total 17.5 ohms. If #26 gauge nichrome wire is used for the heater winding @ 2.6 ohms/ft., this allows 6.7 ft. of wire to be used or 80.4 inches. The length of the highly heated section is 39.4 inches; thus the average length of wire per inch is 2.0 inches. To calculate the number of turns N, per inch this gives, on a rod of diameter D, solve the equation:

$$\text{Length of wire/inch} = \frac{1^2}{N^2 \pi^2 D^2} \quad \text{for } N.$$

In this case N is 4.53 turns/inch. This is not fine enough to ensure even heating in the rod, so double wind the wire and hook it up in parallel,

so that each of the two wires will be twice as long as before and N will now be 10.07 turns/inch of double wire. This is quite satisfactory and will be used as the average turns/inch and corresponding 4.08 inches/inch of wire wound in the active core region of the rod.

The need is for a chopped cosine power distribution in the heater rod, with a peak to average of 1.20. The chopped cosine is approximated by 5 step functions, from the centerline to the blanket, each region 10 cm. long. The ratio of the power in each region to the average power is shown in Table 1.

Now calculate the amount of wire to be used in each of the 5 step function regions based on the average amount as 4.08 inches/inch. (See Table 1).

Given the values of "N" from 7 to 13 and their corresponding lengths of wire per inch, one can deduce which N is the best for which step function. This is shown in Table 2.

The values of "N" appropriate for each region were then chosen as shown in Table 2. With the winding as given in Table 2 the peak to average is 1.25 and this is how the core heating section was wound.

B. Blanket Region

The ratio of the blanket average power to the core average power is 1.20. The number of turns of #26 gauge nichrome needed, if the core region is 4.12 inches/inch, is .20 inches/inch, which is impossible since the minimum is 1 inch/inch. Therefore the need is for a larger wire which will give about .022 ohms/inch. A wire of .056" diameter nichrome has a resistance of .0183 ohms/inch and can be fitted through the .062" ID hole in the inner ceramic tube. If this wire is used the ratio of the average power in the blanket to the core average is about 24:1 which is acceptable for the blanket.

IV Techniques for Fabrication

A. Winding the Double Wire Nichrome on the 1/8" ID Ceramic

A lathe was used as the basic tool for winding the ceramic rods. The

TABLE #1

Region	Power/Average Power	Inches of Wire/Inch of Rod
1	1.207	4.896
2	1.138	4.64
3	1.025	4.182
4	.898	3.66
5	.729	2.97

TABLE #2

Turns/Inch	Inches/Inches	Region	Inches wound
7	2.92	5	7
9	3.52	4	8
10	4.04	3	8
11	4.43	-	-
12	4.81	2	8
13	5.19	1	8

ceramic rods are tubes 1/8" OD and 0.062" ID. The lathe was used so that the carriage speed could be varied and along with that, the variation in turns per inch from 7 turns/inch to 13 turns/inch. The rotational speed of the rod was 39 revolutions/minute.

The design called for the threading of two nichrome wires simultaneously so that the total resistance could be kept low around 20 ohms. To accomplish this, a tube cutter was modified so that the rollers would just touch the ceramic on top and bottom. The top roller had two grooves in it so that as the carriage moved the wires would wrap smoothly onto the ceramic. See Figure 1 for the roller and ceramic rod.

The bending moment on the ceramic rod is significant enough to cause fracture when winding unless the rod is supported. This called for the fabrication of a holder. The holder moves on the carriage and the ceramic rod goes through it to keep the bending at a minimum. The ceramic rods cannot be deformed much before breakage occurs, so that very careful alignment of the holder and rollers is a necessity. See Figures 2 for the holder and 3 for the whole set up.

B. Cementing and Further Fabrication

The wound ceramic rods are coated with "Saureisen" cement and then dried. Then a strip of brass shim is added to the blanket region of the rod and the double wire wound on top of the brass shim. Then the 0.056" diameter nichrome wire is pushed inside the hole in the ceramic rod.

The outer ceramic sheath is covered with a lead-tin solder tube that has a large enough inside diameter so that the ceramic can be pushed inside without breaking. Then the rod is drawn through a heated die by a dead weight of lead brick so that the outside diameter is about 0.050" larger than the outside diameter of the ceramic sheath.

The wire wound ceramic rod is pushed into the ceramic sheath and Saureisen cemented in place. Then the wires at the bottom of the lower blanket, the brass shim and the center nichrome wire are all silver soldered together for a good electrical connection.

The rod is then complete and only needs to be electrically connected from the top to the 240 volt A.C. supply before it can be used.

C. Testing the Heater Rod

A heater rod was set up unclad and without the central nichrome wire. The rod was given 45% of 120 volts by an autotransformer. A chromel-alumel thermocouple of size 28 gauge was slid inside the 0.062" ID hole in the heater rod. This gave the inside temperature as a function of distance along the rod since the wire could be pushed or pulled into or out of the inside hole. Then a surface thermocouple was made from 0.010" diameter copper-constantan and the surface temperatures of the sheath were recorded. Both thermocouples had ice bath cold junctions and were read by a potentiometer.

The power distribution is proportional to the heat transferred per inch on the rod. You have $\nabla T = qR_{\text{thermal}}$ and the R_{thermal} is assumed constant so that $q \propto \nabla T$ and $P \propto q$; therefore $P \propto \nabla T$ where $\nabla T = T(\text{inside}) - T(\text{surface})$. The power distribution was experimentally found by finding the ∇T 's at many points on the rod. See Figure 5.

The results for this test method show that there may be some hot spots on the rod. The hot spots may or may not really exist since there is no way to tell whether the inner thermocouple is really touching the inside ceramic tube. See Figure 1.

To get a better result a different test method was employed. The test rod was fixed at a given height from an optical bench. Then irradiance readings were taken of the rod from a fixed distance and height from the rod at 2 cm. intervals along the length of the rod. The instruments used were a radiant flux detector and radiant flux meter. (See figure 4.) The data

points were basically heat flux readings so that the relative power distribution was given by the flux detector. These results give a better cosine distribution with virtually no hot spots and closer to the theoretical predicted curve. See Figure 6.

A half size unit was pulsed for 20 seconds at 16 amperes. It glowed red hot within 3 seconds in the high heat section but did not melt the blanket section and the rod did not burn up.

The first in loop test was conducted on December 8, 1975. The rod overall resistance was 22 ohms and the applied voltage was 260 volts. This level of power was maintained for 45 seconds. The heater was dismantled after the experiment and it suffered no adverse effects. It will be reclad and used in later experiments.

CONCLUSIONS

The heater rods that have been designed and fabricated will work for the design conditions. However, if the amperage is much more than 16 amperes, say 20 amperes, the nichrome wire most probably will burn up at some spot in the heater. Also, it is not known whether the same heaters can be repeatedly used at 4 kilowatts, 16 amperes for more than 20 seconds without breakage.

The heaters could be improved by better winding, or using more than five steps, or using non-integral turns per inch for the nichrome wire.

Figure 1 - Nichrome Wire Roller

Figure 2 - Ceramic Rod Holder

Figure 3 - Overall Winding Setup

Figure 4 - Radiant Flux Detector and Optical Bench

FIG. 5

Power Distribution as Calculated From Thermocouple Readings

FIG. 6

Power Distribution as Calculated From Radiant Flux Readings