A Gamma Heated Subassembly For
Sodium Boiling Experiments

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by

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INTRODUCTION

An important aspect of the study of Liquid Metal Fast Breeder Reactor (LMFBR) safety is the consequence of sodium boiling. The occurrence of sodium boiling under certain flow and power conditions in an LMFBR can potentially initiate a major accident for several reasons:

1. The change in state of the sodium (liquid to vapor) may sharply reduce the heat transfer effectiveness causing a mercurial temperature rise of cladding and fuel, and lead to cladding failure and fuel meltdown.
2. Rapid reactivity changes (both positive and negative) may occur owing to voiding, oscillation, or reentry of liquid sodium.
3. Pressure surges from boiling, subsequent condensation of the sodium-vapor bubbles, or surges resulting from physical interaction between liquid sodium and molten fuel may damage the core structure or produce reactivity changes by creating rapid motion of the fuel (38).

Thus the study of the process of boiling sodium, and the development of an instrument to detect boiling become of paramount interest.

The analysis of boiling and two-phase flow of liquid sodium, however, depends upon data in which large apparent discrepancies exist (17-20) in values reported for boiling initiation superheat, void fraction, and for measured and predicted values of two-phase flow pressure drop (21,24). Additionally, the bulk of the incipient boiling superheat data has been obtained under conditions which do not even remotely resemble those existing in an LMFBR (25,39). Given such conflicting and unsuitable data, formulation of liquid sodium boiling inception theories

for LMFBFR's becomes extremely difficult. Moreover, extension of these data for development and evaluation of a boiling detection device is almost impossible.

It is apparent, therefore, that a need exists for further liquid sodium boiling experiments, and that these experiments should be carried out in an LMFBFR. In this thesis the design of a system to boil sodium in an LMFBFR is examined. This design should be regarded as a first step in a series of boiling experiments.

The reactor chosen for the design of the boiling apparatus is the Experimental Breeder Reactor-II (EBR-II), located at the National Reactor Testing Station in Idaho. This reactor is at present the only LMFBFR operating in the United States. A general layout of EBR-II is shown in Figure 1.

Design of a sodium boiling assembly centers around two sets of criteria which can be broadly classified as design objectives and design requirements.

Design Requirements

Design requirements originate from two sources. The paucity of sodium boiling data and the critical need for prediction of incipient sodium boiling conditions in an LMFBFR militates for an instrumented boiling assembly. An instrumented boiling assembly would also be necessary for testing of a boiling detection device. This requirement dictates that the boiling experiment be carried out in one of the two instrumented subassembly positions (5F3 or 5D2, see Fig. 2) in EBR-II. Instrumented subassembly (INSAT) characteristics are given in Table 1. The position of INSAT in EBR-II is shown in Figure 5.

Figure 1. EBR-II Layout

TABLE 1
INSAT CHARACTERISTICS

SUBASSEMBLY	
NUMBER	2
LOCATION	5F3,5D2
CONFIGURATION	HEX. TUBE
MATERIAL	304 SS.
DIMENSIONS (IN)	
ACROSS FLATS	1.907 ± 0.005
INSIDE FLATS	1.827 ± 0.003
OVERALL LENGTH (LES LEAD LENGTH)	93-37/64
POWER OUTPUT (KW)	270
NEUTRON FLUX (n/cm ² -sec)	2×10^{15}
COOLANT TEMPERATURE AT INLET (°F)	700
FLOWRATE THROUGH SUBASSEMBLY (gpm)	59
OVERALL LENGTH (FT)	36
ESTIMATED TOTAL WEIGHT (lb)	300
NUMBER OF LEADS	23

*This table has been reproduced from Reference 41.

S = SAFETY ROD

C = CONTROL ROD

SSCR = DROP ROD

SS = STAINLESS STEEL REFLECTOR
SUBASSEMBLY

B = BLANKET SUBASSEMBLY

XNNN = TYPICAL EXPERIMENTAL
IRRADIATION SUBASSEMBLIES

P = SIMULATED EXPERIMENTAL
IRRADIATION SUBASSEMBLIES
(~ HALF WORTH DRIVER SUBASSEMBLIES)

NO IDENTIFICATION: DRIVER SUBASSEMBLIES,
ROWS 1-7,
DEPLETED URANIUM
BLANKET SUBASSEMBLIES,
ROWS 11 AND BEYOND.
STAINLESS STEEL
REFLECTOR, ROWS 7-10

Figure 2. INSAT Locations

The second source of design requirements derives from the general requirements for the conduct of any experiment in EBR-II (41). These requirements are in part a result of the innate design features of EBR-II and also a consequence of the need to minimize hazards to the reactor. The most important restrictions for a sodium boiling assembly are:

1. The surfaces of experimental components that contact the reactor primary coolant sodium must be made of Austenitic Stainless Steel or of other materials that are known to be compatible with sodium at the maximum coolant temperatures and flow rates to which the experimental components are expected to be exposed in the reactor.

2. The exit coolant temperature from an experimental subassembly must not ordinarily differ by more than 100°F from the average exit coolant temperature for driver fuel or blanket subassemblies assumed to be in the core position surrounding the experimental subassembly. For the INSAT positions, the allowable outlet temperature is 848°F to 1048°F.

Design Objectives

A sodium boiling experiment has not been conducted in a reactor in the United States to date. Thus, one of the design objectives for the boiling apparatus becomes safety. Another is reliability. The third objective is prototypicality. This last objective is necessary in order for the experimental data to be the most indicative of actual behavior in an LMFBR. These requirements are the very cyñosure of the design for they constrain the type of structural material used in the apparatus and the method of heating.

There are many methods that could be used for heating in the boiling assembly. Among these are electrical, fission, gamma, exothermal

chemical, etc. Electrical and exothermal chemical may be excluded from the standpoint of reliability. Electrical would also require power leads. These extra leads possibly would mean a reduction in the total number of sensor leads. Fission, which is a reliable method, and the most prototypical in representing the actual situation in an LMFBR, suffers from the safety aspect. Because of the lack of data for sodium boiling in a reactor, reactor response to boiling and the conditions for preventing cladding dryout are not as well known as one would like. Consequently, a gamma heated device becomes a conservative first step and appears to be the most desirable in light of the design objectives stated above.

It is apparent, however, that a heating method for all circumstances cannot be quickly chosen. In general, it appears that gamma heating is the optimum to satisfy all of the design objectives, except prototypicality, provided a suitable gamma-ray absorber exists. In actual fact, only after a careful consideration of all heating methods concomitant with the desired experimental results, could a selection of heating source be made. Such a task is beyond the scope of this thesis.

The remainder of this work will concern itself with the gamma heated boiling assembly. This entails a description of the system, an explanation of the design of the major components, and a demonstration of system operation. In addition, an evaluation of the system to meet EBR-II experimental requirements and safety restrictions is also undertaken. The main result of the thesis will be to show the feasibility of using a gamma heated boiling assembly in EBR-II.

SYSTEM DESCRIPTION

Gamma heating has several advantages over other methods of heating previously given. The method is reliable, and does not depend upon any outside power leads or controls. Heat flux resulting from gamma heating is low obviating the need to develop any new structural material. There need be no allowance in the design for fission product gases, etc.

Although gamma heating has some advantages, it also possesses certain drawbacks. The neutron and gamma flux in the assembly and hence the heat flux are not precisely known. Gamma heating is not substantial and the resulting heat flux in the assembly will be small. A small heat flux means flow through the assembly must be reduced. Additionally, whatever heat is available from the heated section must be concentrated exclusively in the liquid sodium passing through the heated section. The need to avoid heat loss implies insulation of the boiling section from surrounding subassemblies.

A drawing of a lateral view of the subassembly is shown as Figure 3. The following components may be distinguished:

1. Seven pins comprising the actual heater section
2. Outer insulating can
3. Upper and lower flow meters
4. Upper and lower retainers
5. Mixer section
6. Thermocouples and void sensors

In this section the basic features of the subassembly will be described. The subassembly characteristics are summarized in Table 2.

Figure 3. Lateral View of the Assembly

TABLE 2
BOILING SUBASSEMBLY CHARACTERISTICS

LOCATION (IN EBR-II)	5F3,5D2
CONFIGURATION	STANDARD INSAT OUTER DIMENSIONS AND HEX CAN
MATERIAL OF HEX CAN	304 SS
DIMENSIONS (IN)	
INSIDE FLATS	1.827 $\pm$ 0.003
INSIDE CAN	1.420
GAMMA HEATED PINS	
NUMBER IN SUBASSEMBLY	7
MATERIAL	TANTALUM
DIMENSIONS (IN)	
DIAMETER	0.40 $\pm$ 0.001
LENGTH	20
CLADDING	
MATERIAL	INCONEL X-750
DIMENSIONS (IN)	
WALL THICKNESS	0.010 $\pm$ 0.0005
LENGTH	30
SPACER WIRE	
MATERIAL	INCONEL X-750
DIAMETER (IN)	0.040 $\pm$ 0.0005
INSULATING CAN	
MATERIAL	INCONEL X-750
INSULATING MATERIAL	ARGON GAS
GAS ANNULUS (IN)	0.070
POWER OUTPUT AT 75% REACTOR POWER (KW)	21.57
COOLANT TEMPERATURE AT INLET ($^{\circ}$ F)	700
FLOWRATE THROUGH SUBASSEMBLY (gpm)	1.44
COOLANT TEMPERATURE RISE ($^{\circ}$ F)	
INNER SECTION	1029
OUTER SECTION	37
OUTLET TEMPERATURE	1042
NUMBER OF LEADS	20

A typical pin is shown in Figure 4. This pin consists of twenty inches of tantalum, clad with Inconel X-750. The upper portion of the pin is hollow and is filled with argon gas. The choice of tantalum as the gamma absorber is based upon several factors. Tantalum possesses the highest gamma energy absorption coefficient of any material, with the exception of uranium and lead (6). In addition, tantalum has a relatively high cross section for fast neutrons, and tantalum is compatible with liquid sodium (8). Tantalum also has a high melting point, 5400°F. Both of these latter properties make tantalum desirable from a safety standpoint. The high gamma and neutron heating properties make tantalum the most advantageous material for use as a gamma heater.

The cladding chosen for the tantalum is Inconel X-750. Although tantalum is compatible with liquid sodium, it has exhibited a comparatively high corrosion rate in experiments conducted in EBR-II (8,9). Assuming only a forty-three day residence time for the boiling apparatus (the normal operating cycle for EBR-II), the actual amount of tantalum released into the liquid sodium would be small. The corrosion products of tantalum, however, would create a nuisance activity in the coolant which is not necessary. Furthermore, from results of previous experiments (9), tantalum is not recommended for use unclad in EBR-II. Hence a thin cladding is provided.

The usual cladding material of EBR-II is 304 Stainless Steel. This cladding material, however, may appreciably lose mechanical strength at the temperatures the subassembly must operate at to boil liquid sodium (approximately 1729°F). Consequently, Inconel X-750 was chosen. This material has evinced excellent corrosion resistance in experiments in

Figure 4. Lateral View of a Single Pin

Figure 5. Complete Core Arrangement Showing the Position of INSAT

EBR-II (8,9), and has good mechanical strength in the subassembly temperature operating range.

Each of the Inconel clad tantalum pins is wrapped with a spacer wire and the seven pin assembly is placed within an insulating can. This can contains an annular space of 0.070 in., which is filled with argon gas. The can serves a twofold purpose. One is to provide thermal insulation for liquid sodium flowing past the tantalum pins from neighboring assemblies in EBR-II. The second intention of the can is for pressure pulse protection. Under certain conditions of extremely low flow, violent boiling can occur in which the subassembly could be voided and be refilled with liquid sodium (53). The can offers protection to the surrounding subassembly hexagonal wall, preventing deformation.

The upper and lower retainers are designed to prevent escape of pieces of the heater section of the assembly, if the heater section should break apart. This event, although very unlikely, could result in tantalum being scattered throughout the reactor core. As has been noted above, this event would create an unnecessary activity in the liquid sodium coolant and on core and heat transfer surfaces.

Various instrumentation is also provided at several locations in the subassembly. The types of sensors will merely be described. A complete account of their employment and interaction in boiling experiments is beyond the intention of this thesis.

These six general components comprise the essential features of the sodium boiling apparatus. In the next section, the specific design of each component and the operation of the assembly will be considered.

COMPONENT DESIGN

In this section the design of each component in the boiling assembly is delineated and overall assembly operation is evaluated. The following areas of component design may be distinguished:

- Gamma and neutron heating in tantalum
- Hydraulic design
- Sodium superheat
- Temperature distributions and stress considerations
- Decay heating

In addition, an economic analysis is given.

Once the preliminary design of the boiling assembly was established, computer simulation was used to model assembly operation. The code selected for this purpose was COBRA-IIIC (45). A summary of the principal features of this code and its input is presented in this section.

All boiling assembly design was performed at a specified reactor power and flow. Since some error will be present in any system design, the design must be flexible enough to account for these variations, or the operating conditions for the system must be capable of alteration to offset design error. Because of the small size of INSAT, individual sub-assembly controls, such as flow valves, could not be used. Thus the EBR-II reactor itself had to be used for adjusting to deviations in design values. The subassembly is designed to boil at 75% reactor power and 100% reactor flow. By using these conditions as the reference case, lower than predicted gamma and neutron heating rates may be corrected by an increase in power or a decrease in flow in the boiling assembly. The

initiation and termination of each boiling experiment may also be controlled by increasing and decreasing reactor power. The reactor may then be operated for a normal cycle (43 days for EBR-II) and boiling experiments may be accomplished at set frequencies.

Gamma and Neutron Heating

The most crucial aspect of the feasibility of the design is the amount of gamma and neutron heating in the tantalum rods. The neutron and gamma fluxes used for this calculation were determined for the core configuration shown in Figure 6. This core configuration is given in reference 41.

In order to calculate the gamma heating rate, the following assumptions were made:

1. The energy range of 0.1 to 10 Mev is adequate to describe gamma radiation in a fast critical assembly (48).
2. The absorption and scattering of photons may be accounted for by three processes: Compton effect, photoelectric effect, and pair production (49).
3. Gamma radiation is attenuated in a "straight ahead" process. A buildup factor is used to account for secondary radiation.¹
4. A flat axial gamma heating rate.²

The energy absorption coefficient accounts for all three of the above mentioned photon interaction processes. The variation of gamma radiation

¹This buildup factor method gives results which are generally in good agreement with experimental results (4).

²The actual gamma heating profile that exists in EBR-II was taken into account when using the COBRA code to evaluate boiling assembly operation.

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DEPLETED URANIUM
BLANKET SUBASSEMBLIES,
ROWS 11 AND BEYOND,
STAINLESS STEEL
REFLECTOR, ROWS 7-10

Figure 6. Reference Core Configuration

is then given by:

$$\phi_g = \phi_{g0} e^{-u_a(R-r)}$$

and the energy deposited is:

$$Q = B u_a E \phi_g$$

where,

- B is the buildup factor
- u_a is the energy absorption coefficient, cm^{-1} , at energy E
- ϕ_g is the gamma flux at any point, $\text{p/cm}^2\text{-sec}$, at energy E
- ϕ_{g0} is the gamma flux incident on the rod, $\text{p/cm}^2\text{-sec}$, at energy E
- R is the outer radius of the rod, cm

The gamma flux was divided into twenty energy groups. The energy deposited from each group was then calculated. The total energy added to the pin was found by integrating the heat added by each group over the radius and length of each pin. As may be seen from Figure 7, the gamma heating rate quickly decreases above and below the core. Thus pin length was limited to 20 inches, and the tantalum section of the pin is centered in the reactor core for maximum heating.

The neutron heating was calculated in a similar manner using the following assumptions:

1. Only the (n, gamma) reaction was considered of any significance for heating (4).
2. A neutron spectrum of 0.29 to 3680 Kev was used (48).
3. All the gamma radiation produced by neutron capture was assumed to be absorbed in the immediate vicinity of its point of emission.

Figure 7. Axial Gamma Heating Rate for Iron

4. Straight ahead attenuation was assumed for the neutron flux.

A twenty-two group neutron spectrum was used. The procedure employed for calculating neutron heating was similar to that used for gamma heating. The total heat produced in the tantalum pins is 23.57 KW at 75% reactor power. The procedure used for heating calculations for gamma and neutron fluxes may be found in reference 4.

Hydraulic Design

The hydraulic design for the boiling assembly will be explained in this section. The program COBRA-IIIC was used to evaluate the hydraulic performance of the boiling assembly. This code will be summarized and the hydraulic design will then be presented.

COBRA-IIIC is a computer code designed to perform both steady state and transient subchannel analysis of nuclear fuel rod bundles while concurrently solving for fuel rod temperatures. It computes the flow and enthalpy in the subchannels (or channels if they are the model basis) during both boiling and non-boiling conditions by including the effects of both turbulent and diversion crossflow mixing. The mathematical model neglects sonic velocity propagation. Thus the model is limited to transients in which the transient times are greater than the time for a sonic wave to pass through the channel (45).

The equations of the model are solved by using a finite difference scheme which gives a boundary value flow solution for both steady state and transients. The transient boundary conditions are inlet enthalpy, inlet mass velocity, rod surface heat flux, and exit pressure. The fluid model noding is one radial and numerous axial nodes for each fuel assembly. The fuel temperature model combines both axial and radial

nodes. The main features of the code are paraphrased from reference 45 as follows:

- COBRA-IIIC can consider transients of the intermediate to fast speed--no sonic velocity propagation effects are considered.
- The numerical scheme involves a boundary solution where the transient boundary conditions are the inlet flow, inlet enthalpy, rod surface heat flux, and exit pressure.
- Temporal and spatial acceleration of diversion cross flow is included in the transverse momentum equation.
- Forced diversion cross flow from mixing vanes is included.
- Methods are available for analysis of partially blocked channels.

In order to perform calculations with COBRA-IIIC for boiling liquid sodium, several correlations and various input data are required to obtain meaningful solutions. The correlations used in the subassembly design will be outlined below. English engineering units are used throughout the code. The input used for evaluation of subassembly performance is shown in Appendix A.

The first set of data input required by the code consists of fluid properties. These are temperature, liquid specific volume, vapor liquid thermal conductivity, and surface tension of the liquid. These are all entered as a function of saturation pressure. Reference 45 was used as the source of the required data for sodium.

The single-phase friction factor of Koo (43) was used:

$$f/4 = 0.0014 + 0.125(\text{Re})^{-0.32}$$

where Re is the Reynolds number. The friction factor was corrected to

account for the effects of a lower liquid viscosity near a heated wall.

Both void fraction and two-phase friction multiplier were specified as polynomial functions. These functions were obtained by a least squares fit to data given by Baroczy (44) for two-phase sodium flow. These polynomials are functions of the sodium quality, and the coefficients of the polynomials are supplied as inputs.

The axial heat flux profile for EBR-II was inputted as a function of relative rod length. This profile is constant with time and is common to all rods.

Dimensions of flow channels, areas of flow channels, and rod gap spacings are all supplied as inputs.

Fuel rod dimensions, fuel rod layout and radial power peaking factors are shown for the case of gamma heating in Figure 8.

Turbulent mixing models must be established. For liquid sodium, the correlation most widely used is:

$$\beta = 0.0124(D/S)Re^{-0.1}$$

where,

D is the hydraulic diameter, in.

S is the rod spacing, in.

β may be considered as a ratio of diversion cross flow to axial mass flow

This model was established empirically by Millhollen (13). Beta is not varied as a function of axial length, hence the turbulent mixing model ignores spacer and blockage induced turbulent subcooled mixing.

In addition to the above variables there are several input parameters which are unique to the COBRA code. The diversion cross flow

Figure 8. Seven Pin Geometry Layout

resistance factor has little physical significance. For liquid sodium and wire wrap a value of 0.5 was used (13). A turbulent momentum factor is assigned which represents the relative importance of convective and conductive thermal transport. A value of 0.0 was used for liquid sodium (for water the value would be 1.0). The allowable fractional error in flow convergence was chosen as 1.0×10^{-3} , because of the low flows involved in the boiling assembly.

There are several reasons why the COBRA-IIIC code was chosen for assembly evaluation. First of all, the code was available and was easily adaptable to the CDC-6400. COBRA-IIIC is also a recognized standard code for thermal-hydraulic calculations. Perhaps the most important reason of all, however, is that the accuracy of COBRA calculations has been experimentally determined in EBR-II (13). This experiment was conducted for the sole purpose of comparing COBRA calculated temperatures to temperatures measured in INSAT. The difference between COBRA temperature calculations for each channel in INSAT and the measured temperatures were negligible, and in general,

This good correlation indicates that the COBRA code, as it is now used, is adequate in predicting fuel test assembly coolant channel temperatures in EBR-II. (13)

COBRA-IIIC was employed in the assembly flow and temperature analysis using the inputs mentioned above. Two different rod layouts were used with the COBRA code. One rod layout, given in Figure 8, is the complete inner assembly comprised of the seven tantalum pins, Inconel cladding, wire wrap and circular wall of the insulating can, and void sensors. The other layout used is shown in Figure 9. It is a one-sixth geometry layout, but in addition to the inner pins this layout also contains the outer bypass channel and the insulating can. The one-sixth

Figure 9. One-sixth Geometry Layout

geometry case gives representative results for the entire boiling assembly, including nominal sodium outlet temperature from the subassembly. Heat loss through the insulating can was modeled by varying the radial power factors until the proper amount of heat was added to both the inner portion of the assembly and to the bypass channels. Heat loss from the boiling assembly was accounted for in the seven pin geometry by reducing the total heat added from the tantalum pins by the amount of heat loss through the insulating can. Peaking factors for the seven pin geometry are shown in Figure 10.

Two different layouts were used owing to the difficulty of simulating the entire assembly on COBRA. The one-sixth geometry also allowed many different cases to be evaluated at reduced cost.

Once the reference reactor power was established (75%), subassembly flow variations were studied using COBRA-IIIC with the objective of producing boiling in the subassembly at 75% power. Moreover, flow and flux sensitivities to boiling were established.

The mass flux required in the subassembly for boiling is $0.062 \text{ Lb}_m/\text{hr-ft}^2 \times 10^6$. By use of two orifice plates the above flow will exist in the subassembly when the reactor pumps are at 100% flow. Total flow rate through the assembly is 1.44 gpm, or approximately 2.4% of normal INSAT full flow.

In order to establish the susceptibility of assembly performance to flux and flow variations, a sensitivity study of the assembly was carried out. The sodium flow rate and the gamma and neutron flux variation effects on assembly were investigated around the reference flow and reactor power established above. COBRA-IIIC results indicate that at the reference flow, boiling will still occur with up to 10% deviation in the

Figure 10. Radial Peaking Factors Used in Assembly Design

heat flux. Boiling in the assembly was more sensitive to changes in flow rate. A 10% decrease in flow rate gives boiling with a higher quality, but does not seem to yield violent boiling which could void the entire assembly. Although calculation provides nominal design values, it is recommended that an assembly built for EBR-II operation undergo out of core flow tests to verify and possibly adjust flow conditions.

Sodium Superheat

Any design of a device which proposes to boil liquid sodium must consider sodium superheat. It is well known that the liquid adjacent to the heating surface must become superheated in order to initiate a bubble (50). In the case of liquid sodium, determining the degree of superheat necessary to boil is difficult. Because of the low Prandtl numbers associated with liquid metals (in this case, $Pr = .0038$), the temperature profiles are much less abrupt at the heating surface than in the case of nonmetallic liquids. Also, liquid sodium has very good wetting characteristics. This in turn makes cavities more likely to be flooded, so that there is an absence of nucleation centers (50).

A review of recent literature, addressing itself to the amount of superheat present during sodium boiling, suggests that the degree of superheat may be correlated to the rate of temperature increase (temperature ramp), velocity of the fluid, previous flow-temperature history of the boiling apparatus, and heat flux (33,51). It may also be related to the amount of entrained inert gas in the liquid sodium (35). There is by no means universal agreement on the parameters that govern the amount of superheat or the mechanisms that explain observed effects in recent sodium boiling experiments (see, for example, the discussion at the end of reference 51).

In order to estimate the degree of superheat that would be present in the boiling assembly, the correlation of Pezzilli, as reported by Dwyer (33), was used. This correlation is given by:

$$(t_w - t_{sat}) = \frac{2(t_w - t_{sat})^*}{(Re^*/Re)^{0.88} + (Re/Re^*)^{0.88}}$$

where,

- $(t_w - t_{sat})$ is the degree of superheat, °F
- $(t_w - t_{sat})^*$ is the maximum amount of superheat for the particular case, °F
- Re is the Reynolds number
- Re^{*} is the Reynolds number at which incipient boiling superheat will be the same as that for pool boiling

The study of Dwyer used 316 SS, with a polished surface finish (14-18 microin.). When this correlation is assumed for the EBR-II boiling sub-assembly as designed, a superheat value of approximately 110°F is obtained. This superheat should only be regarded as approximate, however. This value of superheat is close to the value for pool boiling and thus it should probably be considered as an upper limit for superheat in the assembly. It should be noted that there are many variables in the Dwyer experiment which will not necessarily be similar to the EBR-II assembly, such as surface roughness, etc.

Experimental evidence (33) shows that a value of approximately 40°F may be the lower limit for the boiling assembly. Experiments in boiling sodium out-of-core under similar conditions of heat flux and flow in the assembly indicate a superheat of 20°F to 100°F (53).

The boiling device was designed to boil at a superheat of approximately 80°F. This is considered to be a reasonable value in light of known experimental evidence and correlations.

The COBRA-IIIC code has no provision for superheated boiling. Consequently, in order to insure the sodium boiling apparatus would actually boil liquid sodium in EBR-II with superheat, COBRA input was modified for superheat. This modification consisted of changing the outlet plenum pressure so that an 80°F superheat was reflected in the saturation temperature.

Temperature Distribution

The final exit temperatures of each channel of the boiling subassembly are given in Figure 11, just prior to the onset of boiling. An axial temperature profile for channel 1 is given in Figure 12 for the boiling case. These are the temperature profiles calculated by COBRA-IIIC. Complete axial and radial temperatures for each channel are given in Appendix A.

The low heat flux present in the tantalum pins combined with the high thermal conductivity of both tantalum and Inconel result in a very low temperature decrease from the center of the pin to the pin wall. During normal operation this temperature difference is only a few degrees Fahrenheit.

Although the temperature differences within a pin are small, the subassembly will operate at a high temperature (considerably higher than other subassemblies in EBR-II). Thus differential expansion must be taken into account. To allow for differential expansion, the tantalum pins are held only at the bottom of the subassembly by a grid spacer.

Figure 11. Temperature Distribution of the Assembly (Exit) Prior to Boiling Initiation

Figure 12. Axial Temperature Profile of Channel 1

There is sufficient clearance between the top of the pins and the mixer section for expansion.

Each pin contains a hollow space above the tantalum. This space can also accommodate some differential expansion within the pin. It could also conceivably be used for instrument location. The space is filled with argon gas.¹ The pressure at the top of the pin during assembly operation is approximately 624 psi. The insulated space at the top of the pin helps insure that the majority of heat is added from the tantalum pin. By localizing the position of heat addition, the approximate place of initiation of boiling is more closely defined. This aids instrument location within the assembly.

The relatively low heat generation in the tantalum implies that as much heat as possible must be imparted to the sodium in the inner section of the boiling assembly. Due to the high conductivity of liquid sodium, a means must be provided to insulate part of the liquid sodium from the surrounding reactor subassemblies. For this purpose, an insulating can is installed between the tantalum pins and the outer subassembly wall. This can is fabricated out of Inconel-X750 and contains an annulus which is filled with argon gas. This allows an 8% loss of the total heat added from the center section by the tantalum pins.

One of the design requirements cited earlier was the restriction on the outlet temperature of the INSAT. The sodium in the heated section will be at a temperature of approximately 1729°F. In order to reduce this temperature, some of the liquid sodium is bypassed around the insulating can. This sodium is then recombined with the boiling sodium in

¹A ceramic insulator may be used instead, depending upon the method of pin fabrication.

the mixer section. The maximum outlet temperature of 1048°F was achieved by varying the flow through the outer channels in the subassembly. This flow study was accomplished with the one-sixth geometry model for COBRA-IIIC. The bypass flow also cools the insulating can. The flow in the bypass channels is approximately 2.8 times the flow through the inner assembly. An example of one-sixth geometry for the conditions of 75% power and full flow is given in Appendix A.

Stress Analysis

In this section the various stresses pertaining to the components will be considered. It should be emphasized that detailed stress calculations were not accomplished. Maximum stresses (in accordance with reference 41) were calculated for all components in order to ascertain if any component should be altered or redesigned.

Stress may originate from either a temperature gradient or mechanical loading (5). In considering the thermal stresses, maximum temperature differences were used. The maximum stress components for the tantalum pin are the axial and tangential components (5). These stresses reach their maximum point away from the end faces of the pin and are 0.5% of yield stress. At the end faces, the tangential stress is approximately 1% of yield strength.

The Inconel cladding was considered as a tube conducting heat from inner to outer surface. Internal heat generation in the cladding was slight and therefore neglected. In this case, the maximum stresses are the circumferential and axial stresses (5). These are equal and occur at the inner surface of the cylinder. This stress represents approximately 6% of yield stress. Temperature stresses in the other

components of the boiling subassembly are low and do not present a problem, with the exception of the mixer section.

The design of the mixer section is affected by two conditions which result from solutions to other subassembly design problems. These conditions are high temperature gradient between boiling section and bypass channels, and pressure pulses from collapsing bubbles. The mixer section was thickened to allow for the high temperature gradient (approximately 900°F) across the inner portion of this section.

Mechanical stresses from pressure pulses must also be examined. Pulses from collapsing bubbles in the mixer section can be as high as 400 atmospheres (46). This section of the boiling assembly has been made as massive as possible and in its present design can withstand the anticipated pressure pulses and temperature gradients.

Tantalum has also shown some swelling under irradiation (42), which could possibly produce some mechanical stress. Using the correlation developed by Pitner and Bates (42), the swelling should be on the order of 0.3% $\Delta V/V$. This swelling is the total that will occur over a 43-day period at 1700°F.

Decay Heat

Decay heating of the tantalum must be considered, since it is relatively high (42). Decay heating was computed for the tantalum using twenty-two neutron energy groups. Total decay heating immediately after shutdown, assuming a 43-day irradiation time at 75% power, is 71.21 W. This is approximately 0.3% of the total power generated in the pins during reactor operation. Table 3 gives the decay heating rate as a function of time. Assembly operation immediately after shutdown is shown in

Figure 13 for both auxiliary pump flow and natural circulation. Natural circulation is sufficient to cool the subassembly immediately after shutdown with no boiling.

TABLE 3
DECAY HEAT GENERATION

<u>TIME</u>	<u>HEAT GENERATION</u>
6 hr	243.04 Btu/hr
12 hr	234.76 Btu/hr
18 hr	226.77 Btu/hr
1 day	211.58 Btu/hr
2 days	184.2 Btu/hr
5 days	121.54 Btu/hr

If natural circulation flow continues to decrease after shutdown as shown in the Experimenters Guide (41), boiling may possibly reinitiate. If superheat and other factors affecting superheat are ignored, then the power to flow ratio is sufficient for the assembly to boil about 1 minute after shutdown (with natural circulation). This boiling is mild and would continue for approximately 8 to 10 minutes after shutdown. It must be emphasized, however, that because of the extremely low flow from natural circulation, the conditions in the assembly are similar to those for pool boiling in this case. Pool boiling of liquid sodium takes place with superheats in excess of 100°F (24). Thus, although the power to flow ratio is sufficient for boiling with natural convection, the requisite conditions for boiling may not actually exist in the assembly after shutdown.

CHANNEL EXIT SUMMARY RESULTS

CASE 2 DECAY HEAT WITH ALX PUMP FLOW

DATE

MASS BALANCE - -

MASS FLOW IN 2.35228E-12 LB/SEC
 MASS FLOW OUT 2.35228E-12 LB/SEC
 MASS FLOW ERROR -2.52779E-12 LB/SEC

ENERGY BALANCE - -

FLOW ENERGY IN 8.42360E+00 BTU/SEC
 ENERGY ADDED 1.42436E-01 BTU/SEC
 FLOW ENERGY OUT 8.56578E+00 BTU/SEC
 ENERGY ERROR -2.50827E-04 BTU/SEC

CHANNEL (NO.)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/FT3)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/FR-FT2)
1	366.71	765.81	53.34	.000	.000	.0022	.0510
2	385.93	765.54	53.34	.000	.000	.0043	.0428
3	366.57	764.25	53.86	.000	.000	.0165	.1120

CHANNEL EXIT SUMMARY RESULTS

CASE 3 DECAY HEAT WITH NATURAL CIRCULATION FLOW

DATE

MASS BALANCE - -

MASS FLOW IN 1.15114E-02 LB/SEC
 MASS FLOW OUT 1.15114E-02 LB/SEC
 MASS FLOW ERROR 4.67434E-14 LB/SEC

ENERGY BALANCE - -

FLOW ENERGY IN 4.21180E+00 BTU/SEC
 ENERGY ADDED 1.42436E-01 BTU/SEC
 FLOW ENERGY OUT 4.35398E+00 BTU/SEC
 ENERGY ERROR -2.50656E-04 BTU/SEC

CHANNEL (NO.)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/FT3)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/FR-FT2)
1	406.05	831.68	52.78	.000	.000	.0011	.0256
2	406.02	831.58	52.79	.000	.000	.0022	.0214
3	367.26	764.50	53.84	.000	.000	.0083	.0560

Figure 13. Subassembly Outlet Temperatures With Decay Heating

Sensor Location

The objectives of sensor location are twofold. One purpose is to furnish a means of collection of sodium boiling data. The other is to provide a method for monitoring subassembly operation. Abnormal operation may then be quickly detected and corrected. The theory of the placement of these sensors is not a part of this thesis. Hence, only the location of the sensors will be described. There are three types of sensors: flow meters, thermocouples, and void detectors.

The flow meters are the standard permanent magnet type for the EBR-II INSAT. Operation of these flow meters is similar to that of a D. C. generator (32). As the conducting liquid sodium moves through the flow meter tube placed in a stable magnetic field, a potential is developed across the tube at right angles to the field. Obviously, this potential is proportional to the volumetric flow rate of the liquid sodium.

Thermocouples are the second type of sensor provided. These will be placed on the surface of the outer six tantalum pins. The thermocouples will replace the wire wrap of these tubes at staggered height intervals of one inch. For example, one tube could have a thermocouple located at 15 inches, another at 16 inches, etc. A second wire wrap thermocouple will be provided on each of the outer six tantalum pins. Each of these second thermocouples will be placed seven inches above the other thermocouple already on the tube. Thus, if the first tube had a thermocouple located at 15 inches, the second thermocouple would be located above the first thermocouple at 22 inches. The leads from the thermocouples will be brought up the assembly and around the upper flow meter. The upper portion of each of the six outer tantalum pins will be double wire wrapped.

Void sensors will also be located in the subassembly. These will be placed just on the inside of the inner insulating can wall. They may be staggered in height so as to sense a larger region. These detectors sense sodium vapor by measuring changes in conductivity of the liquid sodium.

The total number of leads for all these detectors is 20, which is within the capability of INSAT.

Economic Analysis

A broad economic assessment was undertaken for the boiling assembly. The principal source of the assessment was Argonne National Laboratory, although Battelle Northwest Laboratory, Hanford Engineering Laboratory, and two private firms were also consulted. The approximate cost of fabrication of the entire subassembly, including instrumentation, is \$25,000 to \$40,000 (52). When the cost of quality assurance, paper-work necessary for EBR-II, and required testing of the boiling assembly is included, the total price is \$250,000 to \$500,000 (52). These costs, however, should be regarded as approximate. Any unforeseen problem, such as fabrication of the Inconel-clad tantalum pins, could raise the cost considerably.

SAFETY ANALYSIS

Any experimental device which is to be used in EBR-II must be analyzed for loss of flow condition and for a 125% reactor overpower condition. These accidents are considered in this section. In addition, a critical heat flux for the assembly is determined.

Results given previously for decay heating have shown that auxiliary pump flow and natural convection flow were found sufficient to cool the subassembly immediately after reactor shutdown. Thus the boiling assembly will not offer a hazard to the reactor during a loss of flow accident followed by a reactor scram if auxiliary pump flow is available. The two most hazardous cases are then loss of flow without reactor shutdown, and reactor shutdown with only natural circulation.

The case of loss of flow without reactor shutdown is the most dangerous of the two cases. As a worse case, entire voiding of the subassembly was assumed. The outer cladding was taken as an adiabatic wall, and the reactor was assumed to continue operation at 75% power. Since the thermal conductivities of tantalum and Inconel are high, they may be assumed to be thin walled thermally (31). Thus the heat balance is:

$$q''S + q'''V = \rho C_p \frac{dT}{dt}$$

where,

q'' is the heat flux, Btu/hr-ft²

q''' is the volumetric heat generation rate, Btu/hr-ft³

V is the volume, ft³

S is the surface area, ft²

ρ is the density, lbm/ft³

C_p is the specific heat, Btu/lbm-°F

t is the time, hr

T is the temperature, °F

Solution of this equation for an adiabatic wall gives a heating rate of approximately 33°F/min. Assuming that the initial cladding temperature was 1729°F, this would give 22 minutes before cladding meltdown. Thus, even in the extremely unlikely event of subassembly voiding or loss of coolant flow without reactor scram, there should be adequate time for the operator to take action before cladding failure.

Although the probability of voiding the entire assembly is low, there is also the possibility that the assembly will boil for some time after reactor shutdown from decay heating. Using the decay heating rate in tantalum and again assuming the assembly is completely voided and no heat is lost in the tantalum pins, the temperature rise is on the order of 0.1°F/min. The duration of decay heat boiling in the assembly is thus much shorter than the amount of time required for cladding failure.

The other required accident is a 125% overpower condition. Since the subassembly is designed to boil at 75% reactor power, subassembly operation must then be evaluated at 94% reactor power. This evaluation was accomplished by use of COBRA at 100% subassembly flow. Average outlet temperature was 1148°F, which is below the saturation temperature. If the assembly power is raised to 125%, a temperature of approximately 1250°F was reached.¹

¹This temperature was calculated by extrapolation of COBRA results for lower power cases. COBRA would not give results for this high power combined with the low flow in the assembly.

The critical heat flux for the assembly was estimated from the correlation of Lowermilk (derived from data of Hoffman and Krakoviak) as reported by Dwyer (24). This correlation is:

$$(Q/A)_c = 270(1/D)^{0.2}(D/L)^{0.85}(G)^{0.85}$$

where,

$(Q/A)_c$ is the critical heat flux, Btu/hr-ft²

D is the hydraulic diameter, ft

L is the length of the assembly, ft

G is the mass flux through the assembly, Lbm/hr-ft²

A graph showing boiling inception and critical heat flux is given in Figure 14, for the inner channels. Although the region of safety cannot be precisely determined by this critical heat flux correlation, the equation is believed to give conservative values (50). The point of boiling inception for the assembly as computed by COBRA-IIIC is also given in Figure 13.

Figure 14. Critical Heat Flux and COBRA-Predicted Region of Boiling

DESIGN EVALUATION

At this point, it is perhaps appropriate to evaluate the overall design with reference to the stated design objectives and requirements. The following design requirements have been satisfied:

1. The subassembly is instrumented for obtaining data.
2. All of the experimental components are made of materials which are compatible with liquid sodium.
3. The exit coolant temperature is within the maximum allowable outlet temperature for INSAT.

The gamma heated assembly has been shown to be safe for a loss of flow accident and an overpower accident. There is sufficient operator reaction time during a complete voiding of the boiling assembly. Reliability of the heater is assured since there are no moving parts in the assembly and no power leads that must be provided. An adequate margin for flow error calculations or heat flux calculations is provided by designing the assembly for boiling at 75% reactor power and 100% flow. Thus, the gamma heated assembly is feasible for EBR-II.

Additionally, experiments conducted in EBR-II will advance the present state of knowledge in the area of sodium boiling. Sodium boiling in a reactor will be a considerable improvement toward discovery of mechanisms of sodium boiling inception under prototypical conditions. The success and durability of an instrument to detect onset of sodium boiling can also be tested using the gamma heated assembly. Finally, the gamma heated experiments will provide the groundwork for potential future experiments with a fission heated assembly.

It is recommended that the gamma heated assembly be constructed and used in EBR-II. The next step involves more detailed drawings, instrumentation of the assembly, and flow testing. Some variations on this basic design could also be considered. The most promising of these is an assembly with gamma heated outer pins and electrically heated central pin. Such an arrangement would provide better heat flux control and could operate over a wider range of conditions than the totally gamma heated assembly.

REFERENCES

1. Koch, L. J. et al., "Hazard Summary Report Experimental Breeder Reactor II (EBR-II)," ANL-5719, 1964.
2. Koch, L. J. et al., "Addendum to Hazard Summary Report Experimental Breeder Reactor II (EBR-II)," ANL-5719 (Addendum), 1964.
3. Berry, W. E., Corrosion in Nuclear Applications, John Wiley, 1971.
4. Jaeger, R. G., ed., "Shielding Fundamentals and Methods," in Engineering Compendium on Radiation Shielding, Springer-Verlag, 1961.
5. Smith, L. W., "Structural Analysis," in Reactor Handbook, edited by Stuart McLain and John H. Martens, Interscience, 1964.
6. Leipunshii, O. I., Novoyhilov, B. V., and Sakharov, V. N., The Propagation of Gamma Quanta in Matter, Pergamon, 1965.
7. Ford, W. D., "Bubble Growth and Collapse in Narrow Tubes with Non-uniform Initial Temperature Profiles," ANL-7746, 1970.
8. Ruther, W. E. et al., "Materials-Coolant Interactions in EBR-II," ANL-7670, 1970.
9. Greenberg, S. et al., "The EBR-II Materials Surveillance Program: II. Results of Surv-2," ANL-7682, 1970.
10. Smith, D. L., "Empirical Formula for Interpolation of Tabulated Photon Photoelectric Cross Sections," ANL-7796, 1971.
11. Rockwell, T. III, ed., "Reactor Shielding Design Manual," TID-7004, USAEC, 1956.
12. Goldstein, H., and Wilkins, J. E. Jr., "Calculations of the Penetration of Gamma Rays," NYO-3075, Oak Ridge, 1954.
13. Millhollen, M. K., and Sutey, A. N., "EBR-II Instrumented Sub-assembly Test Interim Report," BNWL-1424, 1970.
14. Greenberg, S., "The EBR-II Materials Surveillance Program: I. Program and Results of Surv-1," ANL-7624, 1969.
15. Argonne National Laboratory, "Reactor Physics Division Annual Report," ANL-7410, 1968.
16. Smith, A. B. et al., "Fast Neutron Scattering from Tantalum, Rhenium, and Platinum," ANL-7363, 1968.
17. Holtz, R. E., and Singer, R. M., "A Study of the Incipient Boiling of Sodium," ANL-7608, 1970.

18. Holtz, R. E., and Singer, R. M., "On the Superheating of Sodium at Low Heat Fluxes," ANL-7383, 1967.
19. Holtz, R. E., "The Effect of the Pressure-Temperature History upon Incipient-Boiling Superheat in Liquid Metals," ANL-7184, 1966.
20. Holtz, R. E., "A Study of the Initiation of Nucleate Boiling in the Liquid Metals," ANL-6980, 1964.
21. Logan, D. et al., "Studies of Boiling Initiation for Sodium Flowing in a Heated Channel," AI-AEC-12767, 1970.
22. Unruh, W. G., and Tomlinson, M., "Mean Gamma Ray Energy Absorption Coefficients," Nuclear Applications, Sept. 1967, Vol. 3:548-549.
23. Stehn, J. R., ed., Naval Reactors Physics Handbook, Knolls Atomic Power Laboratory, 1954.
24. Dwyer, O. E., "Recent Developments in Liquid Metal Heat Transfer," Atomic Energy Review, 1966, Vol. 4:3-92.
25. Noyes, R. C., and Lurie, H., "Boiling Sodium Heat Transfer," Proceedings of the Third International Heat Transfer Conference, 1966, Vol. 5:92-100.
26. Mohr, D., and Gillette, J. C., "A Code for Analyzing Parallel Channel Thermal-Hydraulics in EBR-II During Natural Convection Conditions," American Nuclear Society Transactions, 1975, Vol. 21:92-100.
27. Tapuru, A., "Diversion Cross Flow Between Two Communicating Parallel Flows," American Nuclear Society Transactions, 1975, Vol. 21:414.
28. Wright, S. A., and Albrecht, R. W., "Sodium Boiling Detection in LMFBR's by Acoustic-Neutronic Cross Correlation," American Nuclear Society Transactions, 1975, Vol. 21:478-479.
29. Fontana, M. H. et al., "Effect of Inlet Blockage on 19-Rod Simulated LMFBR Fuel Assemblies," American Nuclear Society Transactions, 1973, Vol. 17.
30. Schlechtendahl, E. G., "Sieden des Kuehlmittels in Natriumgekuehlten Schnellen Reaktoren," KFK-1020, 1969.
31. Rohsenow, W. M., and Hartnett, J. P., ed., Handbook of Heat Transfer, McGraw-Hill, 1973.
32. Smaardyk, A. et al., "Design and Analysis of Instrumented Sub-assembly for EBR-II," ANL-7423, 1968.
33. Kays, W. M., and London, A. L., Compact Heat Exchangers, McGraw-Hill, 1964.

34. Dwyer, O. E. et al., "Incipient Boiling Superheat for Sodium in Turbulent Channel Flow: Effects of Heat Flux and Flow Rate," International Journal of Heat Transfer, 1973, Vol. 16.
35. Winterton, R.H.S., "Liquid Metal Superheat in Forced Convection," International Journal of Heat Transfer, 1975, Vol. 18:205-212.
36. Holtz, R. E. et al., "The Prediction of Incipient Boiling Superheats in Liquid Metal Cooled Reactor Systems," Nuclear Engineering and Design, 1971, Vol. 16:253-265.
37. Hampel, C. A., ed., Rare Metals Handbook, Reinhold, 1961.
38. Kelber, C. N., "Phenomenological Research in LMFBR Accident Analysis," Nuclear Safety, 1973, Vol. 14:304-314.
39. France, D. M. et al., "Experimental Determination of Sodium Superheat Employing LMFBR Simulation Parameters," Journal of Heat Transfer, August 1974:359-364.
40. Yevick, J. G., ed., Fast Reactor Technology: Plant Design, MIT Press, 1966.
41. Argonne National Laboratory, Guide for Irradiation Experiments, in EBR-II, USAEC, 1975.
42. Thorely, A. W., and Tyzack, G., "Corrosion Behavior of Steels and Nickel Alloys in High Temperature Sodium," (SM-85/18), Proceedings of the Symposium on Alkali Metal Coolants-Corrosion Studies and System Operating Experience, IAEA, 1966.
43. Bates, J. F., and Pitner, A. L., "Dimensional Stability of Tantalum Control Rods in LMFBR's," Nuclear Technology, 1972, Vol. 16:406-409.
44. Baroczy, C. J., "SODIFAZE A Steady-State Multichannel Boiling Sodium Code," AI-AEC-12804, 1971.
45. Rowe, D. S., "COBRA-IIIC: A Digital Computer Program for Steady State and Transient Thermal Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements," BNWL-1695, 1974.
46. Golden, G. H., and Tokar, J. V., "Thermophysical Properties of Sodium," ANL-7323, 1967.
47. Theofanous, T. G., et al., "Sodium Bubble Collapse and Pressure Generation," American Nuclear Society Transactions, 1969, Vol. 12: 909-911.
48. Miller, L. B., and Jarks, R. E., "Local Modification of Irradiation Conditions," ANL/EBR-035, 1971.
49. Evans, R. D., The Atomic Nucleus, McGraw-Hill, 1955.

50. El-Wakil, M. M., Nuclear Heat Transport, International, 1971.
51. Dwyer, O. E. et al., "Incipient-Boiling Super Heats for Sodium in Turbulent Channel Flow: Effect of Rate of Temperature Rise," Journal of Heat Transfer, 1974, Vol. 95:159-165.
52. Argonne National Laboratory, private communication, August, 1975.
53. Eisenhower, S. W., private communication to R. W. Albrecht, July, 1975.

APPENDIX A

Sample COBRA Input

Seven Pin Bundle Temperature Results, COBRA-IIIC

Bundle Outlet Temperature at Normal Operation
(one-sixth geometry)

SAMPLE COBRA INPUT

INPUT FOR CASE	1	7-PIN WIRE WRAP GEOMETRY	DATE	TIME
NOM READING CARD GROUP NO.	1			
NOM READING CARD GROUP NO.	2			
NOM READING CARD GROUP NO.	3			
NOM READING CARD GROUP NO.	4			
NOM READING CARD GROUP NO.	7			
NOM READING CARD GROUP NO.	8			
NOM READING CARD GROUP NO.	9			
NOM READING CARD GROUP NO.	10			
NOM READING CARD GROUP NO.	11			
NOM READING CARD GROUP NO.	12			
NOM READING CARD GROUP NO.	-3			

FLUID PROPERTY TABLE									
P	T	VF	VG	HF	HG	VISC.	KF	SIGMA	
.001	600.00	.01842	409806.00000	357.49	2227.58	.75580	42.98000	.01161	
.003	700.00	.01856	170122.00000	365.88	2234.13	.71390	42.18000	.01162	
.007	750.00	.01870	83102.00000	371.19	2240.18	.67670	41.33000	.01143	
.014	800.00	.01885	41266.00000	375.43	2245.77	.64370	40.62000	.01124	
.026	850.00	.01900	21653.00000	411.61	2250.94	.61420	39.85000	.01105	
.052	900.00	.01915	11432.00000	420.73	2255.74	.58770	39.04000	.01086	
.093	950.00	.01930	6863.00000	441.31	2260.23	.56370	38.35000	.01067	
.160	1000.00	.01946	4111.00000	450.86	2264.44	.54190	37.61000	.01048	
.260	1050.00	.01962	2549.00000	471.88	2268.44	.52210	36.81000	.01029	
.420	1100.00	.01978	1632.00000	491.88	2272.27	.50040	36.01000	.01000	
.600	1150.00	.01995	1075.00000	511.87	2275.97	.48720	35.47000	.00991	
1.000	1200.00	.02011	720.90000	511.85	2279.60	.47170	34.79000	.00972	
1.490	1250.00	.02029	503.40000	531.85	2283.17	.45740	34.09000	.00953	
2.150	1300.00	.02046	356.30000	540.85	2286.72	.44420	33.42000	.00934	
3.040	1350.00	.02064	257.20000	561.89	2290.28	.43190	32.76000	.00915	
4.230	1400.00	.02082	189.10000	570.95	2293.86	.42040	32.11000	.00896	
5.770	1450.00	.02100	141.40000	592.06	2297.47	.40900	31.47000	.00877	
7.760	1500.00	.02119	107.40000	617.21	2301.10	.39900	30.84000	.00857	
10.270	1550.00	.02138	82.77000	627.42	2304.78	.39000	30.22000	.00838	
13.400	1600.00	.02157	64.63000	637.70	2308.47	.38110	29.61000	.00819	
17.170	1650.00	.02177	51.39000	651.05	2312.80	.37270	29.01000	.00800	
21.780	1700.00	.02197	41.25000	664.49	2316.95	.36470	28.42000	.00781	
27.320	1750.00	.02217	33.45000	684.02	2321.10	.35720	27.84000	.00762	
33.930	1800.00	.02238	27.40000	699.05	2325.24	.35010	27.27000	.00743	
41.720	1850.00	.02260	22.64000	715.39	2329.34	.34330	26.72000	.00724	
50.840	1900.00	.02281	18.87000	731.24	2333.38	.33690	26.17000	.00705	
61.430	1950.00	.02303	15.85000	747.22	2337.34	.33070	25.63000	.00686	
73.640	2000.00	.02326	13.41000	763.34	2341.20	.32490	25.11000	.00667	
86.820	2050.00	.02349	11.42000	779.60	2344.94	.31930	24.59000	.00648	
103.500	2100.00	.02372	9.77400	790.01	2348.55	.31390	24.09000	.00629	

FRICITION FACTOR CORRELATION

CHANNEL TYPE 1 FRICT = .500*RE**(-.320) + .0056

WALL VISCOSITY CORRECTION TO FRICTION FACTOR IS INCLUDED

TWO-PHASE FLOW CORRELATIONS

NO SUBCOOLED VOID CORRELATION

BULK VOID FRACTION GIVEN AS A 7 TERM POLYNOMIAL FUNCTION OF QUALITY WITH COEFFICIENTS OF

-7.7352E-02	-8.2644E+01	2.7963E+03	-7.1583E+04	1.0281E+06	-7.6223E+06	2.2638E+07
-------------	-------------	------------	-------------	------------	-------------	------------

FRICTION MULTIPLIER GIVEN AS A 6 TERM POLYNOMIAL FUNCTION OF QUALITY WITH COEFFICIENTS OF

1.0000E+00	1.0417E+03	-5.3301E+04	1.4329E+06	-1.3726E+07	4.5783E+07
------------	------------	-------------	------------	-------------	------------

HEAT FLUX DISTRIBUTION

X/L	RELATIVE FLUX
.000	.423
.067	.922
.133	1.049
.200	1.138

SUBCHANNEL INPUT DATA			HEATED			ADJACENT CHANNEL NO., SPACING, CENTER-TO-CENTER								
CHANNEL NO.	TYPE	AREA (SQ-FT)	HEATED PERIM. (FT)	HEATED PERIM. (FT)	HYDRAULIC DIAMETER (FT)									
1	1	0.022400	0.051700	0.051700	0.115113	2	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
2	1	0.022400	0.051700	0.051700	0.115113	3	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
3	1	0.022400	0.051700	0.051700	0.115113	4	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
4	1	0.022400	0.051700	0.051700	0.115113	5	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
5	1	0.022400	0.051700	0.051700	0.115113	6	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
6	1	0.022400	0.051700	0.051700	0.115113	7	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
7	1	0.022400	0.051700	0.051700	0.115113	8	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
8	1	0.022400	0.051700	0.051700	0.115113	9	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
9	1	0.022400	0.051700	0.051700	0.115113	10	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
10	1	0.022400	0.051700	0.051700	0.115113	11	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
11	1	0.022400	0.051700	0.051700	0.115113	12	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000
12	1	0.022400	0.051700	0.051700	0.115113	13	0.0400	0.3000	6	0.0400	0.3000	7	0.0400	0.3000

BRAY PITLO	=	1200	INCHES
BRAY IMICKHUS	=	6400	INCHES
PH. USM-TLD	=	6200	INCHES

NEW INPUT DATA			FRACTION OF POWER TO ADJACENT CHANNELS (ADJ. CHANNEL NO.)							
NO	TYPE	CIA	PARTIAL POWER							
NO	NO	TYPE	FACTOR							
1	1	22222	ACCG	.1670(1)	.1670(2)	.1670(3)	.1670(4)	.1670(5)	.1670(6)	

2	1	.4200	1.1000	.1670(1)	.1670(6)	.3330(7)	.3330(12)	-.0000(-3)	-.0000(-0)
3	1	.4200	1.1000	.1670(1)	.1670(2)	.3330(7)	.3330(8)	-.0000(-0)	-.0000(-0)
4	1	.4200	1.0500	.1670(2)	.1670(3)	.3330(8)	.3330(9)	-.0000(-0)	-.0000(-0)
5	1	.4200	.9500	.1670(3)	.1670(4)	.3330(9)	.3330(10)	-.0000(-0)	-.0000(-0)
6	1	.4200	.9500	.1670(4)	.1670(5)	.3330(10)	.3330(11)	-.0000(-0)	-.0000(-0)
7	1	.4200	1.0500	.1670(5)	.1670(6)	.3330(11)	.3330(12)	-.0000(-0)	-.0000(-0)

THERMAL PROPERTIES FOR FUEL MATERIAL

5 RADIAL FUEL NODES

FUEL PROPERTIES					CLAD PROPERTIES				
TYPE	COND.	SP. HEAT	DENSITY	DIA.	COND.	SP. HEAT	DENSITY	THICK.	GAP COND.
NO. (B/HR-FT-F)	(B/HR-FT-F)	(B/LB-F)	(LB/FT3)	(IN.)	(B/HR-FT-F)	(B/LB-F)	(LB/FT3)	(IN.)	(B/HR-FT2-F)
1	39.00	.0370	1040.0	.4000	14.90	.1100	503.9	.0100	5000.00

CALCULATION PARAMETERS

CROSSFLOW RESISTANCE, KIJ	.500
MOMENTUM TURBULENT FACTOR	-.0000
PARAMETER, (S/L)	.500
CHANNEL LENGTH	30.00 INCHES
CHANNEL ORIENTATION	.0 DEGREES
NUMBER OF AXIAL NODES	30
NODE LENGTH	1.000 INCHES
NUMBER OF TIME STEPS	-0
TOTAL TRANSIENT TIME	-.000 SECONDS
TIME STEP	.0000 SECONDS
ALLOWABLE ITERATIONS	30
FLOW CONVERGENCE FACTOR	1.000E-02

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MIXING CORRELATIONS

SUBCOOLED MIXING, BETA =	.0124*(D/S)*RE**(-.1000)
BOILING MIXING, BETA IS ASSUMED SAME AS SUBCOOLED	
CONVECTION MIXING, GEOMETRY FACTOR =	1.0000

OPERATING CONDITIONS

SYSTEM PRESSURE =	29.0 PSIA
INLET ENTHALPY =	365.9 BTU/LB
AVG. MASS VELOCITY =	.002 MILLION LB/(HR-SQFT)
INLET TEMPERATURE =	700.0 DEGREES F
AVG. HEAT FLUX =	.038500 MILLION BTU/(HR-SQFT)
UNIFORM INLET TEMPERATURE	
INDIVIDUAL SUBCHANNEL FLOWS SPECIFIED	

SUBASSEMBLY CHANNEL DATA, AT NORMAL OPERATION

CHANNEL EXIT SUMMARY RESULTS

CASE 1 7-PIN WIRE WRAP GEOMETRY

DATE

MASS BALANCE - -

MASS FLOW IN 5.99020E-02 LB/SEC

MASS FLOW OUT 6.02794E-02 LB/SEC

MASS FLOW ERROR 3.17407E-04 LB/SEC

ENERGY BALANCE - -

FLOW ENERGY IN 2.19389E+01 BTU/SEC

ENERGY ADDED 2.05774E+01 BTU/SEC

FLOW ENERGY OUT 4.27281E+01 BTU/SEC

ENERGY ERROR 2.11717E-01 BTU/SEC

CHANNEL (NO.)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/FT3)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/FR-FT2)
1	710.92	1723.06	6.59	.020	.855	.1036	.0925
2	709.91	1729.06	6.76	.020	.851	.1037	.0848
3	710.96	1729.06	6.58	.020	.855	.1032	.0732
4	711.23	1729.06	6.54	.021	.850	.1027	.0627
5	712.55	1729.06	6.33	.021	.851	.1029	.0667
6	712.10	1729.06	6.40	.021	.859	.1034	.0793
7	703.31	1729.06	6.95	.019	.847	.1066	.0652
8	707.41	1729.06	7.21	.018	.841	.1070	.0696
9	705.72	1729.06	7.54	.017	.834	.1069	.0689
10	703.59	1729.06	7.56	.017	.833	.1069	.0690
11	709.24	1729.06	6.88	.019	.849	.1009	.0680
12	703.60	1729.06	6.81	.020	.850	.1066	.0656

CHANNEL RESULTS

CASE 1 7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

BUNDLE AVERAGED RESULTS

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY FRACTION	VOID	FLOW (LB/SEC)	MASS FLUX (MLB/HR-FT2)
0.0	.63	365.88	705.00	53.48	.000	.000	.0600	.0094
1.0	.64	370.99	716.70	53.75	.000	.000	.0600	.0094
2.0	.61	370.07	733.25	53.60	.000	.000	.0600	.0094
3.0	.58	385.84	753.24	53.55	.000	.000	.0600	.0094
4.0	.55	401.53	815.31	52.32	.000	.000	.0600	.0094
5.0	.52	421.03	881.15	52.39	.000	.000	.0600	.0094
6.0	.49	441.55	943.15	51.84	.000	.000	.0600	.0094
7.0	.46	463.61	1020.46	51.24	.000	.000	.0600	.0094
8.0	.43	485.25	1094.56	50.62	.000	.000	.0600	.0094
9.0	.40	507.98	1173.40	49.99	.000	.000	.0600	.0094
10.0	.37	530.98	1247.09	49.34	.000	.000	.0600	.0094
11.0	.34	553.92	1323.49	48.70	.000	.000	.0600	.0094
12.0	.31	576.66	1399.04	48.06	.000	.000	.0600	.0094
13.0	.29	598.88	1472.52	47.45	.000	.000	.0600	.0094
14.0	.26	620.29	1543.01	46.85	.000	.000	.0600	.0094
15.0	.23	640.80	1610.10	46.29	.000	.000	.0600	.0094
16.0	.20	660.31	1673.50	45.76	.000	.000	.0600	.0094
17.0	.18	676.55	1725.35	45.79	.000	.143	.0600	.0094
18.0	.16	685.34	1723.00	46.35	.005	.039	.0600	.0094
19.0	.15	690.29	1723.00	46.15	.008	.732	.0600	.0094
20.0	.14	695.27	1723.06	46.28	.011	.773	.0600	.0094
21.0	.14	699.37	1723.00	46.20	.013	.800	.0600	.0094
22.0	.11	701.05	1723.06	46.49	.015	.823	.0600	.0094
23.0	.10	703.35	1723.06	46.13	.016	.821	.0600	.0094
24.0	.10	704.73	1723.06	46.83	.017	.828	.0600	.0094
25.0	.07	705.82	1723.00	47.59	.017	.833	.0600	.0094
26.0	.05	706.00	1723.00	47.42	.018	.837	.0600	.0094
27.0	.04	707.27	1723.06	47.29	.018	.839	.0600	.0094
28.0	.03	707.76	1723.00	47.19	.018	.842	.0600	.0094
29.0	.01	708.18	1723.06	47.20	.019	.844	.0600	.0094
30.0	.00	708.49	1723.00	47.34	.019	.845	.0600	.0094

CHANNEL RESULTS

CASE 1 7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0 SECONDS DATA FOR CHANNEL 1

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MMD/M ² -FT ²)
.0	.00	309.08	758.00	53.88	.000	.000	.0038	.0328
1.0	.04	371.74	719.14	53.72	.000	.000	.0037	.0359
2.0	.04	378.12	739.97	53.56	.000	.000	.0033	.0773
3.0	.08	393.52	777.32	53.24	.000	.000	.0031	.0714
4.0	.09	409.07	844.27	52.66	.000	.000	.0034	.0774
5.0	.02	430.16	911.37	52.13	.000	.000	.0035	.0669
6.0	.43	451.57	979.10	51.50	.000	.000	.0039	.0845
7.0	.46	471.23	1147.05	50.99	.000	.000	.0039	.0936
8.0	.43	493.49	1122.06	50.37	.000	.000	.0040	.0921
9.0	.40	515.03	1197.23	49.75	.000	.000	.0040	.0927
10.0	.37	540.24	1277.97	49.06	.000	.000	.0040	.0922
11.0	.34	560.09	1345.02	48.46	.000	.000	.0040	.0914
12.0	.31	583.03	1422.09	47.85	.000	.000	.0039	.0909
13.0	.29	605.34	1495.44	47.25	.000	.000	.0040	.0917
14.0	.26	627.74	1567.40	46.63	.000	.000	.0036	.0918
15.0	.23	650.29	1641.00	46.01	.000	.000	.0035	.0905
16.0	.20	673.06	1714.73	45.39	.000	.000	.0037	.0864
17.0	.18	695.39	1729.26	44.37	.000	.003	.0042	.1114
18.0	.16	692.29	1729.00	44.14	.009	.754	.0044	.1020
19.0	.15	695.53	1729.00	43.97	.011	.778	.0044	.0909
20.0	.14	699.31	1729.06	43.81	.013	.802	.0038	.0871
21.0	.12	702.90	1729.06	43.64	.015	.821	.0035	.0839
22.0	.11	705.21	1729.06	43.64	.017	.832	.0035	.0817
23.0	.09	706.57	1729.06	43.37	.020	.838	.0035	.0811
24.0	.08	707.05	1729.06	43.13	.018	.843	.0035	.0808
25.0	.07	708.97	1729.06	42.92	.019	.848	.0035	.0811
26.0	.05	709.91	1729.06	42.76	.020	.851	.0035	.0795
27.0	.04	711.53	1729.06	42.65	.020	.854	.0027	.0610
28.0	.03	711.24	1729.06	42.54	.021	.856	.0029	.0672
29.0	.01	711.51	1729.06	42.49	.021	.857	.0034	.0777
30.0	.00	711.45	1729.06	42.50	.021	.857	.0035	.0810

CHANNEL RESULTS								
CASE	1	7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY						DATE
TIME =	.0	SECONDS	DATA FOR CHANNEL 2					
DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLOW (LBS/HR-FT2)
.0	.58	365.88	730.24	53.53	.000	.000	.0033	.0333
1.0	.64	371.64	718.82	53.73	.010	.010	.0034	.0360
2.0	.61	376.48	741.15	53.55	.030	.030	.0033	.0369
3.0	.58	383.22	775.06	53.25	.050	.050	.0036	.0427
4.0	.55	405.44	831.34	52.79	.090	.090	.0036	.0542
5.0	.52	427.09	911.21	52.21	.090	.090	.0037	.0552
6.0	.49	447.51	968.94	51.65	.090	.090	.0037	.0551
7.0	.45	453.46	1041.93	51.34	.090	.090	.0038	.0575
8.0	.43	492.57	1118.99	50.59	.090	.090	.0035	.0515
9.0	.40	513.29	1205.12	49.05	.090	.090	.0035	.0535
10.0	.37	538.79	1273.13	49.11	.090	.090	.0038	.0585
11.0	.34	562.68	1353.30	48.42	.090	.090	.0040	.0616
12.0	.31	584.11	1423.71	47.83	.090	.090	.0040	.0629
13.0	.29	605.80	1495.30	47.23	.090	.090	.0037	.0565
14.0	.26	623.04	1570.30	46.65	.090	.090	.0036	.0535
15.0	.23	655.22	1643.77	46.02	.090	.090	.0039	.0592
16.0	.20	667.26	1696.01	45.55	.090	.090	.0040	.0630
17.0	.18	681.55	1729.55	45.34	.092	.604	.0031	.0173
18.0	.16	683.71	1729.65	44.16	.095	.688	.0047	.0162
19.0	.15	683.69	1729.66	42.16	.117	.732	.0041	.0344
20.0	.14	694.04	1729.66	40.55	.110	.772	.0033	.0364
21.0	.12	701.76	1729.66	38.82	.124	.856	.0030	.0334
22.0	.11	703.24	1729.66	38.00	.126	.822	.0033	.0374
23.0	.09	705.39	1729.66	7.01	.017	.033	.0034	.0397
24.0	.08	707.64	1729.66	7.28	.028	.064	.0035	.0517
25.0	.07	708.33	1729.66	7.64	.019	.045	.0031	.0378
26.0	.05	703.55	1729.66	6.51	.019	.046	.0030	.0397
27.0	.04	709.44	1729.66	6.75	.020	.051	.0034	.0376
28.0	.03	713.15	1729.66	6.72	.020	.052	.0035	.0311
29.0	.02	715.33	1729.66	6.67	.021	.053	.0035	.0322
30.0	.00	710.40	1729.66	6.67	.020	.053	.0036	.0331

CHANNEL RESULTS								
CASE	1	7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY						DATE
TIME =	.0	SECONDS	DATA FOR CHANNEL 3					
DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY FRACTION	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/HK-FT2)
.0	.03	365.88	730.00	53.98	.000	.000	.0038	.0308
1.0	.64	371.35	717.80	53.73	.000	.000	.0037	.0364
2.0	.61	377.34	737.44	53.55	.000	.000	.0037	.0362
3.0	.58	387.12	769.44	53.31	.000	.000	.0037	.0350
4.0	.55	403.90	824.83	52.34	.000	.000	.0037	.0358
5.0	.52	424.11	841.32	52.29	.000	.000	.0037	.0361
6.0	.49	445.35	901.75	51.71	.000	.000	.0034	.0292
7.0	.40	468.59	1041.38	51.05	.000	.000	.0031	.0271A
8.0	.43	496.48	1132.52	50.28	.000	.000	.0031	.0273
9.0	.40	513.46	1185.83	49.82	.000	.000	.0037	.0355
10.0	.37	538.09	1271.80	49.20	.000	.000	.0030	.0376
11.0	.34	553.54	1342.19	48.52	.000	.000	.0038	.0607
12.0	.31	581.54	1410.17	47.30	.000	.000	.0039	.0591
13.0	.29	603.38	1487.36	47.30	.000	.000	.0039	.0585
14.0	.26	624.23	1551.92	46.72	.000	.000	.0041	.0519
15.0	.23	644.24	1621.43	46.10	.000	.000	.0039	.0509
16.0	.20	663.83	1684.25	45.85	.000	.000	.0040	.0524
17.0	.18	679.30	1723.65	30.00	.000	.000	.0050	.0500
18.0	.16	682.35	1729.00	16.92	.003	.627	.0042	.0501
19.0	.15	687.76	1723.06	13.04	.000	.724	.0037	.0704
20.0	.14	695.79	1723.06	10.21	.011	.775	.0029	.0561
21.0	.12	700.46	1723.66	8.72	.014	.808	.0033	.0703
22.0	.11	703.65	1723.00	7.97	.016	.824	.0034	.0702
23.0	.09	705.20	1723.66	7.54	.017	.832	.0035	.0502
24.0	.08	706.55	1729.00	7.37	.018	.836	.0035	.0511
25.0	.07	707.77	1723.00	7.24	.019	.843	.0030	.0525
26.0	.05	708.72	1729.06	6.97	.019	.847	.0030	.0533
27.0	.04	709.35	1729.00	6.80	.019	.849	.0030	.0531
28.0	.03	709.80	1729.00	6.77	.020	.851	.0030	.0530
29.0	.01	710.30	1723.06	6.69	.020	.853	.0036	.0530
30.0	.00	710.78	1729.00	6.61	.020	.854	.0031	.0725

CHANNEL RESULTS

CASE 1

7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0

SECONDS

DATA FOR CHANNEL 4

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY FRACTION	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MELB/HQ-FT ²)
0.0	.60	365.88	700.00	53.08	.000	.000	.0030	.0000
1.0	.64	371.15	717.22	53.74	.000	.000	.0037	.0051
2.0	.61	377.64	730.43	53.58	.000	.000	.0030	.0041
3.0	.58	386.56	707.07	53.32	.000	.000	.0030	.0035
4.0	.55	403.03	622.03	52.57	.000	.000	.0036	.0037
5.0	.52	423.50	883.32	52.51	.000	.000	.0030	.0069
6.0	.49	440.37	963.26	51.58	.000	.000	.0031	.0074
7.0	.40	472.87	1053.23	50.34	.000	.000	.0033	.0069
8.0	.43	483.72	1109.48	50.47	.000	.000	.0037	.0056
9.0	.43	514.41	1193.51	49.78	.000	.000	.0030	.0072
10.0	.37	533.32	1261.33	49.29	.000	.000	.0030	.0070
11.0	.34	557.04	1235.80	48.57	.000	.000	.0030	.0061
12.0	.31	579.54	1400.70	47.30	.000	.000	.0030	.0060
13.0	.29	601.63	1462.57	47.35	.000	.000	.0030	.0079
14.0	.20	622.49	1533.22	40.77	.000	.000	.0030	.0077
15.0	.23	642.02	1610.02	46.22	.000	.000	.0030	.0075
16.0	.20	602.04	1679.11	43.09	.000	.000	.0030	.0030
17.0	.16	677.56	1723.33	43.84	.000	.000	.0030	.0073
18.0	.10	635.05	1729.00	44.20	.005	.007	.0032	.0070
19.0	.15	631.95	1723.06	44.27	.009	.052	.0037	.0055
20.0	.14	633.12	1723.00	9.32	.013	.095	.0033	.0062
21.0	.12	702.21	1723.00	8.23	.015	.029	.0034	.0062
22.0	.11	704.42	1729.06	7.73	.017	.000	.0034	.0070
23.0	.09	705.20	1723.00	7.44	.017	.030	.0030	.0058
24.0	.08	707.38	1723.00	7.21	.018	.041	.0035	.0058
25.0	.07	733.02	1723.00	6.39	.013	.040	.0030	.0057
26.0	.05	709.37	1729.00	0.05	.019	.040	.0030	.0050
27.0	.04	709.03	1729.00	0.77	.020	.052	.0036	.0050
28.0	.03	710.42	1729.00	6.67	.020	.053	.0036	.0049
29.0	.02	711.10	1723.00	6.50	.020	.050	.0031	.0071
30.0	.00	710.03	1729.06	0.04	.020	.054	.0027	.0026

CHANNEL RESULTS

CASE 1 7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0 SECONDS DATA FOR CHANNEL 5

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/M ² -FT ²)
.0	.60	369.83	73.00	53.88	.000	.000	.0038	.0008
1.0	.64	371.35	717.06	53.73	.000	.000	.0037	.0006
2.0	.61	377.38	737.56	53.58	.000	.000	.0037	.0040
3.0	.53	387.14	703.52	53.31	.000	.000	.0037	.0048
4.0	.55	404.32	825.03	52.84	.000	.000	.0034	.0079
5.0	.52	426.42	893.99	52.23	.000	.000	.0034	.0072
6.0	.49	452.15	984.34	51.52	.000	.000	.0034	.0053
7.0	.46	469.54	1042.22	51.03	.000	.000	.0036	.0059
8.0	.43	493.40	1121.70	50.37	.000	.000	.0039	.0055
9.0	.40	513.87	1191.05	49.81	.000	.000	.0039	.0054
10.0	.37	536.28	1264.76	49.20	.000	.000	.0039	.0060
11.0	.34	550.19	1337.71	48.55	.000	.000	.0039	.0058
12.0	.31	560.76	1411.01	47.93	.000	.000	.0039	.0050
13.0	.29	602.16	1483.34	47.33	.000	.000	.0039	.0050
14.0	.26	623.42	1553.23	46.75	.000	.000	.0039	.0057
15.0	.23	643.29	1620.27	46.19	.000	.000	.0039	.0052
16.0	.20	663.66	1684.37	45.65	.000	.000	.0036	.0052
17.0	.18	681.26	1723.06	45.33	.002	.551	.0040	.0064
18.0	.16	685.98	1723.06	44.10	.000	.631	.0040	.0052
19.0	.15	691.29	1723.06	44.01	.008	.746	.0039	.0056
20.0	.14	697.47	1723.06	9.00	.012	.791	.0036	.0054
21.0	.12	702.54	1723.06	8.22	.015	.829	.0035	.0050
22.0	.11	705.43	1723.06	7.00	.017	.833	.0035	.0054
23.0	.09	707.24	1723.06	7.26	.018	.840	.0035	.0059
24.0	.08	708.72	1723.06	6.97	.029	.847	.0035	.0057
25.0	.07	709.79	1723.06	6.73	.020	.850	.0035	.0051
26.0	.05	710.44	1723.06	6.67	.020	.853	.0035	.0051
27.0	.04	711.06	1723.06	6.57	.020	.850	.0035	.0052
28.0	.03	711.70	1723.06	6.46	.021	.858	.0031	.0052
29.0	.01	711.27	1723.06	6.53	.021	.850	.0027	.0027
30.0	.00	711.70	1723.06	6.46	.021	.858	.0029	.0004

CHANNEL RESULTS

CASE 1 7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0 SECONDS DATA FOR CHANNEL 6

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CC-FT)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/M ² -FT ²)
.0	.08	369.88	733.00	53.38	.000	.000	.0038	.0368
1.0	.04	371.64	713.02	53.73	.000	.000	.0037	.0356
2.0	.01	377.92	733.31	53.50	.000	.000	.0037	.0351
3.0	.58	388.09	772.65	53.23	.000	.000	.0034	.0370
4.0	.55	407.13	835.24	52.75	.000	.000	.0031	.0423
5.0	.52	430.08	917.75	52.7	.000	.000	.0034	.0736
6.0	.49	450.95	980.36	51.35	.000	.000	.0038	.0662
7.0	.46	472.74	1052.87	50.74	.000	.000	.0039	.0718
8.0	.43	493.28	1121.34	50.37	.000	.000	.0040	.0723
9.0	.40	515.60	1195.04	49.70	.000	.000	.0040	.0729
10.0	.37	537.81	1269.00	49.12	.000	.000	.0040	.0731
11.0	.34	560.30	1340.72	48.43	.000	.000	.0040	.0731
12.0	.31	582.30	1417.90	47.88	.000	.000	.0040	.0726
13.0	.29	604.40	1490.72	47.27	.000	.000	.0040	.0726
14.0	.26	629.83	1561.27	46.68	.000	.000	.0040	.0724
15.0	.23	640.62	1629.05	46.11	.000	.000	.0036	.0736
16.0	.20	667.88	1699.02	45.53	.000	.000	.0034	.0779
17.0	.18	686.75	1729.36	45.50	.006	.732	.0040	.0721
18.0	.16	699.73	1729.00	45.14	.007	.732	.0044	.0720
19.0	.15	695.10	1729.00	45.20	.011	.775	.0039	.0700
20.0	.14	700.55	1729.06	45.59	.014	.809	.0035	.0741
21.0	.12	704.34	1729.06	7.70	.017	.830	.0035	.0713
22.0	.11	707.52	1729.00	7.19	.018	.842	.0035	.0704
23.0	.09	708.94	1729.00	6.33	.019	.848	.0035	.0703
24.0	.08	710.14	1729.00	6.72	.020	.852	.0035	.0704
25.0	.07	711.11	1729.00	6.50	.020	.850	.0035	.0707
26.0	.05	711.76	1729.06	6.49	.021	.850	.0035	.0707
27.0	.04	712.05	1729.00	6.40	.021	.859	.0031	.0708
28.0	.03	712.12	1729.06	6.39	.021	.859	.0027	.0619
29.0	.01	712.47	1729.00	6.34	.021	.861	.0029	.0600
30.0	.00	712.18	1729.06	6.38	.021	.860	.0034	.0777

CHANNEL RESULTS

CASE 1 7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0 SECONDS DATA FOR CHANNEL 7

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CC-FT)	EQUIL QUALITY FRACTION	VOID FRACTION	FLOW (LB/SEC)	MASS FLOW (MLB/HR-FT2)
.0	.08	365.88	700.00	53.58	.000	.000	.0062	.0000
1.0	.54	371.03	715.81	53.74	.000	.000	.0064	.0000
2.0	.61	376.70	730.35	53.59	.000	.000	.0065	.0001
3.0	.58	385.56	744.34	53.55	.000	.000	.0067	.0000
4.0	.55	400.86	814.01	52.93	.000	.000	.0068	.0001
5.0	.52	419.23	870.53	52.41	.000	.000	.0068	.0000
6.0	.49	440.71	940.35	51.34	.000	.000	.0066	.0000
7.0	.46	461.83	1015.04	51.25	.000	.000	.0066	.0001
8.0	.43	483.77	1083.63	50.84	.000	.000	.0066	.0001
9.0	.40	506.21	1164.47	50.61	.000	.000	.0067	.0000
10.0	.37	526.56	1238.03	49.38	.000	.000	.0064	.0000
11.0	.34	552.00	1317.30	48.73	.000	.000	.0063	.0000
12.0	.31	575.32	1394.00	48.78	.000	.000	.0063	.0000
13.0	.29	598.17	1473.15	47.45	.000	.000	.0064	.0000
14.0	.26	619.85	1541.54	46.84	.000	.000	.0065	.0000
15.0	.23	639.66	1607.03	46.30	.000	.000	.0067	.0000
16.0	.20	659.56	1671.09	45.76	.000	.000	.0066	.0000
17.0	.18	674.97	1721.08	45.34	.000	.000	.0075	.0001
18.0	.16	683.32	1729.00	45.94	.004	.648	.0071	.0007
19.0	.15	699.06	1729.06	46.21	.007	.731	.0060	.0000
20.0	.14	695.14	1729.06	46.22	.011	.775	.0060	.0001
21.0	.14	699.06	1729.06	46.22	.013	.812	.0068	.0001
22.0	.11	701.93	1729.00	46.30	.015	.816	.0069	.0000
23.0	.09	703.07	1729.06	46.37	.016	.825	.0064	.0001
24.0	.08	705.26	1729.06	46.37	.017	.832	.0064	.0001
25.0	.07	708.06	1729.06	46.37	.018	.836	.0064	.0000
26.0	.05	707.55	1729.06	46.18	.018	.842	.0067	.0000
27.0	.04	708.24	1729.06	46.19	.019	.845	.0068	.0001
28.0	.03	708.93	1729.06	46.19	.019	.847	.0063	.0001
29.0	.01	709.29	1729.06	46.19	.019	.849	.0065	.0001
30.0	.00	709.70	1729.06	46.19	.020	.850	.0065	.0001

CHANNEL RESULTS

CASE 1 7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0 SECONDS DATA FOR CHANNEL 8

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY FRACTION	VOID FRACTION	FLOW (LB/SEC)	MASS FLOW (LB/HR-FT2)
.0	.66	365.66	733.00	53.08	.000	.000	.0002	.0007
1.0	.64	370.91	716.43	53.75	.000	.000	.0004	.0034
2.0	.61	376.44	734.50	53.50	.000	.000	.0006	.0009
3.0	.58	385.20	763.15	53.36	.000	.000	.0007	.0003
4.0	.55	399.99	612.73	52.35	.000	.000	.0007	.0003
5.0	.52	418.45	672.01	52.44	.000	.000	.0000	.0000
6.0	.49	438.27	638.00	51.31	.000	.000	.0000	.0009
7.0	.46	459.20	1007.80	51.32	.000	.000	.0000	.0007
8.0	.43	480.93	1033.15	50.72	.000	.000	.0005	.0009
9.0	.40	503.40	1150.30	50.08	.000	.000	.0002	.0013
10.0	.37	527.99	1237.13	49.40	.000	.000	.0001	.0000
11.0	.34	552.88	1320.05	48.70	.000	.000	.0001	.0038
12.0	.31	577.02	1400.24	48.03	.000	.000	.0002	.0019
13.0	.29	596.00	1474.90	47.41	.000	.000	.0004	.0037
14.0	.26	620.14	1542.50	46.84	.000	.000	.0007	.0004
15.0	.23	639.60	1600.44	46.32	.000	.000	.0007	.0004
16.0	.20	658.13	1600.40	45.80	.000	.000	.0006	.0003
17.0	.16	676.32	1715.34	45.39	.000	.000	.0005	.0007
18.0	.16	685.00	1723.00	44.93	.000	.007	.0000	.0004
19.0	.15	689.93	1723.00	42.86	.008	.734	.0008	.0076
20.0	.14	694.40	1723.00	40.43	.020	.770	.0009	.0000
21.0	.12	698.00	1723.00	9.36	.012	.794	.0000	.0007
22.0	.11	700.32	1723.00	8.75	.014	.807	.0003	.0027
23.0	.09	702.04	1723.00	8.34	.015	.816	.0002	.0014
24.0	.08	703.04	1723.00	7.98	.016	.824	.0002	.0011
25.0	.07	705.00	1723.00	7.61	.017	.831	.0002	.0003
26.0	.05	700.97	1723.00	7.49	.017	.835	.0007	.0000
27.0	.04	700.81	1723.00	7.32	.018	.839	.0003	.0076
28.0	.03	707.43	1723.00	7.21	.018	.841	.0000	.0079
29.0	.01	707.41	1723.00	7.12	.019	.843	.0009	.0001
30.0	.00	700.29	1723.00	7.04	.019	.845	.0009	.0000

CHANNEL RESULTS

CASE 1 7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0 SECONDS DATA FOR CHANNEL 9

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MKG/HR-FT2)
.0	.00	300.88	730.00	50.88	.000	.000	.0002	.0000
1.0	.04	370.06	710.28	57.76	.000	.000	.0005	.0000
2.0	.01	375.72	732.12	53.62	.000	.000	.0004	.0000
3.0	.00	384.14	750.09	50.09	.000	.000	.0004	.0000
4.0	.05	390.00	807.16	52.99	.000	.000	.0003	.0000
5.0	.02	416.87	807.09	52.49	.000	.000	.0003	.0000
6.0	.49	430.63	932.02	51.95	.000	.000	.0004	.0000
7.0	.10	456.75	990.60	51.09	.000	.000	.0003	.0000
8.0	.43	470.16	1070.33	50.30	.000	.000	.0001	.0000
9.0	.10	501.45	1148.59	50.14	.000	.000	.0000	.0000
10.0	.37	520.37	1228.40	49.47	.000	.000	.0000	.0000
11.0	.34	548.90	1300.82	48.82	.000	.000	.0000	.0000
12.0	.31	572.08	1363.04	48.17	.000	.000	.0000	.0000
13.0	.29	594.09	1450.68	47.54	.000	.000	.0002	.0000
14.0	.20	615.34	1520.68	46.35	.000	.000	.0002	.0000
15.0	.23	630.19	1590.05	46.40	.000	.000	.0002	.0000
16.0	.20	655.29	1657.26	45.87	.000	.000	.0000	.0000
17.0	.18	670.81	1707.45	45.40	.000	.000	.0005	.0000
18.0	.10	681.20	1729.06	48.47	.002	.002	.0005	.0000
19.0	.15	680.33	1720.06	44.41	.005	.002	.0006	.0000
20.0	.14	690.25	1720.06	41.93	.006	.737	.0009	.0000
21.0	.12	694.04	1720.06	40.54	.010	.768	.0008	.0000
22.0	.11	690.09	1729.06	9.73	.022	.780	.0007	.0000
23.0	.09	693.58	1720.06	9.20	.013	.797	.0006	.0000
24.0	.06	700.21	1720.06	8.78	.014	.807	.0006	.0000
25.0	.07	701.59	1720.06	8.44	.015	.814	.0009	.0000
26.0	.05	702.92	1720.06	8.13	.015	.821	.0007	.0000
27.0	.04	703.80	1720.06	7.94	.016	.825	.0006	.0000
28.0	.03	704.47	1720.06	7.80	.016	.828	.0006	.0000
29.0	.01	705.07	1720.06	7.57	.017	.831	.0006	.0000
30.0	.00	705.82	1720.06	7.52	.017	.834	.0009	.0000

CHANNEL RESULTS

CASE

1

7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0

SECONDS

DATA FOR CHANNEL 10

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY FRACTION	VOID	FLOW (LB/SEC)	MASS FLUX (MLB/HR-FT ²)
.0	.00	365.88	700.00	53.88	.000	.000	.0002	.0623
1.0	.64	370.33	714.52	53.76	.000	.000	.0062	.0614
2.0	.61	375.45	731.25	53.60	.000	.000	.0062	.0619
3.0	.58	383.66	758.11	53.41	.000	.000	.0062	.0617
4.0	.55	397.76	804.40	53.11	.000	.000	.0062	.0610
5.0	.52	415.70	863.52	52.52	.000	.000	.0063	.0604
6.0	.49	434.40	925.41	52.02	.000	.000	.0063	.0601
7.0	.46	454.94	993.61	51.44	.000	.000	.0063	.0599
8.0	.43	477.21	1067.78	50.82	.000	.000	.0059	.0583
9.0	.40	500.67	1146.61	50.10	.000	.000	.0058	.0578
10.0	.37	523.78	1221.09	49.52	.000	.000	.0057	.0570
11.0	.34	547.00	1300.51	48.87	.000	.000	.0057	.0567
12.0	.31	570.05	1377.09	48.22	.000	.000	.0059	.0565
13.0	.29	591.83	1449.25	47.53	.000	.000	.0057	.0567
14.0	.26	613.53	1520.77	47.02	.000	.000	.0057	.0569
15.0	.23	634.21	1588.59	46.45	.000	.000	.0057	.0569
16.0	.20	653.67	1652.50	45.92	.000	.000	.0058	.0574
17.0	.18	669.06	1703.77	45.49	.000	.000	.0060	.0598
18.0	.16	678.00	1729.00	27.42	.001	.395	.0036	.0557
19.0	.15	689.87	1729.06	22.18	.008	.734	.0052	.0510
20.0	.14	694.15	1729.06	11.51	.010	.768	.0001	.0605
21.0	.12	697.04	1729.06	9.40	.012	.792	.0064	.0641
22.0	.11	693.32	1729.06	9.50	.013	.802	.0066	.0651
23.0	.09	700.33	1729.06	8.75	.014	.817	.0060	.0653
24.0	.08	701.32	1729.06	8.51	.014	.813	.0069	.0684
25.0	.07	702.23	1729.06	8.29	.015	.817	.0066	.0660
26.0	.05	702.95	1729.06	8.13	.015	.821	.0066	.0659
27.0	.04	703.54	1729.06	8.00	.016	.824	.0066	.0657
28.0	.03	704.06	1729.06	7.88	.016	.826	.0067	.0662
29.0	.01	704.90	1729.06	7.71	.017	.830	.0069	.0664
30.0	.00	705.22	1729.06	7.64	.017	.832	.0070	.0690

CHANNEL RESULTS

CASE 1

7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0

SECONDS

DATA FOR CHANNEL 11

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/HQ-FT ²)
.0	.58	365.88	733.00	53.38	.000	.000	.0062	.0027
1.0	.64	370.56	715.28	53.76	.000	.000	.0063	.0028
2.0	.52	372.80	732.40	53.62	.000	.000	.0063	.0028
3.0	.58	384.27	760.03	53.39	.000	.000	.0064	.0033
4.0	.55	398.81	807.84	52.98	.000	.000	.0065	.0044
5.0	.52	416.35	865.07	52.50	.000	.000	.0065	.0049
6.0	.49	435.92	932.47	51.37	.000	.000	.0063	.0028
7.0	.40	457.05	1000.04	51.38	.000	.000	.0062	.0012
8.0	.43	479.91	1070.77	50.75	.000	.000	.0061	.0000
9.0	.47	502.49	1152.06	50.22	.000	.000	.0060	.0000
10.0	.57	525.53	1228.28	49.48	.000	.000	.0059	.0000
11.0	.34	548.48	1300.40	48.80	.000	.000	.0061	.0000
12.0	.31	570.66	1370.13	48.20	.000	.000	.0059	.0000
13.0	.29	593.34	1454.22	47.58	.000	.000	.0058	.0000
14.0	.26	615.07	1520.85	46.97	.000	.000	.0056	.0000
15.0	.23	635.82	1593.85	46.44	.000	.000	.0059	.0000
16.0	.25	655.66	1658.45	45.80	.000	.000	.0060	.0000
17.0	.18	672.80	1707.45	45.45	.000	.000	.0055	.0000
18.0	.16	681.40	1723.00	48.16	.002	.539	.0064	.0040
19.0	.15	685.52	1723.00	44.23	.009	.655	.0065	.0046
20.0	.14	690.70	1723.00	11.74	.008	.742	.0066	.0050
21.0	.12	694.32	1723.00	10.20	.011	.774	.0067	.0061
22.0	.11	697.30	1723.00	9.55	.012	.790	.0068	.0069
23.0	.09	699.96	1723.06	9.20	.013	.800	.0069	.0065
24.0	.08	703.53	1723.06	8.70	.014	.808	.0066	.0057
25.0	.07	701.72	1723.06	8.41	.015	.815	.0066	.0055
26.0	.05	702.65	1723.00	8.20	.015	.819	.0066	.0054
27.0	.04	703.43	1723.00	8.22	.016	.823	.0066	.0058
28.0	.03	704.52	1723.05	7.79	.018	.829	.0068	.0060
29.0	.01	704.93	1723.06	7.70	.017	.830	.0070	.0064
30.0	.02	705.64	1723.06	7.55	.017	.834	.0070	.0062

CHANNEL RESULTS

CASE 1 7-PIN WIRE WRAP GAMMA HEATED ASSEMBLY

DATE

TIME = .0 SECONDS DATA FOR CHANNEL 12

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/HQ-FT2)
.0	.68	365.88	700.00	53.88	.000	.000	.0000	.0020
1.0	.64	370.91	710.43	53.75	.000	.000	.0063	.0025
2.0	.61	376.49	734.64	53.61	.000	.000	.0064	.0037
3.0	.56	385.41	763.65	53.30	.000	.000	.0066	.0057
4.0	.55	400.55	812.93	52.95	.000	.000	.0067	.0067
5.0	.52	418.87	874.01	52.45	.000	.000	.0066	.0067
6.0	.49	433.86	943.23	51.89	.000	.000	.0065	.0066
7.0	.46	461.01	1013.83	51.27	.000	.000	.0065	.0062
8.0	.43	482.89	1080.71	50.67	.000	.000	.0064	.0058
9.0	.40	505.35	1161.01	50.03	.000	.000	.0064	.0052
10.0	.37	528.16	1237.70	49.39	.000	.000	.0065	.0046
11.0	.34	551.35	1311.02	48.78	.000	.000	.0063	.0041
12.0	.31	573.53	1369.65	48.13	.000	.000	.0062	.0034
13.0	.29	596.12	1463.39	47.50	.000	.000	.0062	.0033
14.0	.26	617.92	1535.20	46.90	.000	.000	.0062	.0019
15.0	.23	633.84	1603.71	46.35	.000	.000	.0062	.0035
16.0	.20	657.04	1664.86	45.81	.000	.000	.0064	.0023
17.0	.16	673.91	1717.46	45.37	.000	.000	.0066	.0023
18.0	.10	695.33	1729.00	45.13	.011	.777	.0050	.0000
19.0	.15	690.16	1729.06	9.38	.011	.782	.0064	.0010
20.0	.14	703.35	1729.06	8.82	.014	.806	.0063	.0029
21.0	.12	713.54	1729.06	8.60	.016	.824	.0064	.0032
22.0	.11	725.05	1729.06	7.99	.017	.834	.0066	.0037
23.0	.09	706.55	1729.06	7.37	.018	.838	.0064	.0030
24.0	.08	717.37	1729.06	7.22	.018	.841	.0064	.0032
25.0	.07	707.83	1729.06	7.13	.018	.843	.0064	.0035
26.0	.05	708.12	1729.06	7.08	.019	.844	.0064	.0040
27.0	.04	703.36	1729.06	7.03	.019	.845	.0067	.0000
28.0	.03	718.27	1729.06	7.05	.019	.845	.0069	.0082
29.0	.04	716.86	1729.06	6.94	.019	.847	.0068	.0077
30.0	.00	700.97	1729.06	6.92	.019	.848	.0066	.0054

ONE-SIXTH GEOMETRY SHOWING OPERATION AT BOILING
(BUNDLE AVERAGE RESULTS SHOW ASSEMBLY OUTLET TEMPERATURE)

CHANNEL EXIT SUMMARY RESULTS

CASE 1 1/6-GEOMETRY MODEL AT 75 PERCENT REACTOR POWER, 100 PERCENT FLOW DATE

MASS BALANCE - -

MASS FLOW IN 3.56354E-12 LB/SEC
MASS FLOW OUT 3.56654E-12 LB/SEC
MASS FLOW ERROR -2.12E-11 LB/SEC

ENERGY BALANCE - -

FLOW ENERGY IN 1.37506E+01 BTU/SEC
ENERGY ADDED 3.77734E+00 BTU/SEC
FLOW ENERGY OUT 1.67334E+01 BTU/SEC
ENERGY ERROR -3.9E-05 BTU/SEC

CHANNEL (IN.)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/FT ³)	QUALITY FRACTION	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (MLB/FT ² -FT ²)
1	700.72	1729.15	7.94	.027	.834	.0034	.0737
2	701.02	1729.06	8.98	.024	.812	.0067	.0505
3	377.44	707.74	51.57	.000	.000	.0206	.1736

CHANNEL RESULTS

CASE 1 1/6-GEOMETRY MODEL AT 75 PERCENT REACTOR POWER, 100 PERCENT FLOW DATE

BUNDLE AVERAGED RESULTS

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (C.-F)	DENSITY (LB/CU-FT)	EQUIL QUALITY	VOID FRACTION	FLOW (LB/SEC)	MASS FLUX (M.L./H.-FT ²)
0.0	.51	369.88	715.21	53.23	.000	.000	.0057	.2225
1.0	.70	367.43	715.13	53.41	.000	.000	.0057	.2225
2.0	.73	369.13	715.66	53.74	.000	.000	.0057	.2225
3.0	.72	371.92	719.71	56.51	.000	.000	.0057	.2225
4.0	.53	376.60	719.20	56.40	.000	.000	.0057	.2225
5.0	.60	381.34	724.40	56.13	.000	.000	.0057	.2225
6.0	.52	383.74	714.77	56.55	.000	.000	.0057	.2225
7.0	.53	397.23	719.75	56.50	.000	.000	.0057	.2225
8.0	.50	401.35	813.20	56.25	.000	.000	.0057	.2225
9.0	.53	403.33	814.84	56.33	.000	.000	.0057	.2225
10.0	.51	412.74	813.12	56.01	.000	.000	.0057	.2225
11.0	.47	422.73	819.77	56.23	.000	.000	.0057	.2225
12.0	.44	429.01	919.50	56.40	.000	.000	.0057	.2225
13.0	.44	430.34	932.30	56.66	.000	.000	.0057	.2225
14.0	.38	442.02	933.35	56.70	.000	.000	.0057	.2225
15.0	.35	449.62	973.94	56.27	.000	.000	.0057	.2225
16.0	.42	454.30	933.43	49.71	.000	.000	.0057	.2225
17.0	.23	459.59	1019.19	49.53	.000	.000	.0057	.2225
18.0	.27	462.51	1013.35	44.90	.000	.000	.0057	.2225
19.0	.34	463.93	1013.43	35.18	.000	.225	.0057	.2225
20.0	.22	469.42	1123.51	36.19	.000	.205	.0057	.2225
21.0	.21	469.09	1132.03	36.46	.000	.203	.0057	.2225
22.0	.16	467.64	1039.21	32.16	.000	.230	.0057	.2225
23.0	.10	467.92	1036.50	31.63	.000	.297	.0057	.2225
24.0	.13	467.33	1036.10	31.05	.000	.301	.0057	.2225
25.0	.11	467.07	1033.31	31.21	.000	.304	.0057	.2225
26.0	.03	465.32	1033.23	31.00	.000	.307	.0057	.2225
27.0	.07	469.21	1033.79	31.33	.000	.318	.0057	.2225
28.0	.04	469.27	1042.32	31.27	.000	.320	.0057	.2225
29.0	.02	469.09	1041.71	31.24	.000	.321	.0057	.2225
30.0	.00	469.40	1042.00	31.29	.000	.321	.0057	.2225

CHANNEL RESULTS

CASE 1

176-GEOMETRY MODEL AT 75 PERCENT REACTOR POWER, 100 PERCENT FLOW

DATE

TIME = .0 SECONDS DATA FOR CHANNEL 1

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (26-F)	DENSITY (LB/OJ-FT)	QUALITY FRACTION	VELOCITY FRACTION	FLOW (LB/SEC)	MASS FLUX (LB/HM-FT ²)
.0	.07	705.80	705.80	58.83	.000	.000	.0039	.0039
1.0	.06	371.29	717.35	53.74	.000	.000	.0037	.0037
2.0	.05	377.23	737.30	51.53	.000	.000	.0037	.0037
3.0	.04	387.13	759.44	53.31	.000	.000	.0036	.0036
4.0	.03	404.20	820.55	52.54	.000	.000	.0036	.0036
5.0	.02	425.13	894.70	52.06	.000	.000	.0037	.0037
6.0	.01	440.56	965.17	51.67	.000	.000	.0037	.0037
7.0	.00	450.55	1037.25	51.00	.000	.000	.0037	.0037
8.0	.00	459.00	1100.73	50.44	.000	.000	.0036	.0036
9.0	.00	513.55	1169.00	49.41	.000	.000	.0037	.0037
10.0	.07	536.16	1204.50	49.17	.000	.000	.0039	.0039
11.0	.04	554.53	1230.84	48.54	.000	.000	.0039	.0039
12.0	.01	571.01	1248.22	47.93	.000	.000	.0039	.0039
13.0	.00	612.29	1293.44	47.33	.000	.000	.0039	.0039
14.0	.00	622.97	1302.82	46.76	.000	.000	.0039	.0039
15.0	.03	641.03	1316.37	46.22	.000	.000	.0039	.0039
16.0	.07	662.74	1378.15	45.70	.000	.000	.0039	.0039
17.0	.17	676.73	1725.52	45.30	.000	.000	.0039	.0039
18.0	.25	684.93	1729.00	14.67	.000	.670	.0039	.0039
19.0	.23	657.71	1729.16	13.17	.000	.712	.0044	.0044
20.0	.13	692.17	1719.00	11.29	.000	.753	.0039	.0039
21.0	.11	646.13	1711.00	9.30	.011	.703	.0036	.0036
22.0	.11	637.55	1719.00	9.13	.023	.739	.0039	.0039
23.0	.09	701.53	1729.16	8.79	.024	.818	.0034	.0034
24.0	.07	732.00	1729.16	8.55	.025	.826	.0034	.0034
25.0	.05	703.00	1729.16	8.17	.016	.822	.0034	.0034
26.0	.05	704.16	1729.16	7.88	.010	.820	.0034	.0034
27.0	.04	704.08	1729.16	7.75	.017	.829	.0034	.0034
28.0	.03	709.16	1729.16	7.55	.017	.831	.0034	.0034
29.0	.01	709.50	1729.16	7.58	.017	.832	.0034	.0034
30.0	.00	705.71	1729.16	7.54	.017	.834	.0034	.0034

CHANNEL RESULTS

CASE 1

176-GEOMETRY MODEL AT 75 PERCENT REACTOR POWER, 210 PERCENT FLOW

DATE

TIME = .0

SECONDS

DATA FOR CHANNEL 2

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CU-FT)	QUALITY	VELOCITY FRACTION	FLOW (LB/SEC)	MASS FLOW (LB/HK-FT ²)
.0	.07	305.00	720.0	53.03	.000	.000	.0000	.0000
1.0	.05	371.74	740.80	53.75	.000	.000	.0000	.0000
2.0	.04	370.17	733.23	53.51	.000	.000	.0000	.0000
3.0	.03	364.53	751.15	53.30	.000	.000	.0000	.0000
4.0	.05	344.74	751.74	52.38	.000	.000	.0000	.0000
5.0	.06	417.13	800.20	52.48	.000	.000	.0000	.0000
6.0	.05	430.43	900.11	51.30	.000	.000	.0000	.0000
7.0	.05	430.50	1000.00	51.33	.000	.000	.0000	.0000
8.0	.05	470.75	1071.57	50.79	.000	.000	.0000	.0000
9.0	.07	500.51	1145.45	50.26	.000	.000	.0000	.0000
10.0	.37	520.00	1220.00	49.50	.000	.000	.0000	.0000
11.0	.30	540.70	1230.17	48.40	.000	.000	.0000	.0000
12.0	.30	505.11	1270.90	48.07	.000	.000	.0000	.0000
13.0	.24	590.23	1440.95	47.07	.000	.000	.0000	.0000
14.0	.20	610.47	1510.01	47.07	.000	.000	.0000	.0000
15.0	.20	631.77	1530.58	46.50	.000	.000	.0000	.0000
16.0	.20	600.97	1640.23	45.99	.000	.000	.0000	.0000
17.0	.17	606.42	1690.23	45.57	.000	.000	.0000	.0000
18.0	.15	675.39	1700.65	45.33	.000	.000	.0000	.0000
19.0	.13	631.93	1720.56	47.02	.000	.000	.0000	.0000
20.0	.12	607.07	1720.10	46.18	.000	.711	.0000	.0000
21.0	.11	632.00	1720.10	46.20	.000	.712	.0000	.0000
22.0	.11	690.47	1720.06	46.00	.000	.771	.0000	.0000
23.0	.04	630.00	1720.00	46.33	.000	.781	.0000	.0000
24.0	.07	637.36	1720.00	46.50	.000	.740	.0000	.0000
25.0	.06	634.76	1720.00	46.50	.000	.746	.0000	.0000
26.0	.05	639.16	1720.00	46.50	.000	.740	.0000	.0000
27.0	.04	639.70	1720.00	46.50	.000	.740	.0000	.0000
28.0	.04	700.29	1720.00	46.10	.000	.807	.0000	.0000
29.0	.04	700.71	1720.00	46.00	.000	.803	.0000	.0000
30.0	.04	701.12	1720.00	46.58	.000	.801	.0000	.0000

CHANNEL RESULTS

CASE 1 2/C-GEOMETRY MODEL AT 75 PERCENT REACTOR POWER, 100 PERCENT FLOW DATE

TIME = .0 SECONDS DATA FOR CHANNEL 7

DISTANCE (IN.)	DELTA-P (PSI)	ENTHALPY (BTU/LB)	TEMPERATURE (DEG-F)	DENSITY (LB/CO-FI)	EQUIL QUALITY FRACTION	VOLE FRACTION	FLOW (LB/SEC)	HEAT FLUX (MW/M ² -FT ²)
0.0	.35	355.86	713.50	53.88	.000	.000	.0250	.1736
1.0	.40	366.35	708.50	53.57	.000	.000	.0250	.1736
2.0	.39	366.24	712.29	53.57	.000	.000	.0250	.1736
3.0	.38	366.59	712.27	53.46	.000	.000	.0250	.1736
4.0	.42	367.70	703.93	53.65	.000	.000	.0250	.1736
5.0	.73	367.74	700.17	53.43	.000	.000	.0250	.1736
6.0	.75	359.43	706.32	53.81	.000	.000	.0250	.1736
7.0	.73	359.25	711.63	53.79	.000	.000	.0250	.1736
8.0	.75	369.95	713.23	53.77	.000	.000	.0250	.1736
9.0	.95	370.67	715.64	53.75	.000	.000	.0250	.1736
10.0	.63	371.45	713.23	53.73	.000	.000	.0250	.1736
11.0	.51	372.21	722.71	53.72	.000	.000	.0250	.1736
12.0	.57	372.39	720.22	53.69	.000	.000	.0250	.1736
13.0	.54	373.74	725.67	53.67	.000	.000	.0250	.1736
14.0	.51	374.40	725.33	53.65	.000	.000	.0250	.1736
15.0	.47	375.25	731.23	53.63	.000	.000	.0250	.1736
16.0	.44	375.91	732.43	53.62	.000	.000	.0250	.1736
17.0	.42	376.33	734.24	53.60	.000	.000	.0250	.1736
18.0	.36	376.64	735.23	53.57	.000	.000	.0250	.1736
19.0	.35	375.82	735.73	53.59	.000	.000	.0250	.1736
20.0	.32	376.39	735.29	53.59	.000	.000	.0250	.1736
21.0	.28	377.25	736.74	53.58	.000	.000	.0250	.1736
22.0	.25	377.21	737.51	53.53	.000	.000	.0250	.1736
23.0	.24	377.26	737.28	53.58	.000	.000	.0250	.1736
24.0	.19	377.31	737.33	53.58	.000	.000	.0250	.1736
25.0	.15	377.35	737.43	53.58	.000	.000	.0250	.1736
26.0	.13	377.38	737.54	53.58	.000	.000	.0250	.1736
27.0	.09	377.40	737.61	53.58	.000	.000	.0250	.1736
28.0	.06	377.41	737.67	53.57	.000	.000	.0250	.1736
29.0	.03	377.43	737.71	53.57	.000	.000	.0250	.1736
30.0	.01	377.44	737.74	53.57	.000	.000	.0250	.1736

APPENDIX D

A Fission Heated Subassembly for Sodium Boiling Experiments in EBR-II

L. Dodd