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An Innovative Fuel Design Concept for Improved Light Water Reactor Performance and Safety

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Table of Contents

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List of Figures

ABSTRACT

Light water reactor (LWR) fuel performance is limited by thermal and mechanical constraints associated with the design, fabrication, and operation of fuel in a nuclear reactor. These limits define the lifetime of the fuel, the maximum power at which the fuel can be operated, the probability of fuel structural failure over the fuel lifetime, and the transient performance of the fuel during an accident. The purpose of this research was to explore a technique for extending fuel performance by thermally bonding LWR fuel with a non-alkaline liquid metal alloy. Current LWR fuel rod designs consist of enriched uranium oxide (UO_2) fuel pellets enclosed in a zirconium alloy cylindrical clad. The space between the pellets and the clad is filled by an inert gas (typically helium). Due to the thermal conductivity of the gas, the gas space thermally insulates the fuel pellets from the reactor coolant outside the fuel rod, elevating the fuel temperatures.

Filling the gap between the fuel and clad with a high conductivity liquid metal thermally "bonds" the fuel to the cladding, and eliminates the large temperature change across the gap, while preserving the expansion and pellet loading capabilities. The resultant lower fuel temperature directly impacts fuel performance limit margins and also core transient performance.

The application of liquid bonding techniques to LWR fuel was explored for the purposes of increasing LWR fuel performance and safety. A modified version of the ESCORE fuel performance code (ESBOND) has been developed under the program to analyze the in-reactor performance of the liquid metal bonded fuel. An assessment of the technical feasibility of this concept for LWR fuel is presented, including the results of research into materials compatibility testing and the predicted lifetime performance of Liquid Metal Bonded LWR fuel. The results of this research showed that liquid metal bonded BWR peak fuel temperatures are 400°F lower at beginning-of-life, and 200°F lower at end-of-life compared to conventional fuel.

1.0 INTRODUCTION

In an effort to enhance the safety and performance of water reactors, the development of various innovative fuel designs was explored. Since many of the safety concerns of nuclear reactor fuel are associated with high fuel temperatures, an innovative fuel design that operates at lower temperatures, for a given power level, would be inherently safer.

Current LWR fuel rod operational limits include thermal/mechanical limits such as cladding stress and strain, fuel rod internal pressure, and maximum fuel temperature. These limits result largely from the thermal characteristics of the fuel when operated at high linear power levels (kW/ft). The high centerline temperature results from the poor thermal conductivity of the oxide fuel and the large temperature drop across the pellet/clad gas gap. The resultant temperatures define such limits as the maximum permitted power at normal operation and the fuel temperature margin to melting during anticipated reactor transients. High operating temperatures result in high energy storage conventional light water reactor fuel rod designs. This significantly increases the likelihood of fuel rod damage during loss of coolant events.

The thermal resistance for heat transfer through the fuel pellet to the coolant for a typical LWR fuel rod at the beginning of life is composed of: 1) thermal resistance through the fuel pellet (53%), 2) thermal resistance through the gas gap (35%), 3) thermal resistance through the cladding (5%), and 4) the film drop between the clad surface and the coolant (7%). The ability to transfer heat out of the fuel rod can be best influenced by modifying the fuel pellet to decrease the thermal resistance, and secondly by reducing the thermal resistance across the gas gap. The purpose of the gap is to facilitate the loading of pellets into the rods during fabrication. The gap also allows for thermal expansion and radiation swelling of the fuel, as well as the creepdown of the clad. The heat transfer through the fuel pellet can be enhanced by either increasing the fuel thermal conductivity (e.g. changing from UO_2 to a fuel material with a higher thermal conductivity, or by adding material to U02 to increase the thermal conductivity). In our research, neither of these alternatives were found operationally acceptable for LWR fuel. Alternative fuel materials or heat transfer accelerants are still under review. Therefore, reducing the large thermal resistance associated with the pellet/cladding gap was investigated under this research grant.

Like liquid metal reactor (LMR) fuel, the use of a liquid metal bond in a light water reactor fuel rod would enhance the heat transfer between the fuel and the reactor coolant, resulting in significantly lower operating temperature, and a safer fuel design. For this reason, it was proposed that liquid bonding techniques be investigated for possible use in LWR fuel design.

The safety benefits resulting from lower fuel operating temperatures that influenced the development of liquid bonded LMR fuel can be applied to LWR fuel. In order to achieve the high power levels and long fuel life needed in power reactors, fuel temperature considerations are a principal design limitation. By substituting liquid metal for helium within the radial gap, the thermal resistance is dramatically reduced, and the fuel temperature is significantly lower for a given power level. Meanwhile, the function of the gap during fabrication and operation is still maintained. The lower radial temperature profile leads to significantly lower stored energy in the fuel pellet, which is of primary concern during reactor transients. Additionally the lower temperature reduces the thermal expansion of the pellet and fission gas release, both fuel performance enhancers.

To utilize liquid bonding techniques in LWR fuel design, the bonding liquid (liquid metal) must be chemically compatible with reactor materials including fuel (U02), cladding (Zircaloy-4), coolant (water), as well as fission products, shims, etc. Non-alkaline, low melting point metals such as lead, bismuth, and tin are relatively benign when exposed to water and were judged to be acceptable choices for a bonding liquid.

In addition, the commercial viability of any new fuel design depends upon its ability to replace and coexist with existing LWR fuel. Factors related to the ease of manufacture, the effect of the liquid bond material on fuel assembly parameters, the nuclear interaction, the fission gas release and resultant rod pressure, the performance during reactor transients, and the behavior after failure must be assessed.

The purpose of this research program was to:

1. Evaluate a fuel design for light water reactors which uses a non-alkaline liquid metal alloy between the fuel pellets and cladding to thermally bond the fuel.

The resulting reductions in fuel temperature and stored energy will increase margins for steady-state operation, and improve fuel survivability in the event of an accident.

2. Demonstrate the materials' compatibility among the liquid metal, Zircaloy-4, and UO_2 through comprehensive testing of these materials at typical reactor operating temperatures, and anticipated transient temperatures.
3. Evaluate the performance of liquid bonded LWR fuel using thermalmechanical computer simulation over a typical fuel lifetime, compared with conventional, gas-bonded fuel.

2.0. DESCRIPTION OF PROPOSED FUEL DESIGN

The proposed liquid bonded light water reactor (LBLWR) fuel rod design consists of a standard PWR or BWR fuel rod in which the gas gap between the pellets and the cladding is filled with liquid metal, as is shown in Figure 1. As part of the research, several studies determining the feasibility of LBLWR fuel[4,5,6] were published. The results of these studies showed that non-alkaline, low melting point metals such as lead, bismuth, and tin could be used to thermally bond the fuel rod, and showed that an alloy of 33wt% lead, 33wt% bismuth, and 33wt% tin is the best choice of a bonding liquid, based on lifetime compatibility.

The fuel rod can be assembled by inserting the fuel pellets into the cladding under a vacuum, with the bonding material placed in the bottom. As the rod is heated, the bond material liquifies, and the spring which is used to hold the pellets in place provides pressure. The gap between the pellets and cladding fills with liquid metal, and the rod is pressurized. The rod pressurization is required to reduce the pressure difference between the interior of the fuel rod and the reactor coolant system pressure, which varies from 1050 psia for a BWR to 2200 psia for a PWR. Pressurization reduces the rate at which the cladding creeps down, maintaining the annular gap between the pellets and cladding.

Since the liquid metal is incompressible, it will be displaced as the clad creeps down and the pellet expands. Thus, overpressurization of the fuel rod is avoided. The displaced liquid metal must be compensated for in the design. Methods under consideration are:

1. Partly (~80%) filling the fuel rod with liquid metal at beginning-of-life. The unbonded portion of the rod has low heat generation, and the liquid bond fills the entire rod as the cladding creeps down.
2. Lowering the rod initial pressure at beginning-of-life, and
3. Utilizing a compressible container component which will compress later in the fuel lifetime as the rod pressure increases thereby maintaining a minimum gas pressure, while later minimizing the internal gas pressure.

Radial heat transfer calculations were performed using the TRUMP generalized heat transfer computer program [7]. These calculations show that the steady-state temperature profile varies significantly with the assumed value of the gap conductance as shown in Figure 2. Typical values of helium gap conductances range from 500 Btu/hr-ft^2-°F at beginning-of-life, to 2500 Btu/hr-ft^2-°F after the gap closes. By contrast, the liquid metal bonded fuel gap conductance is several orders of magnitude higher, and results in almost no temperature drop across the gap. Thus, a reduction in fuel centerline temperature of up to 1600°F can be realized compared to conventional gas-bonded fuel for a peak power PWR rod operating at 13 kW/ft at beginning-of-life. The lower stored energy in the liquid bonded fuel resulting from the lower fuel temperatures is of great importance in the event of a loss of coolant accident (LOCA).

The benefits of reduced fuel temperatures are apparent when considering the fuel response to a postulated accident. Figure 3 shows the cladding temperature response for a peak power PWR rod at beginning-of-life during a LOCA. For this calculation, the fuel, at steady-state operating conditions, experiences a step change in the clad-to-coolant heat transfer coefficient from 4000 Btu/hr-ft^2-°F to 10 Btu/hr-ft^2-°F to simulate a loss of coolant. At the same time, the power is assumed to decrease to decay heat levels. In a few seconds, the cladding temperature reaches thermal equilibrium with the fuel and continues to rise slowly due to the decay heat. As is shown in Figure 3, far lower cladding temperatures are calculated for the LBLWR fuel due to the lower stored energy at operating conditions.

The reduced cladding temperatures result in a significant decrease in the zirconium-water reaction as is shown in Figure 4. The rate constant for the reaction is nearly a factor of fifty lower for the LBLWR fuel than conventional gas-bonded fuel rod, and the cladding will resist severe damage far longer, thereby greatly increasing the margin to fuel failure.

Similarly, the lower operating temperatures increase the fuel's chance of surviving a power excursion. The response to a 15% transient overpower event for a peak power PWR rod at beginning-of-life is shown in Figure 5. The conventional gas gap rod experiences center line fuel melting while the liquid bonded rod shows significant margin to melting.

The fuel transient response to a LOCA and unscrammed transient overpower event indicates that the LBLWR fuel is potentially far safer than conventional LWR fuel, avoiding and preventing severe accidents involving fuel damage and hydrogen generation, even for peak power rods.

3.0 MATERIALS COMPATIBILITY STUDIES

Extensive materials compatibility testing was conducted under this research program for candidate non-alkaline liquid metals. First lead and bismuth were tested alone. Both metals exhibit excessive reaction with the Zircaloy-4 cladding and were determined to be unacceptable from a materials compatibility standpoint. A lead-bismuth eutectic alloy (44.8wt% Pb-55.2wt% Bi) was then studied, along with a lead-bismuth-tin alloy (33wt% Pb-33wt% Sn-33wt% Bi). Both of these liquid metal alloys were extensively tested to determine the degree of compatibility with Zircaloy-4 cladding [4]. In addition, the compatibility among lead-bismuth-tin, Zircaloy-4, and UO_2 was investigated [5]. Tests were conducted by exposing the cladding material to the liquid metals at elevated temperatures for extended periods of time. The degree of compatibility was quantified by calculating the loss of wall thickness in the Zircaloy-4 clad. Any chemical reactions between the liquid metals and Zircaloy-4 were also determined.

These studies experimentally determined the extent of corrosion experienced by the Zircaloy-4 cladding material when exposed to the candidate liquid metals at temperatures indicative of:

1. Standard Operating Conditions (SOC). SOC represents the temperatures expected during hot, full power operation of the fuel for extended periods

of time. To simulate SOC, samples were tested at 750°F for 100-3,500 hours.

2. Limiting Accident Conditions (LAC). For reactor fuel, the highest temperatures expected during a design basis event are associated with a Loss of Coolant Accident (LOCA). Heat transfer out of the fuel is significantly decreased leading to a rapid increase in cladding temperature as a result of stored energy in the fuel. For these tests, the temperatures ranged from 1,200°F to 1,500°F for time periods up to 24 hours.

Zr cladding segments approximately six inches in length, were plugged at one end with stainless steel end caps. These sections were then filled with one of the candidate liquid metal alloys. Specimens containing 1. only liquid metal, 2. alumina ($A1_203$) pellets (to simulate the volume effect due to presence of pellets), 3. depleted UO_2 pellets, and 4. SIMFUEL (simulated spent fuel) pellets were tested. For those samples containing pellets, a small amount of liquid metal was placed at the bottom of the tube and then displaced into the gap between the pellet and cladding.

To minimize external oxidation of the tubes, the experiments were conducted in a helium atmosphere. The samples were heated in the furnace apparatus shown in Figure 6, constructed to allow for application of helium and a vacuum.

After cooling, the specimens were sectioned using a diamond cut-off saw and were mounted in 1 in. diameter molds using a quick setting resin. The mounted samples were polished using standard metallographic techniques prior to examination.

Loss of tube wall thickness calculations were made from photomicrographs taken at 100x magnification. Measurements were taken with dial calipers to an accuracy of 0.001 inches. These measurements were compared to measurements from as-manufactured standard tubes, also taken from 100x photomicrographs. From this comparison, an average percent loss of wall thickness was determined as follows:

$$\left[\frac{Standard\ wall - Tested\ wall}{Standard\ wall}\right] X\ 100\ =\ PercentLoss$$

These average loss values were plotted versus testing time in order to generate plots that were used to make predictions over the fuel lifetime.

Intermetallic layers were observed to form at the solid-liquid metal interface. The presence of these layers may have beneficial or harmful effects relative to the cladding performance. Electron probe x-ray microanalysis using wavelength dispersive spectrometry was performed on the reaction layer to determine its chemical composition.

Optical microscopy was used to determine the nature of any liquid metal attack. Polished specimens were anodized, then examined using a metallograph with a polarizer and full wavelength interference plate to view the microstructure of the cladding. Photomicrographs of the internal edge and the main tube wall of the cladding were taken at magnifications up to 500x. Optical microscopy was also employed on the transition layer formed at the solid-liquid metal interface in an attempt to correlate the layer thickness to testing time, as well as to examine the integrity of the layer.

A total of 170 specimens covering 79 tests were used to evaluate the liquid metal interaction with the Zircaloy-4 cladding over a range of temperature-time exposures. The specimens were tested using both the lead-bismuth eutectic and the lead-bismuth-tin alloys. These specimens were evaluated for the amount of tube wall loss and the interaction at the solid-liquid metal interface including any intergranular penetration of the liquid metal. The tube wall loss for the SOC specimens are shown in Figure 7 for lead-bismuth, and Figure 8 for lead-bismuth-tin. These results indicate that the loss of wall thickness is unacceptably high for the lead-bismuth, but is acceptable for the lead-tin-bismuth. Additional studies of lead-bismuth-tin show acceptable Zircaloy-4 losses for a sample tested at 1,215°F for 24 hours to simulate a LOCA (Figure 9).

A photomicrograph of a lead-bismuth-tin specimen tested for 1,000 hours at 750°F is shown in Figure 10. Electron beam microprobe analysis of the reaction layer in this sample is shown in Figure 11. The reaction layer appears lighter in color, remains in contact with the cladding, and is approximately 10 microns thick. Compositional analysis of this layer revealed an approximate composition of 72.8wt% tin and 27.2wt% zirconium, corresponding to a $ZrSn_2$ intermetallic compound. It is apparent that the $ZrSn_2$ intermetallic layer acts as a diffusion barrier for Zr or Sn or both, which, once formed, effectively slows the liquid metal attack on the inner cladding surface. Tin is also currently used as a barrier material in some advanced BWR fuel cladding designs [8]. The results of additional tests showed no significant interaction between the lead-bismuth-tin alloy and the UO_2 pellets under the range of test conditions.

Further studies were carried out and showed that the lead-bismuth-tin alloy exhibited excellent wetting properties, did not significantly react with water, and permitted the migration of gas bubbles through small (~1 mil) gaps. The lead-bismuth-tin alloy appears to meet the materials compatibility requirements for use in a light water reactor fuel design.

An investigation into the nuclear interactions of lead-bismuth-tin indicates that the relatively low thermal neutron absorption of the three metals does not appreciably affect the core neutron economy. Neutron activation and subsequent decay of activation products results in the production of several radioactive isotopes, most notably polonium-210 (less than one gram per assembly at the end-of-life). In addition, a small amount of helium gas is produced from the α-decay of polonium-210, but this quantity is much less than one percent of the fission gas evolved in the fuel. The additional heat load from the activation products is less than 5 watts per assembly at the end-of-life, and is an insignificant fraction of the decay heat load of the spent fuel assembly.

4.0. LIQUID BONDED FUEL ROD THERMAL/MECHANICAL PERFORMANCE

To better charactenze the performance of LBLWR fuel over a typical fuel lifetime, a methodology for predicting fuel rod performance as a function of fuel burnup was necessary. A study was made of all available fuel performance codes to determine the best basis for a code to predict the behavior of LBLWR fuel. To facilitate these predictions, a computer code, ESCORE [9], which was developed by the Electrical Power Research Institute (EPRI), was modified to develop a tool to analyze the LBLWR fuel. - This modified code, ESBOND, was used to determine the thermal/mechanical performance of LBLWR fuel in both pressurized water reactors and boiling water reactors.

The ESCORE code is used by utilities to support the design and licensing of high-burnup fuel designs. ESCORE has been shown to be an effective tool in the determination of fuel rod performance. Parameters such as fuel temperatures, stored energy, swelling, fission gas release, cladding oxidation, and cladding stress and strain are predicted as a function of fuel burn-up. The code analyzes individual fuel rods consisting of uranium dioxide fuel pellets enclosed in Zircaloy cladding. The fuel rod is discretized into several axial segments, for which the code performs radial thermal calculations, as a function of the local linear power. The fission gas released for each segment mixes within the rod to provide a prediction for the rod internal pressure as a function of bumup. The structure of ESCORE, including the major models and the sequence in which they are accessed during a typical run are shown in Figure 12.

The ESCORE code calculates one-dimensional heat transfer in the radial direction across the fuel pellet, through the gas gap, through the cladding, and into the coolant. The gas gap conduction model consists of heat conduction across a gas layer, radiation heat transfer from the outer surface of the pellet to the inner surface of the cladding, and, when applicable, contact conductance between the pellet and cladding. The model predicts a maximum gap conductance coefficient of 3000 Btu/hr-ft^2-°F when the gap is completely closed. Thus, the ESCORE code calculates a radial temperature profile which changes as a function of the local gap conductance, and the gap conductance changes as the fuel and cladding dimensions change.

For the ESBOND code, a modification to the gap conductance model was made to model the conductance through the liquid metal bond. The resulting gap conductance for LBLWR fuel is typically several orders of magnitude higher than for conventional gas bonded fuel, effectively eliminating the temperature drop across the pellet-cladding gap.

For conventional fuel, as the fuel and cladding dimensions change, the available gas plenum volume also changes. Changes in the fuel dimensions occur as a function of burnup, and consists of both densification and swelling in the fuel pellet, and creep in the cladding due to the pressure difference across the cladding wall. The net result is that the gap between the fuel and cladding eventually closes causing a decrease in the fission gas volume. To counter the rapid creep down of the cladding and delay the onset of pellet-clad interaction, fuel rods are pre-pressurized with helium gas prior to irradiation.

The reduction in gas volume is magnified for the LBLWR fuel design. As the annular gap between the fuel pellet and the cladding is reduced, the incompressible liquid metal is displaced. This action further reduces the fission gas volume. The

ESBOND code accounts for liquid metal displacement and accurately calculates the rod internal pressure.

The General Electric 8x8 fuel rod design was analyzed incorporating a liquid metal bond. The maximum rod average burnup is assumed to be 50,000 MWD/MT, which is typical for a fuel rod lifetime. For this analysis, the rod linear power is assumed to be constant 9 kW/ft over the fuel lifetime. For these calculations, an initial pre-pressurization of 3 atmospheres (45 psia) is assumed for both the LBLWR and conventional fuel designs, and the liquid metal level is assumed to be the top of the fuel stack at beginning of life.

The results of the BWR fuel rod calculations for both designs are presented in Figures 13 to 18. Figure 13 shows the fuel and cladding dimensions for the peak axial node as a function of time. The thick cladding coupled with a larger gap allows the gap to close slowly over the fuel lifetime. Both the liquid-bonded and conventional fuel rods exhibit similar behavior as the fuel pellet first shnnks due to densification, then swells over the remainder of the fuel lifetime. The LBLWR fuel pellet diameter is consistently less than the conventional rod by about 2 mils because of lower thermal expansion due to the lower fuel temperatures. Both the LBLWR and conventional BWR fuel cladding creep due to the difference between the internal gas pressure and the external reactor pressure. For the gas bonded fuel, the gap closes in about 700 days, and for the LBLWR rod, due to the lower fuel thermal expansion, the gap closes in about 1100 days. After gap closure, the fuel and cladding remain in contact over the remainder of the fuel lifetime.

Figure 14 shows the gap conductance averaged over the fuel rod length as a function of time. The gap conductance for the conventional rod increases from about 690 Btu/hr-ft^2-°F at BOL, to about 1800 Btu/hr-ft^2-°F at EOL. The gap conductance is consistently several orders of magnitude greater than for conventional fuel, and the thermal resistance due to the liquid metal gap is insignificant over the life of the fuel rod.

Figure 15 shows the average and peak fuel temperatures for both fuel types. Once again, the greatest difference in temperature occurs at BOL where the fuel centerline temperature at the maximum axial power node is over 400°F higher for conventional fuel than for the LBLWR fuel rod. For both fuel rods, the thermal resistance in the UO_2 fuel increases as a function of burnup due to the accumulation of fission products. At the same time, the gap for both fuel types is closing, resulting in an increase in the gap conductance as was mentioned above. The net result of these two competing phenomena is a decrease in the fuel temperature for the conventional fuel rod, as the increase in gap conductance dominates the reduction in fuel thermal conductivity. Conversely, the LBLWR rod experiences an increase in fuel temperatures as the UO_2 fuel conductivity change dominates.

At about 600 days, the difference in centerline temperature between the two designs reaches about 200°F, and remains the same for the duration of the fuel lifetime. The benefits of the liquid metal bond are most apparent at BOL, and slowly decrease over the fuel lifetime.

Figure 16 shows the internal fuel rod pressure as a function of time. There is comfortable margin for both the LBLWR and conventional fuel to remain below the fuel rod internal pressure limit of 1065 psia. Thus, the clad creep down is similar for both fuel designs as is shown in Figure 13. Temperature dependent phenomena such as fission gas release are significantly lower for the LBLWR fuel even at 9 kW/ft due to the lower fuel temperatures, as is shown in Figure 17.

Figure 18 shows the clad diametral strain due to creep as a function of the axial fuel length at EOL. The clad strain is similar for the two designs, but is more highly positive for the conventional fuel rod.

Several conclusions can be drawn from the analysis of BWR fuel:

1. Analysis of the liquid bonded BWR fuel rod indicates that the fuel temperature are significantly lower than those calculated for conventional fuel rods.
2. The maximum benefit for the LBLWR fuel occurs at beginning of life. This is primarily due to the large thermal resistance posed by the gas gap in the conventional fuel rod. This benefit decreases due to the closure of the gap as the fuel burnup increases.
3. Temperature dependent parameters such as fuel thermal expansion, fission gas release, and clad strain are all lower because of the lower temperatures associated with the LBLWR fuel.

Although ESBOND analysis of PWR fuel showed similar trends, the BWR liquid bonded fuel performance characteristics were found to be significantly better when compared to conventional fuel rods. Specifically, the liquid bonded BWR fuel temperatures are significantly lower than the conventional BWR fuel over a larger fraction of the fuel lifetime than was observed for the PWR fuel comparison. This performance primarily results from the thicker cladding in the BWR rod which, combined with the lower system pressure, resists creepdown far longer than the PWR rod, thus keeping the gap between the pellets and the cladding open wider during the fuel lifetime. This condition greatly favors the performance of the LBLWR fuel.

5.0. RESULTS

It was shown that liquid bonded LWR fuel provides thermal advantages over conventional LWR fuel yielding considerable margin in the areas of safety and thermal/mechanical performance. The improvements result from the lower operating temperature and corresponding lower stored energy in the UO_2 fuel. The lower stored energy precludes the onset of a Zirconium-water reaction in even the most severe postulated accidents, as the parabolic rate constant for the reaction is reduced as much as a factor of fifty relative to conventional fuel.

It was concluded that for the lead-bismuth-tin alloy, the liquid metal interaction with the cladding does not pose a problem over the fuel lifetime. The chemical compatibility of the lead-bismuth-tin alloy with the Zircaloy-4 cladding is primarily due to the formation of a $ZrSn_2$ reaction layer between the cladding and the liquid metal which limits further interaction.

Detailed thermal calculations showed that the level of benefit for LBLWR fuel as compared to conventional fuel depends on the value of the gap conductance for the conventional fuel, which can change significantly over the life of the fuel. Typical values of gap conductance for beginning of life when the fuel/cladding gap is open exhibit much higher fuel temperatures for the conventional fuel rod than for the LBLWR rod which has virtually an infinite gap conductance.

The EPRI fuel performance code, ESCORE, was modified, and the resulting ESBOND code was used to analyze liquid bonded fuel designs over a typical lifetime.

Liquid bonded BWR and PWR fuel rods were analyzed. These analyses showed that the temperature dependent parameters such as fuel swelling, fission gas release, and clad strain showed improvement with the use of the liquid metal bond. The results also showed that the benefits of the liquid metal bond are maximized at the beginning of life when the gap conductance for conventional fuel is at a minimum.

Impressive results were observed during the analysis of BWR fuel. The decrease in the fuel temperatures for the liquid bonded fuel relative to conventional fuel is more pronounced than was shown for PWR fuel. This is primarily due to the larger gap which occurs in BWR fuel, which results in an decreased gap conductance at the beginning of life as compared to the PWR fuel rod. In addition, the combination of rod pre-pressurization, thicker cladding, and lower reactor coolant system pressure keeps the gap from closing until very late in the fuel lifetime. This factor allows the liquid bonded BWR fuel rod to exhibit significantly lower fuel temperatures relative to conventional fuel which not significantly diminish over the fuel lifetime.

The Liquid Metal Bonded Light Water Reactor Fuel Program has successfully shown that liquid metal bonding can reduce fuel operating temperatures; resulting in safer and more efficient fuel performance for both steady-state and transient conditions. Based on the results of the materials testing conducted at the University of Florida, the fuel design is considered sufficiently reliable to initiate irradiation testing to provide a demonstration of the benefits of LBLWR fuel, and to provide a data base for the qualification of the performance models. It is proposed that a boiling water reactor fuel design should be tested.

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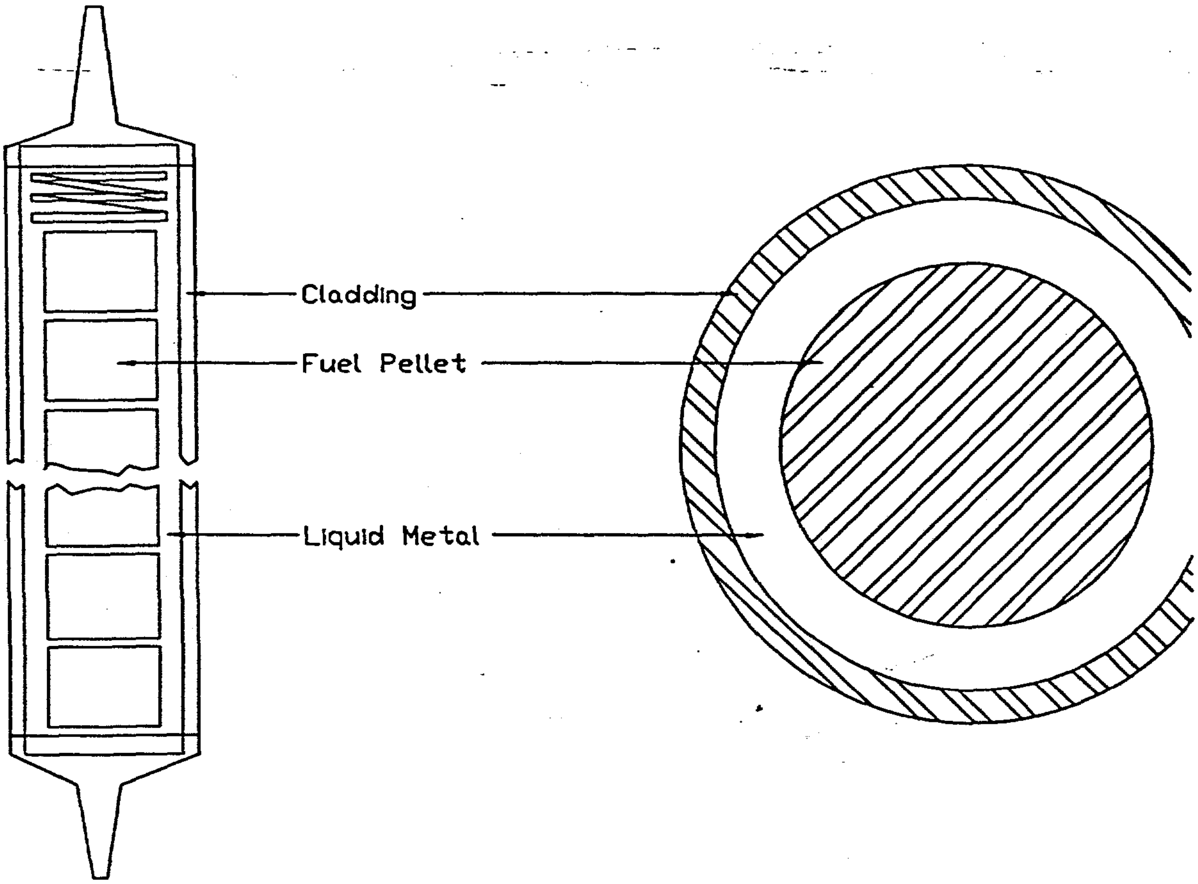

Figure 1: Proposed Liquid Bonded Fuel Rod Design

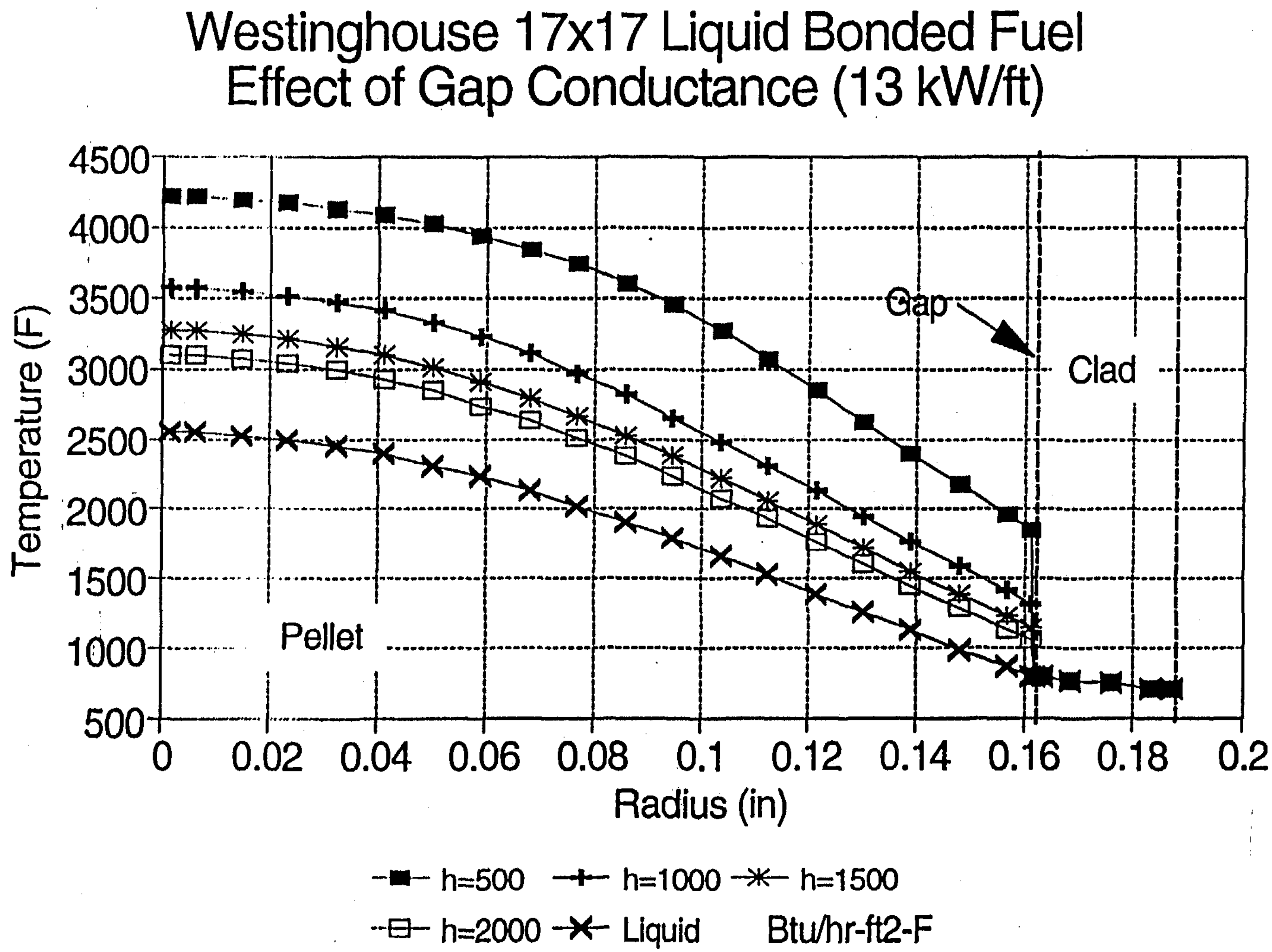

Figure 2: Fuel Temperature Profile vs. Gap Conductance (13 kW/ft)

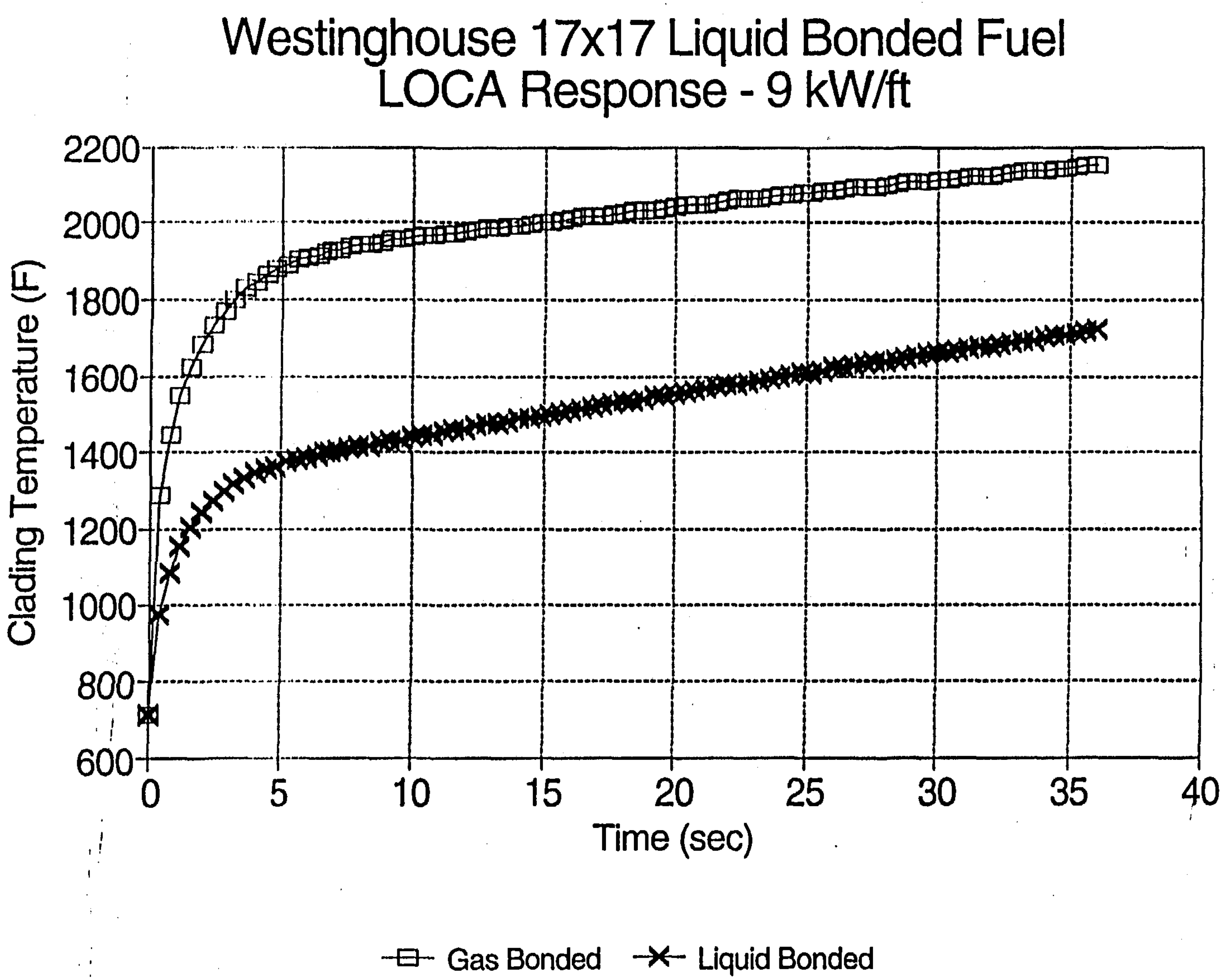

Figure 3: Transient Response to a Simulated LOCA

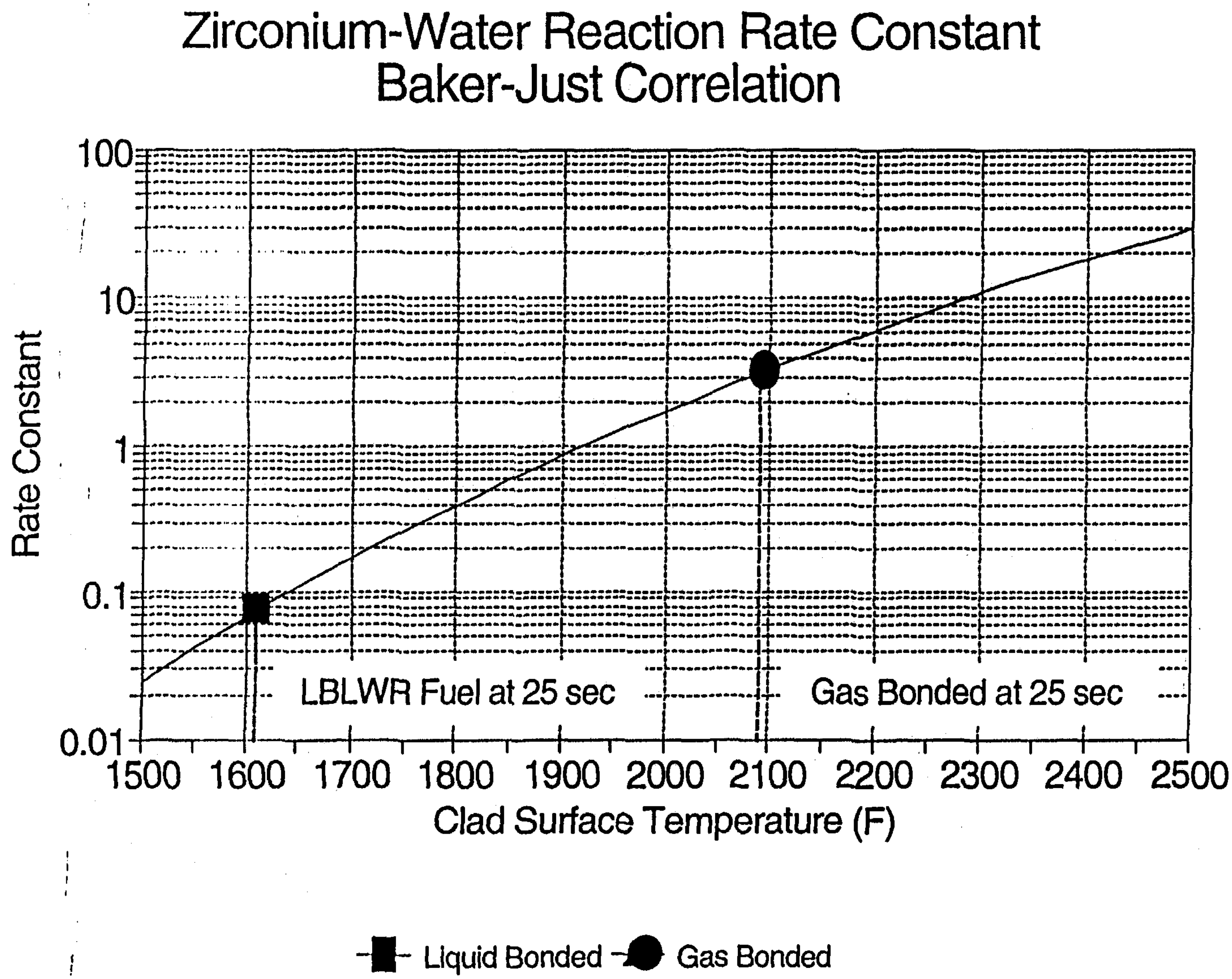

Figure 4: Zirconium-Water Reaction Rate Constant vs. Clad Temperature

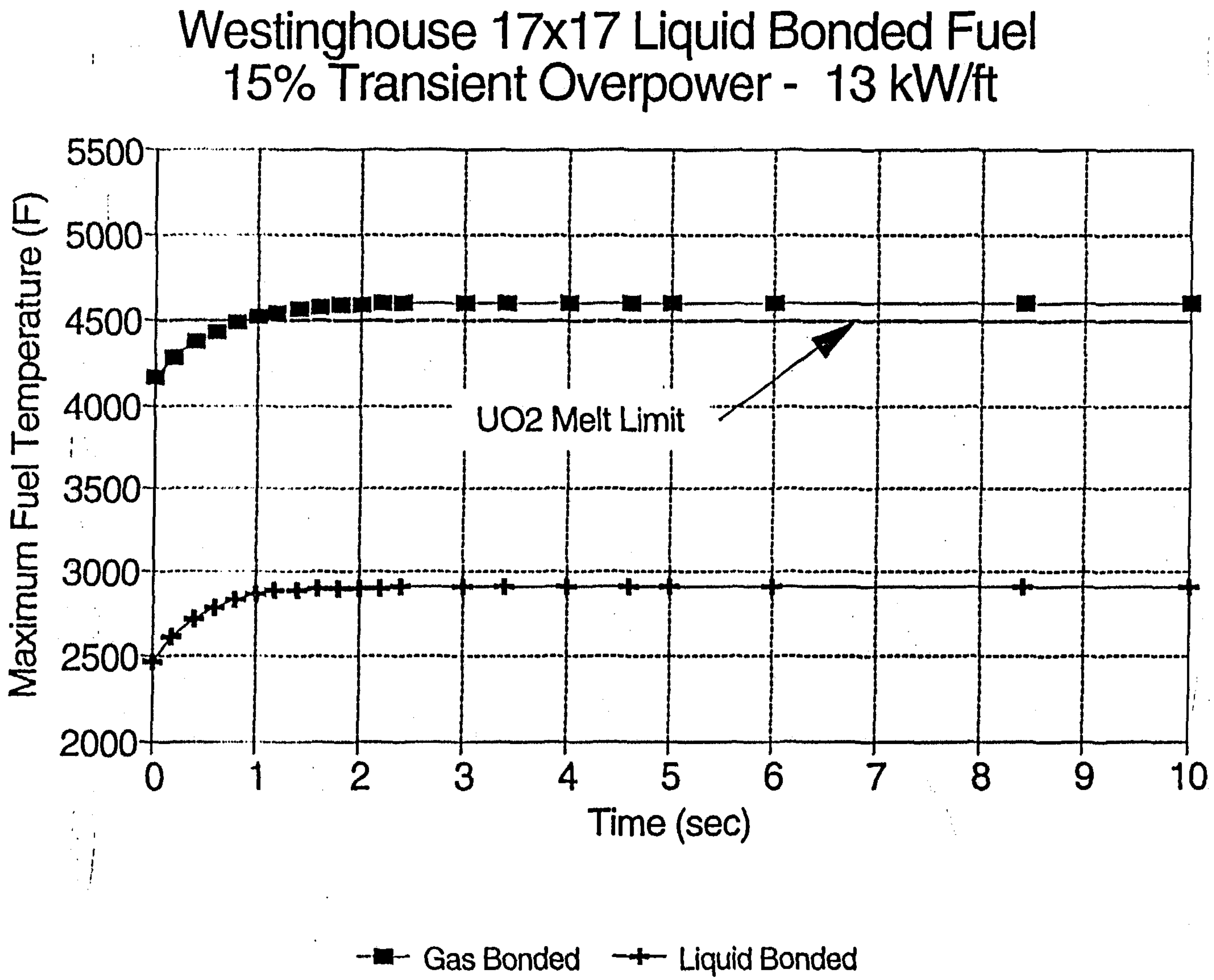

Figure 5: LBLWR Fuel Response to 15% Transient Overpower

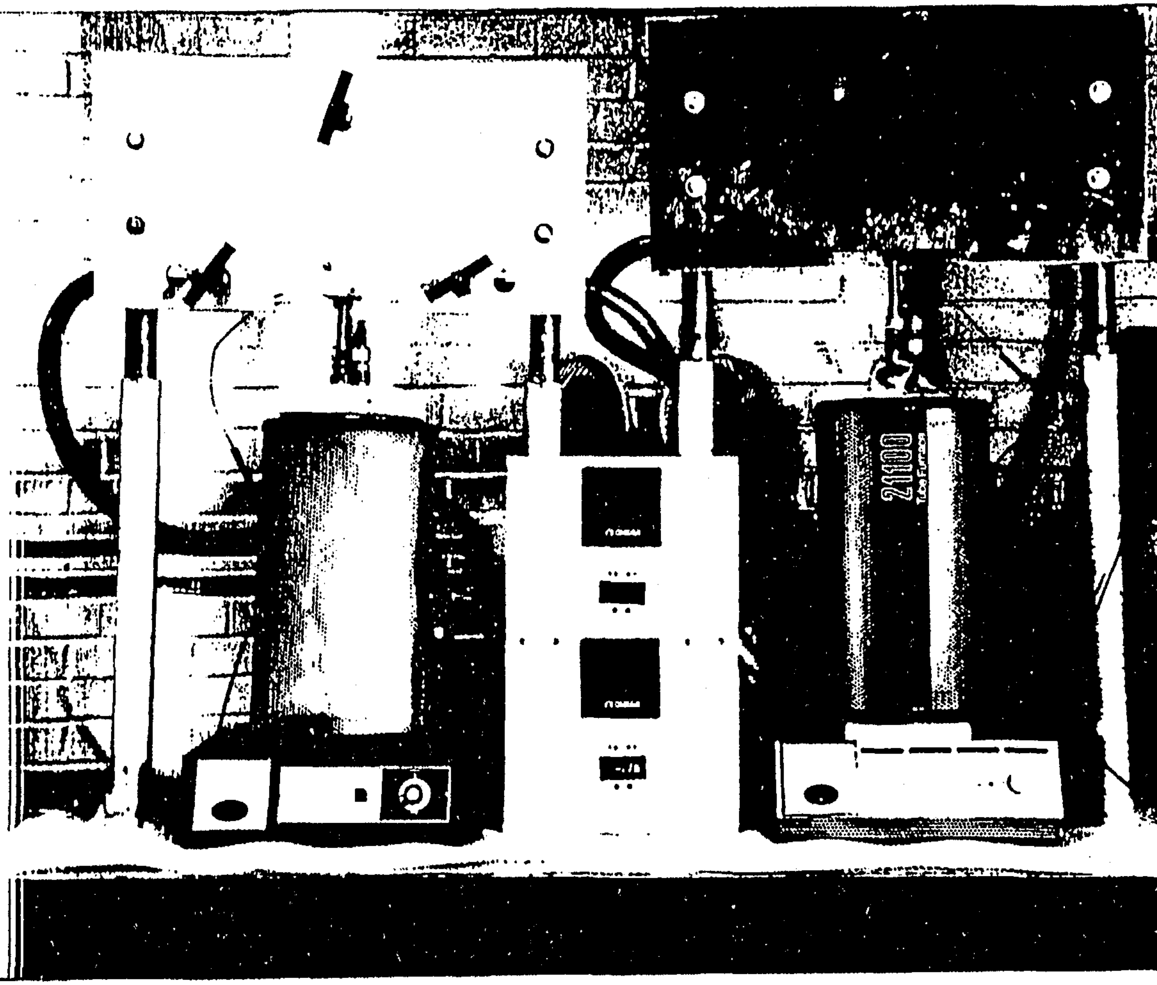

Figure 6: Barnstead-Thermolyne Furnaces for Testing Samples

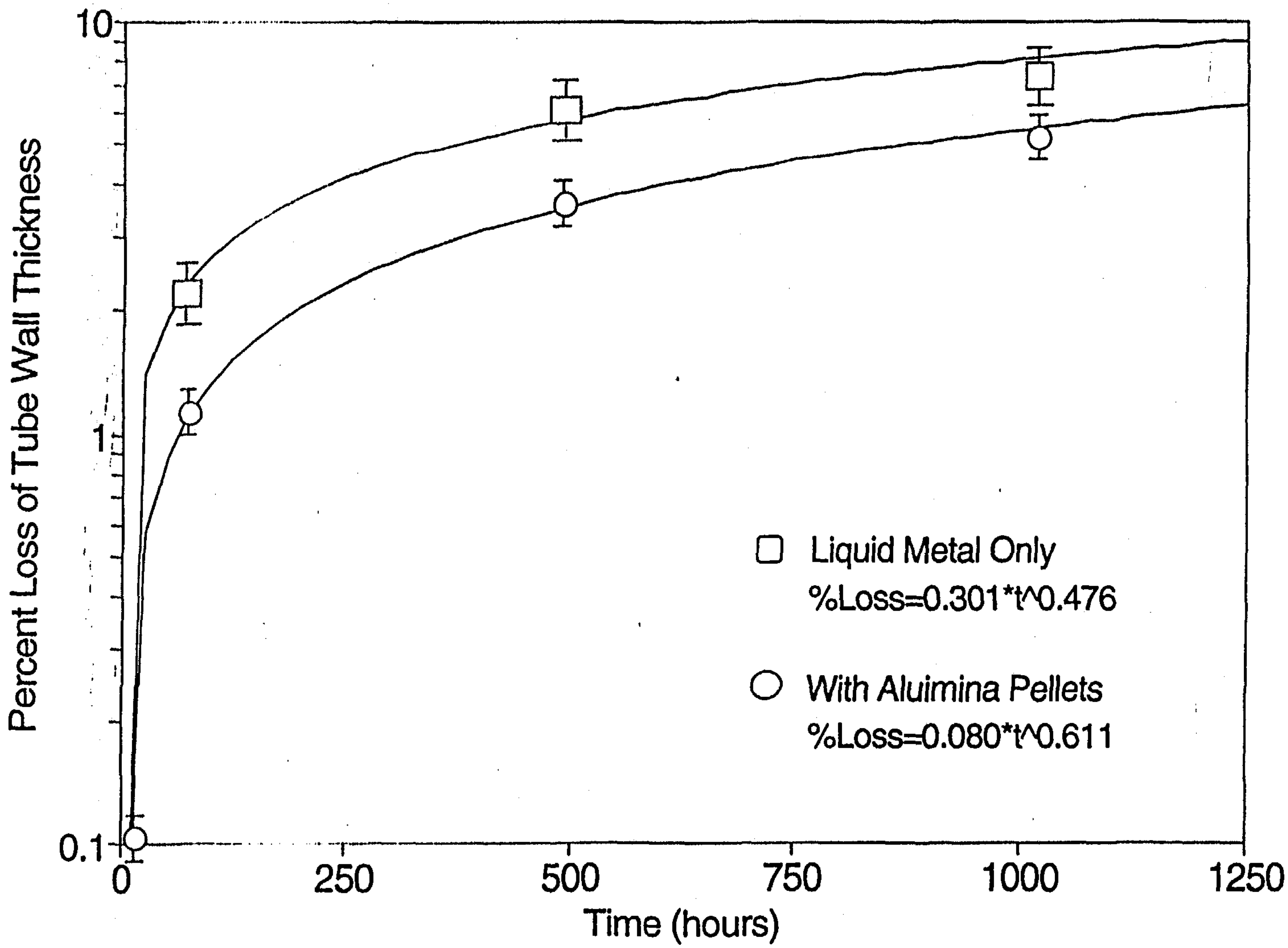

Figure 7: Loss of Wall Thickness, Lead-Bismuth Samples Tested at 750°F for 1000 hours [7]

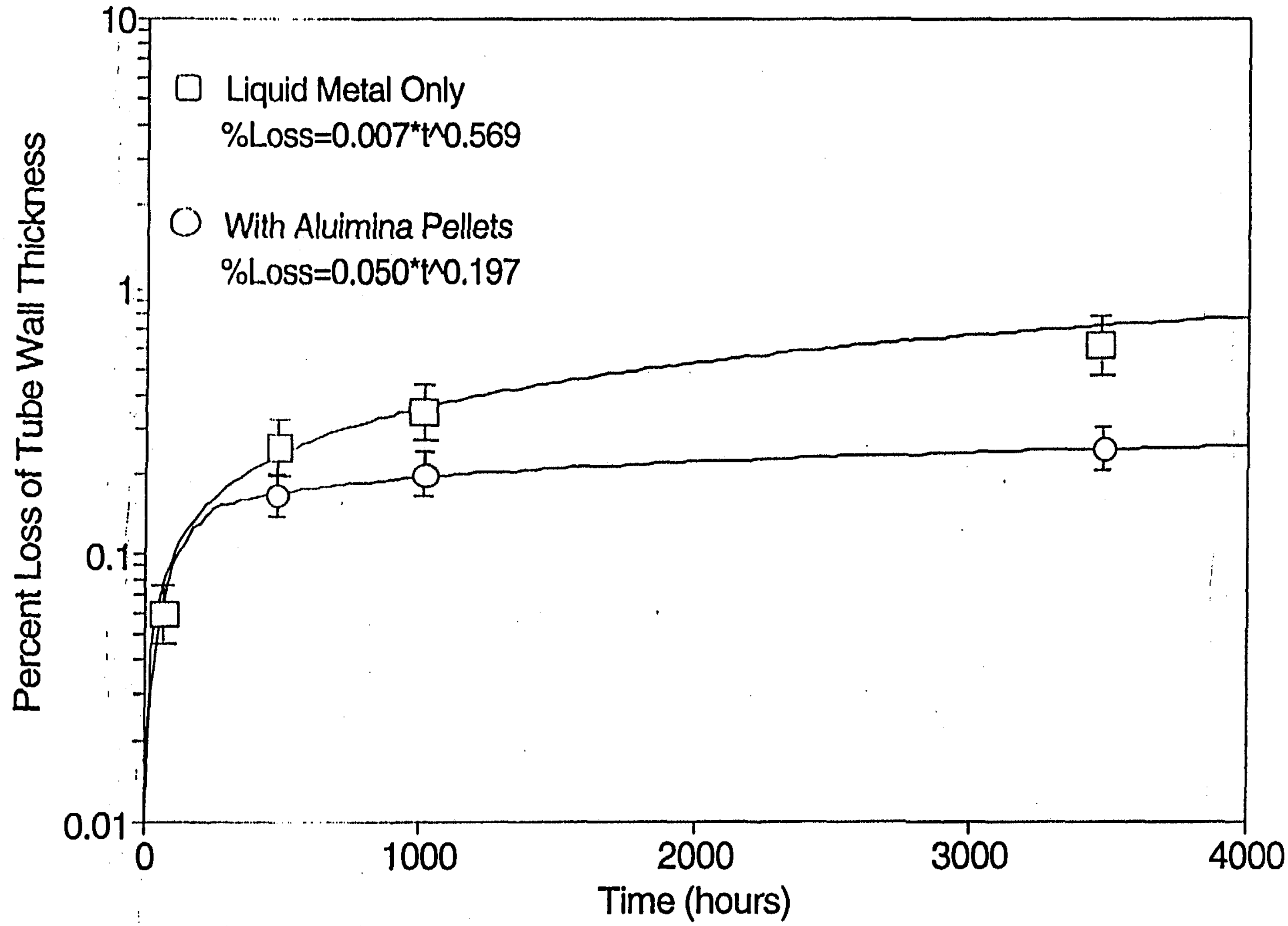

Figure 8: Loss of Wall Thickness, Lead-Bismuth-Tin Samples Tested at 750°F for 3500 hours [7]

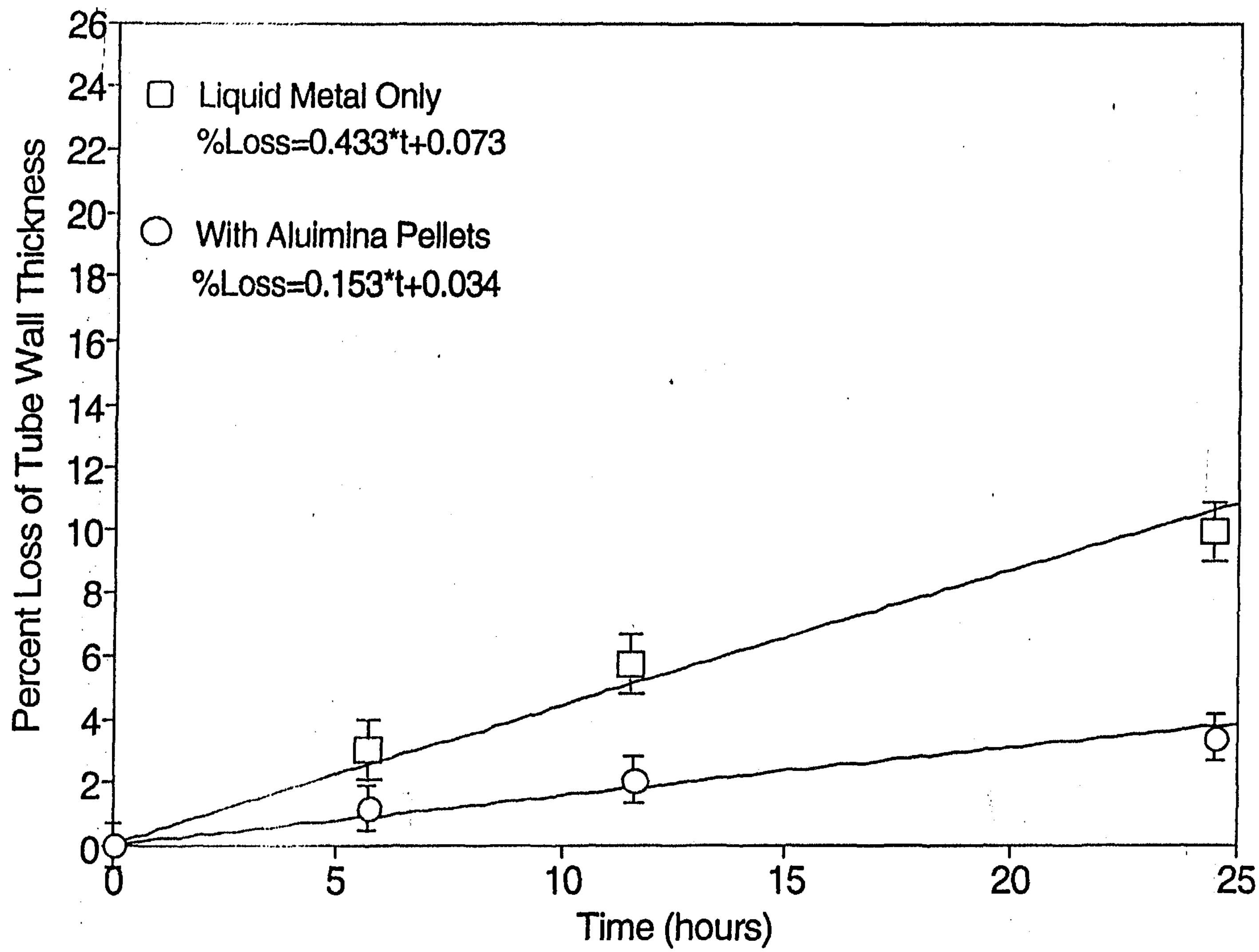

Figure 9: Loss of Wall Thickness, Lead-Bismuth-Tin Samples Tested at 1215°F for 24 hours [7]

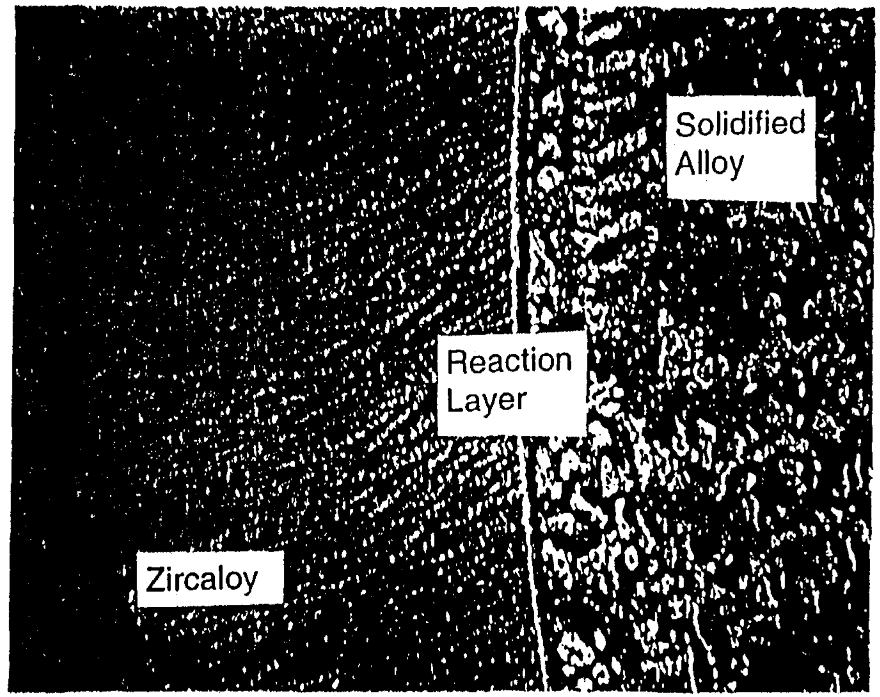

Figure 10: Photomicrograph of Reaction Layer, Lead-Bismuth-Tin Sample, 750°F for 1000 hours

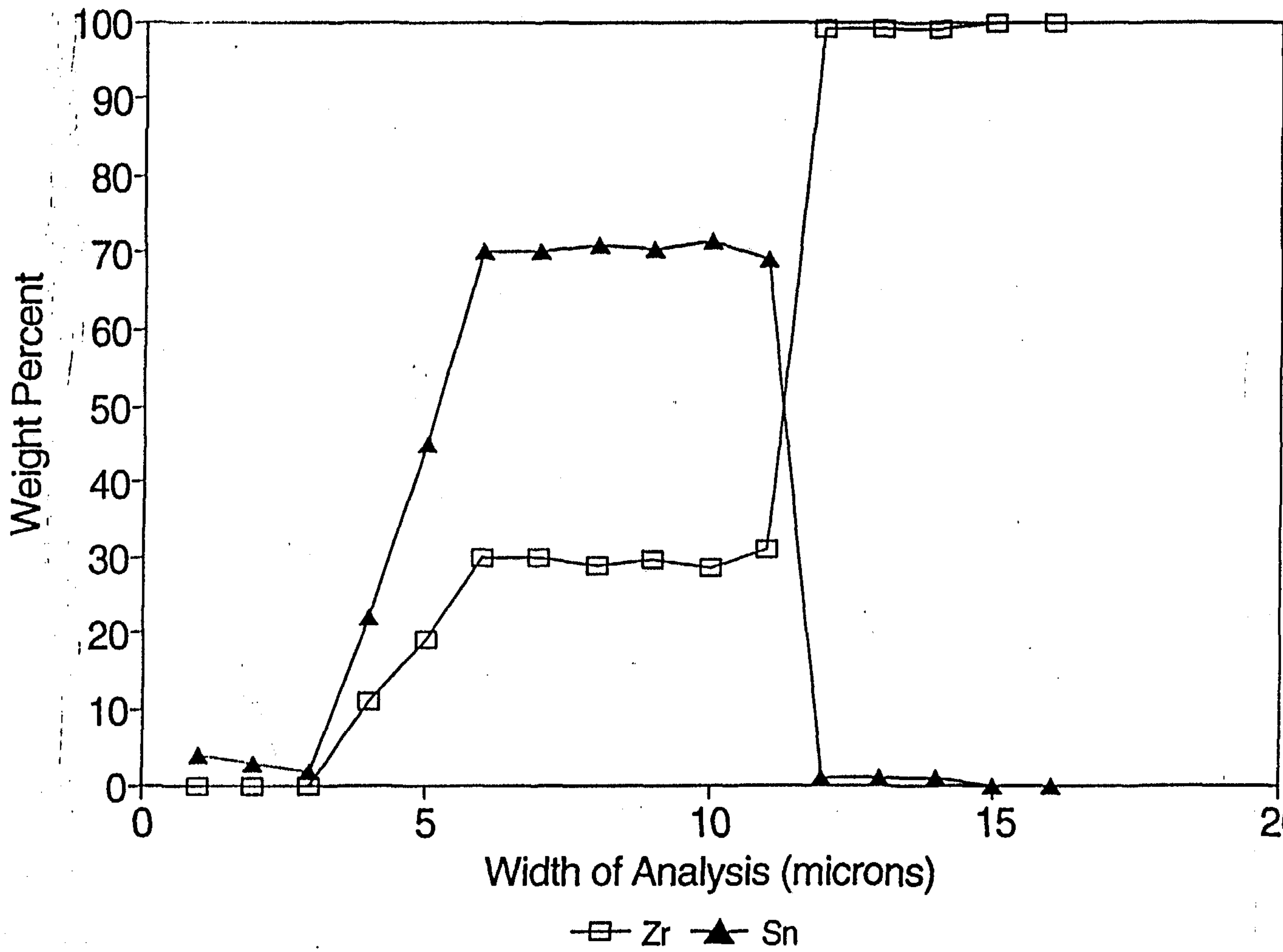

Figure 11: Electron Beam Microprobe Reaction Layer Analysis Lead-Bismuth-Tin Sample

ESCORE LOGIC FLOW DIAGRAM

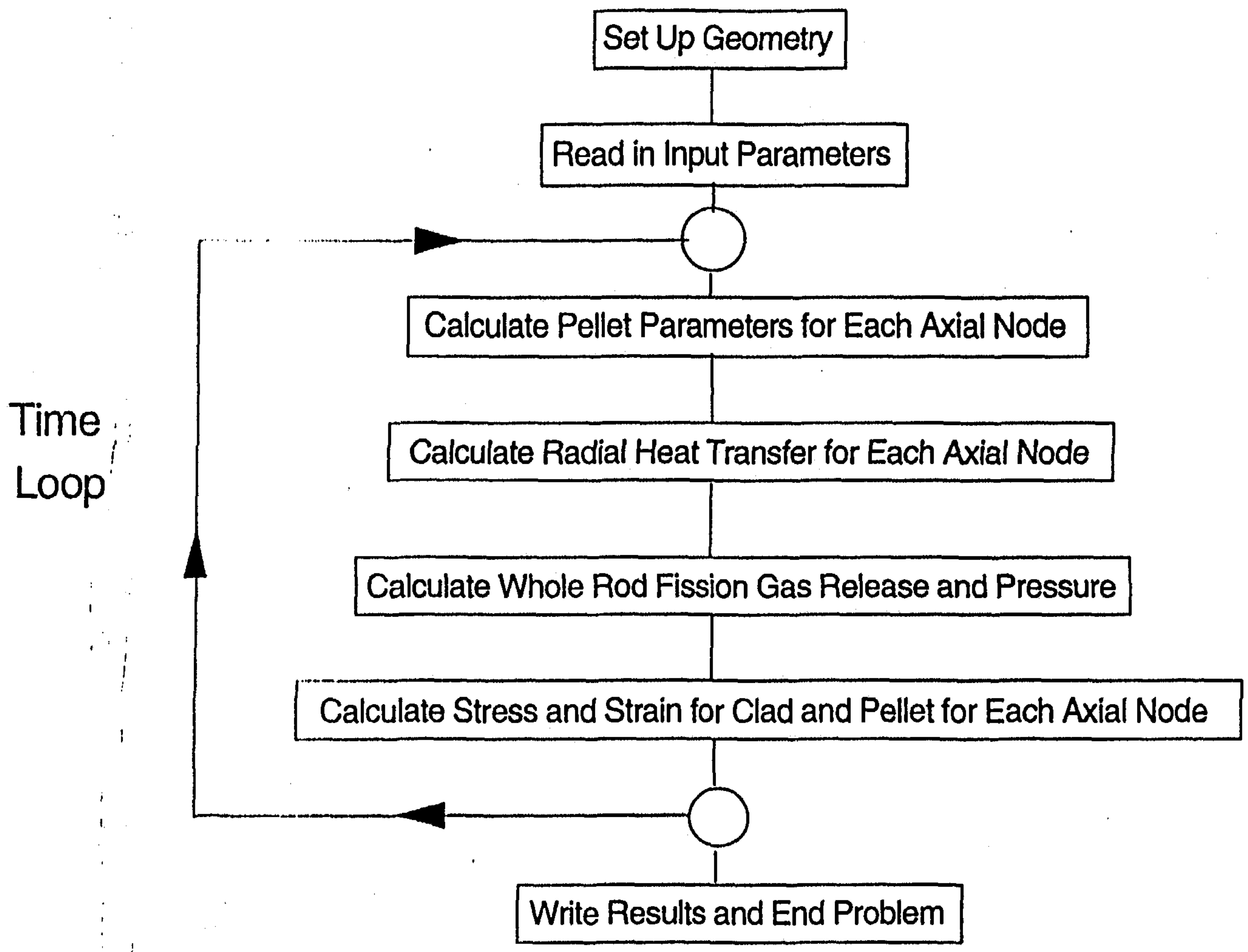

Figure 12: Program Logic Flow Diagram for ESCORE

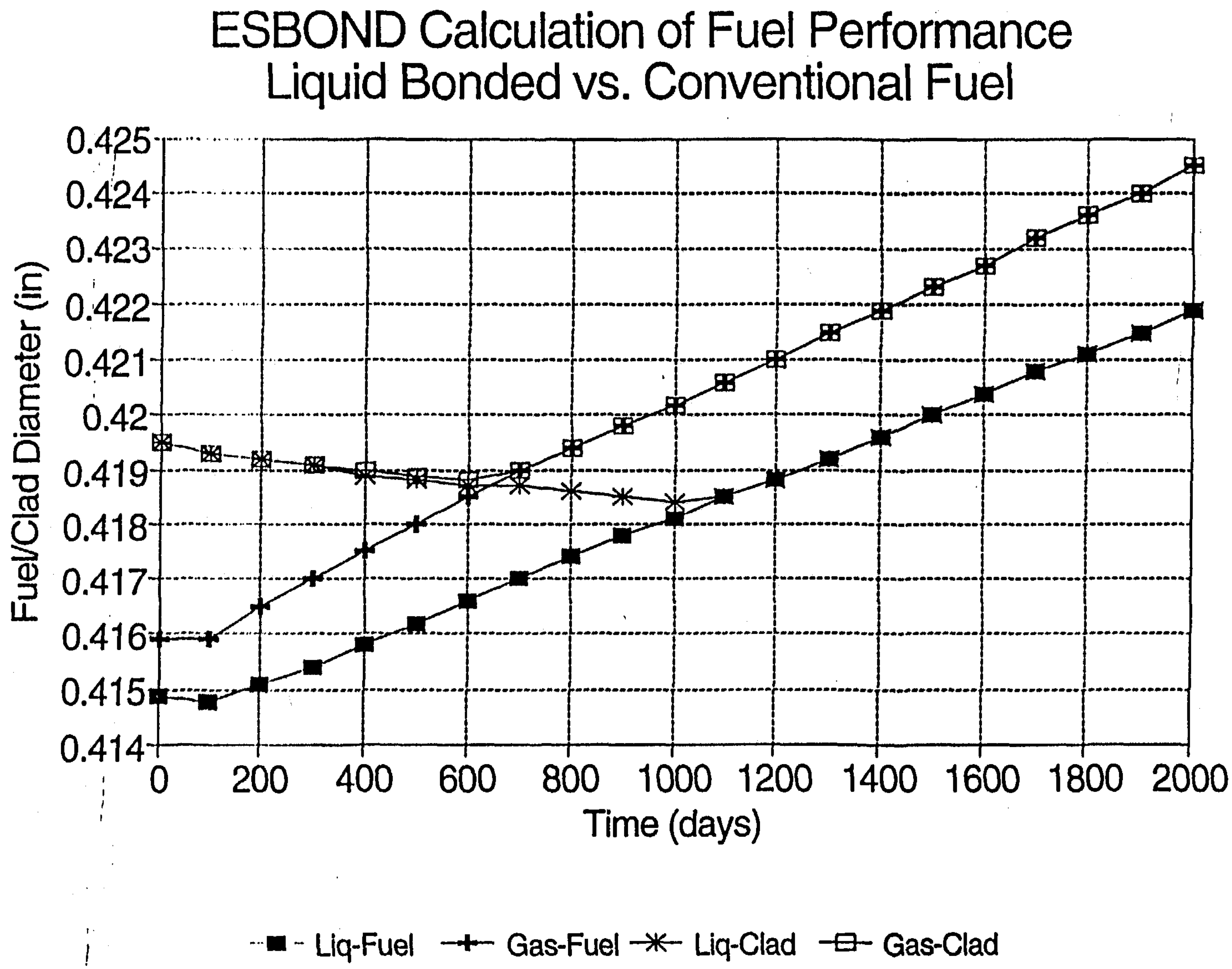

Figure 13: BWR 8x8 Fuel - 9 kW/ft: Rod Dimensions for Peak Node

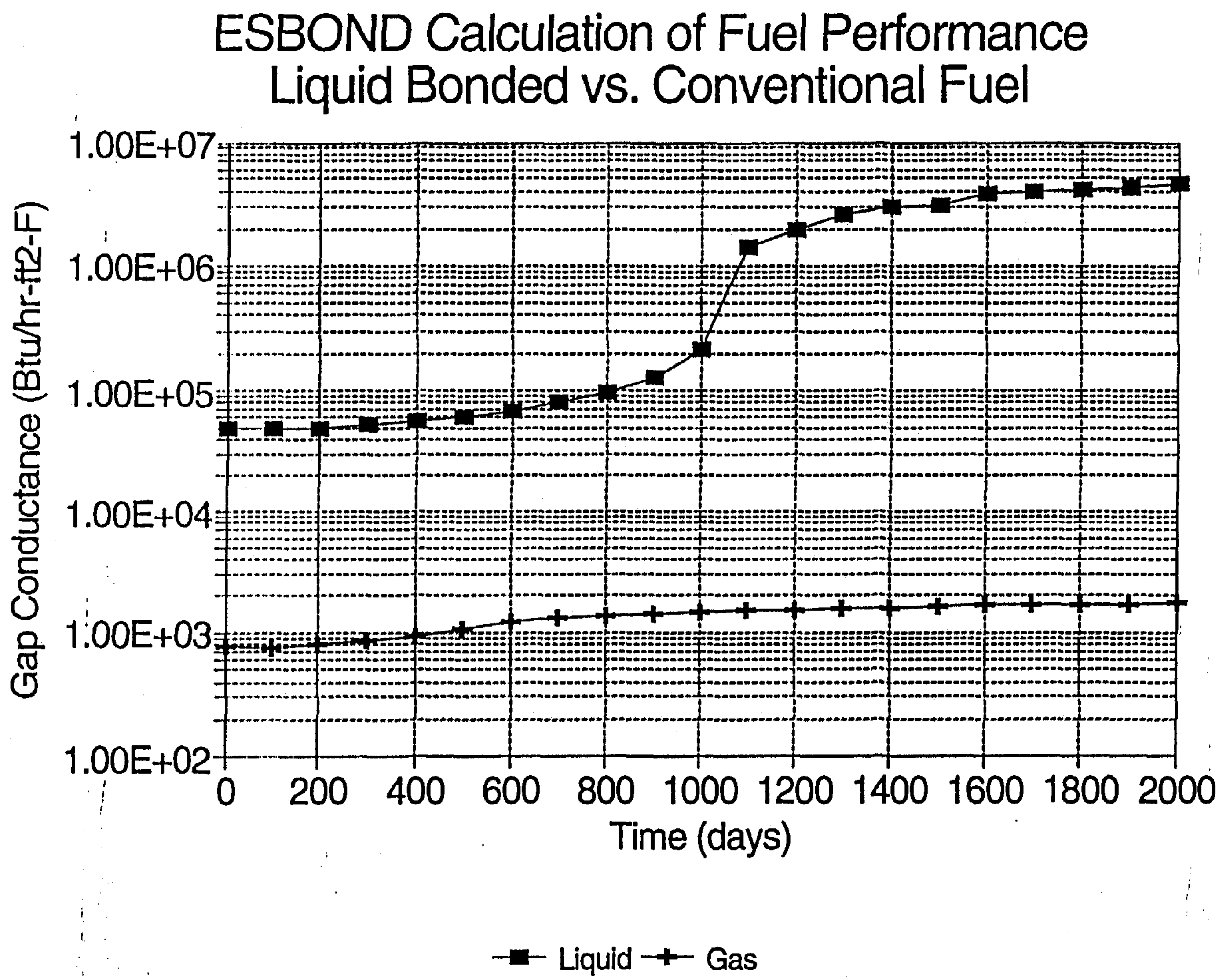

Figure 14: BWR 8x8 Fuel - 9 kW/ft: Average Gap Conductance

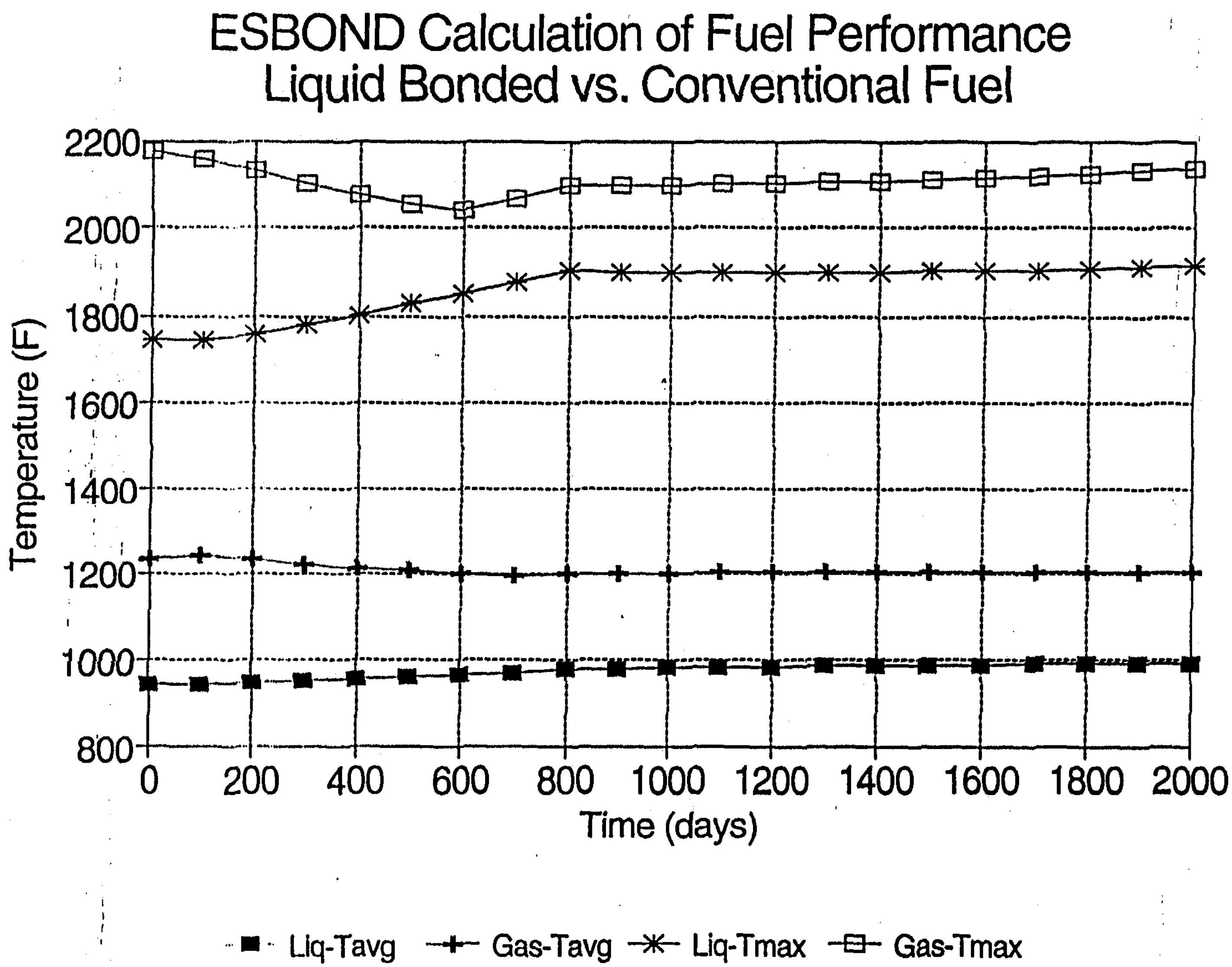

Figure 15: BWR 8x8 Fuel - 9 kW/ft: Fuel Temperatures

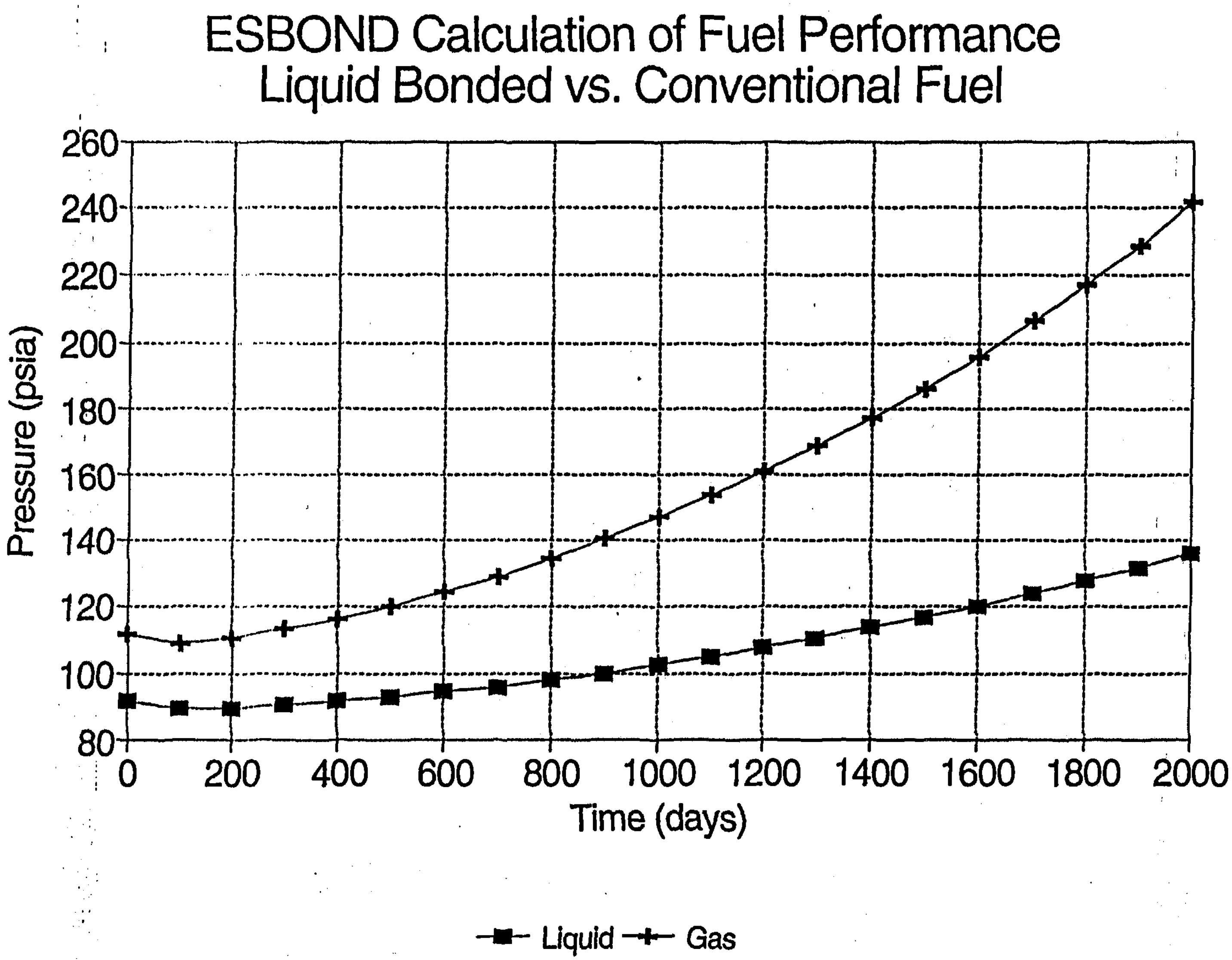

Figure 16: BWR 8x8 Fuel - 9 kW/ft: Rod Internal Pressure

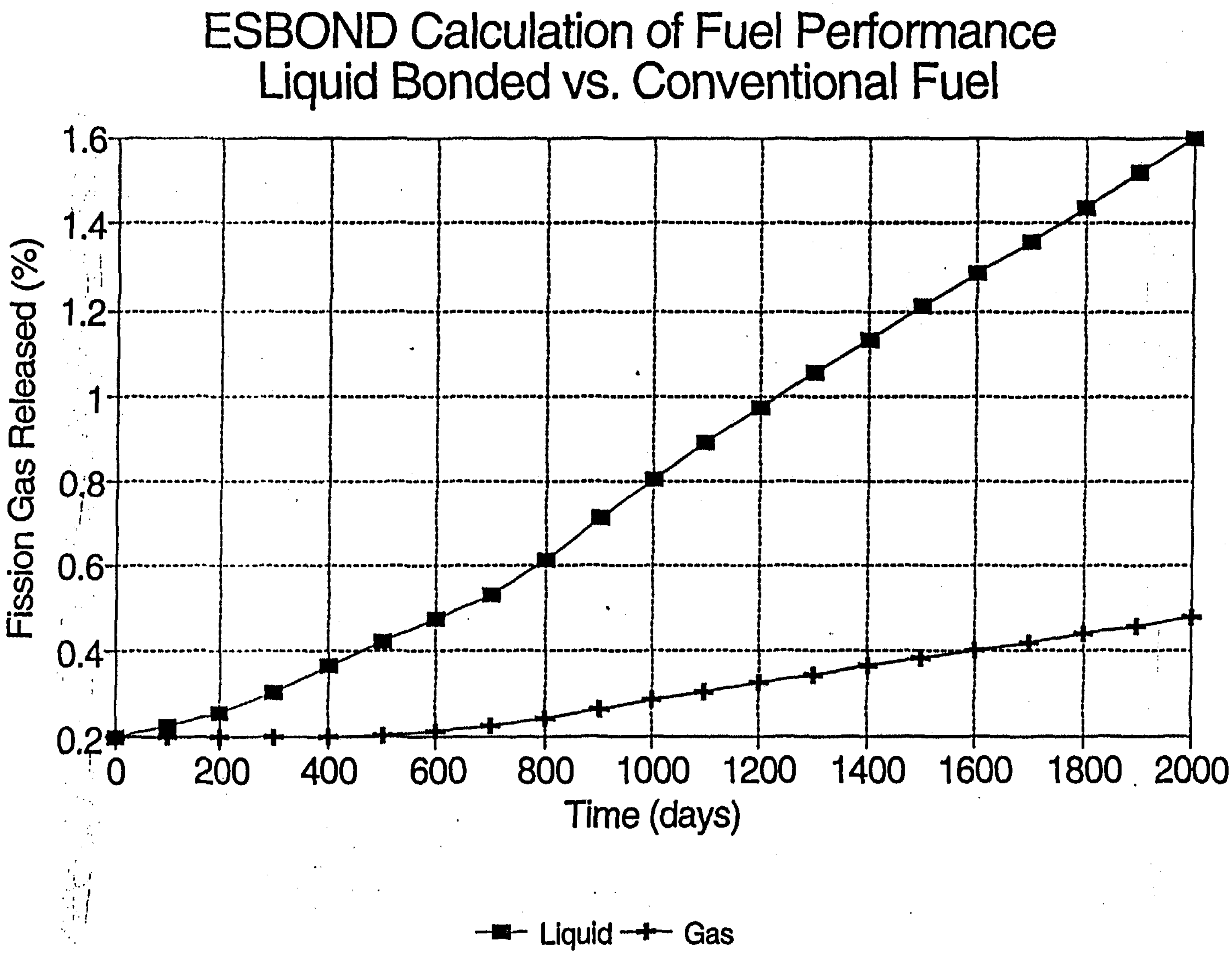

Figure 17: BWR 8x8 Fuel - 9 kW/ft: Fission Gas Released

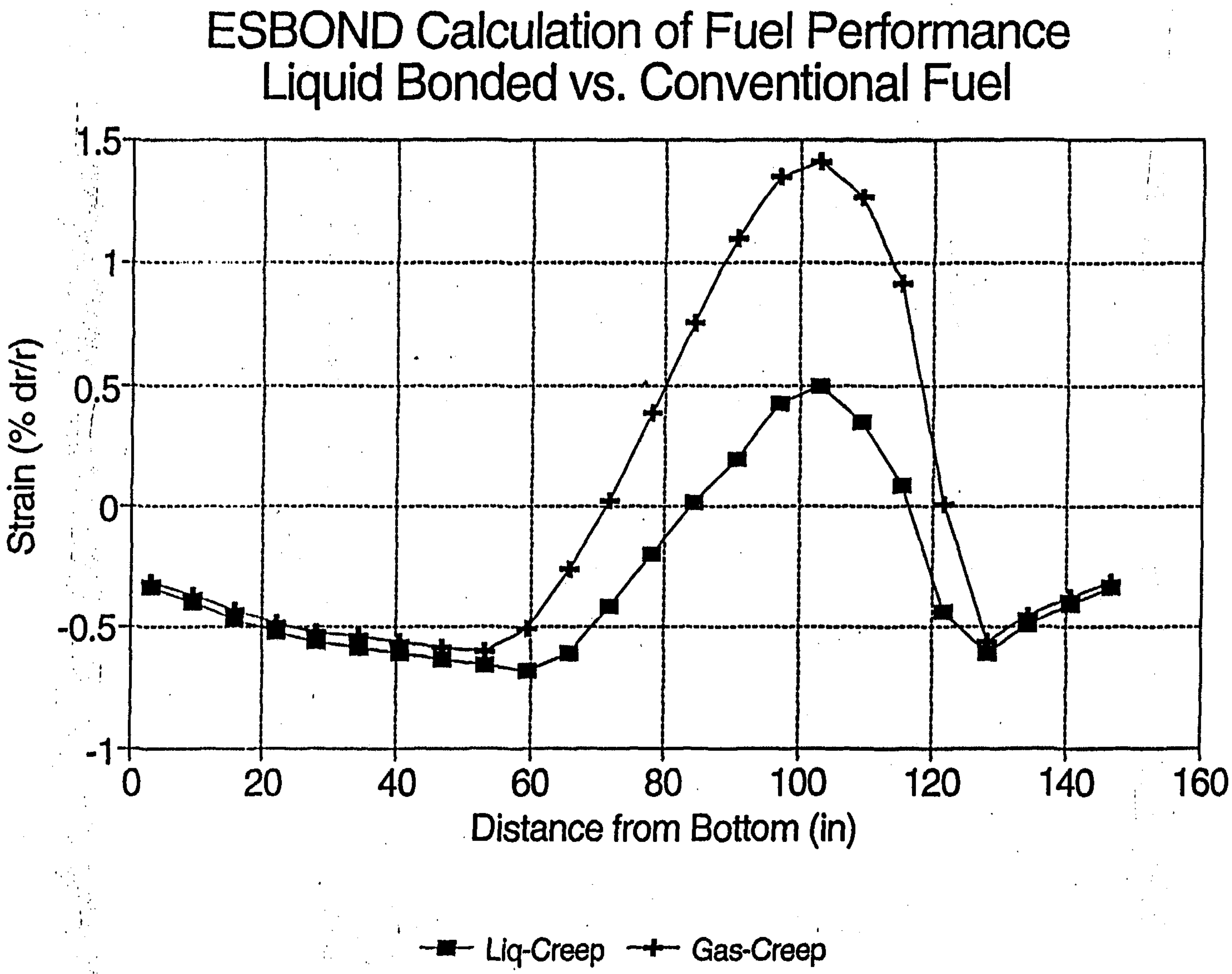

Figure 18: BWR 8x8 Fuel - 9 kW/ft: Clad Strain for Peak Node at EOL