INHERENT SAFETY ADVANTAGES OF CARBIDE FUEL SYSTEMS
and
TECHNICAL ISSUES REGARDING NATURAL CONVECTION IN LMRs

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by

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LIST OF CONTENT

1.0 SCOPE OF WORK

1.1 Scope of Work

The Scope of Work is outlined in the contract as follows:

1. Summarize inherent safety advantages that are unique to the use of a carbide based fuel system. The summary shall cite the advantages and describe supporting arguments and the analysis and experimental program that is needed to demonstrate them.

2. Summarize the technical issues regarding natural convection flow in LMFBR cores. The summary shall list and rank order the issues in the opinion of the author and provide arguments supporting the listed issues and their rank order. The summary shall also discuss the analytical and experimental r&d program believed necessary to resolve the issues.

1.2 Constraints

The Scope of Work is very broad. Safety advantages of carbide fuel systems have been investigated as well as generic and design-specific natural convection issues. The support level for these activities was a total of 8 man-weeks. The discussion of the technical issues is therefore aimed at highlighting the important technical issues rather than being all-comprehensive.

We had to limit the discussion to carbide fuel system safety advantages over oxide fuel systems. An inclusion of metal fuel system would have been very timely (and interesting) but the limited budget available for our work prohibited us from including this fuel type in the evaluation.

This review should not be viewed as a critique of the current carbide fuel program. It is an attempt to identify safety advantages of carbide fuel systems over oxide fuel systems. Ongoing activities, as far as I know them, are reviewed in relation to those issues.

The discussion of natural convection issues in LMRs and the ranking of those issues is based on our own work in this field during the last three years. We identified natural convection issues as important safety issues several years ago and since have seen a greater awareness in the LMR community about their significance. The assessment presented in this report is a summary of our own views and not a summary of views in the LMR community.

2.0 INHERENT SAFETY OF CARBIDE FUEL SYSTEMS

For any fuel system, the designer has to utilize fuel properties like density,
thermal conductivity, melting point, specific heat, etc. to develop optimal
designs. There is no inherently safe fuel. Inherent safety (advantages) of any
fuel system come from the intelligent utilization of fuel properties in the
design of a core/reactor.

Carbide fuel has some unique properties that can be translated into (safety)
advantages over oxide fuel:

	carbide	oxide
melting temperature range, (C)	2300 - 2500	2750-2800
thermal conductivity (W/mK)	14.5	2.4
heavy metal atom density (g/cm-3)	12.9	9.8

Fuel melting point and thermal conductivity determine the linear heat rating
achievable. Carbide fuel designs are capable of ratings in excess of 35 kW/ft
whereas peak oxide fuel ratings are typically well below 15 kW/ft.

The nuclear performance of a core depends crucially on the average core heavy
metal atom density. Carbide fuel designs are capable of heavy metal densities up
to 30% greater than oxide fuel systems.

In the following, specific safety advantages will be described that are
achievable in carbide fuel systems.

2.1 Inherent Safety Advantages

The only qualitative safety advantage of carbide over oxide fuel comes from the
compatibility of carbide fuel with sodium. Oxide fuel reacts with sodium. In my
view, this is a substantial advantage which, however, has often been obscured by
pointing to a potential carbon transport problem in a steel-sodium-carbide fuel
system. For those unfamiliar with carbide fuel systems, the carbon transport
issue is still alive and regrettably distracts from the fuel-sodium compatibili-
ty issue which clearly favors carbide fuel.

The other safety advantages of carbide over oxide fuel systems are all of a
quantitative nature even though carbide fuel systems allow sometimes design
options which oxide fuel systems do not permit. An accumulation of quantitative
advantages turns then into a qualitative advantage.

Both operating conditions as well as specific design features for carbide fuel
systems can enhance safety to a larger degree than for oxide systems. This will
be discussed in the following.

2.1.1 derated cores

For some time, I have advocated derated cores because of the potential advantages, mostly in the safety, but also in the economics area. By derating the core, the following benefits can be derived:

- lower fuel centerline temperature
- lower heat flux
- reduced control rod requirements
- extended fuel life and lower out-of-pile fissile inventory
- lower fabrication/reprocessing/storage cost (mils/kwh)

Carbide fuel systems have clear advantages as far as derating is concerned. The designer has far greater flexibility with a carbide fuel than with an oxide fuel. Even if a sodium-bonded carbide system would be derated to 15 kw/ft it would still be clearly superior to an oxide system. Furthermore, such a derating would permit the use of small diameter carbide rods (0.31 in or even smaller) which have been extensively (and successfully) tested. The lower fuel centerline temperature would increase the margin to melting considerably. Furthermore, the available Doppler reactivity DR would increase substantially because of the larger temperature margin to melting:

$$DR = DC \cdot \ln(T_2/T_1)$$

with DC.......Doppler coefficient
T_1, T_2...operating and limiting temperature, respectively

It is important to note that the Doppler coefficient is a multiplier in this equation and that the requirement of a large Doppler reactivity is equally served by increasing the Doppler coefficient and the logarithmic temperature ratio. Doppler coefficients for carbide and oxide systems are very similar. However, a derated core can show a logarithmic temperature ratio that is over three times that of a fully rated core. Furthermore, an increase in Doppler reactivity due to an increase in the logarithmic temperature ratio is prefered to an increase coming from a larger Doppler coefficient. A larger Doppler coefficient leads to a larger cold-to-hot reactivity margin and therefore larger control rod margin, i.e. more control rods.

Lower heat fluxes are advantageous when coolant boiling has to be assessed. The better internal conversion ratio of carbide fuel reduces the reactivity change over a burn cycle. This effect is greatly enhanced by lowering the rating and with it reducing the burnup swing in reactivity by 50% or even more. This carbide characteristics together with the derating permits a design that virtually eliminates TOP events from the list of core damage initiators.

At this time it is very difficult to assess the economics penalties, if there are any, coming from the derating. Clearly, a derating means a higher fissile inventory, higher cost of fabrication and reprocessing. However, the derating

also extends fuel life. Instead of a 2-year life, a 3-year lifetime or even more, is achievable. This means that the increased cost for fabrication and reprocessing are written off over a longer period of time thus reducing the cost penalty. There are other effects that could totally override the marginal cost increases just alluded to. Derated cores also permit less control rod drives, less complicated head design, and above all, a longer, uninterrupted reactor operation, i.e. a higher capacity factor. This last effect in particular could easily compensate for all other penalties and actually result in lower power cost because of the reduction in the capital cost contribution.

2.1.2 zero burnup swing core

I proposed last year to investigate a zero burnup swing core which, if achievable at all at small plant sizes, requires carbide fuel. Such a core would require only a few low-worth control rods. In case of an accidental control rod withdrawal they would add only little reactivity to the core which could easily be compensated by the negative reactivity coming from the derating as described above. Such a core cannot be designed with oxide fuel unless one uses very large plant sizes (>1000 MWe).

2.1.3 stored heat effect

Carbide fuel systems have a smaller heat capacity than oxide fuel systems, i.e. they store less heat. In case of a pump coastdown, carbide systems have a better power to flow ratio than oxide systems where a large portion of the stored heat is rejected when the flow is already substantially reduced. It is possible to tailor the pump coastdown such that it optimally matches the power decay. However, oxide systems would then require a longer halving time which could adversely affect the establishment of natural convection flow.

2.1.4 sodium void reactivity

It is known that carbide systems have typically a $2 higher sodium void reactivity than oxide systems. However, in my view this handicap can easily be overcome by designing for a voiding incoherence. Last year, I proposed to LANL a reactor concept that is homogeneous but shows the voiding characteristics of a heterogeneous core. Therefore, the high sodium void reactivity of a homogeneous carbide system should not be viewed as a detriment.

2.1.5 vapor explosions vs licensability

In a recent article by Herbst and Matthews on "Uranium-Plutonium Carbide Fuel for Fast Breeder Reactors" (Nuclear Technology, Vol. 63, Oct. 83) it is stated that "a carbide core is potentially more energetic during a hypothetical core

disruptive accident (HCDA) transient". Reference is made to Fauske's vapor explosion model where the spontaneous nucleation temperature of sodium plays a major role. The above cited article states that according to Fauske's model, a UO_2-Na system cannot lead to an explosion whereas a (U,Pu)C-Na model can satisfy the condition for spontaneous nucleation on contact. It is correctly pointed out that Fauske's model is "not totally accepted as a complete description of the events leading to an explosive vapor reaction".

However, based on a review of the literature, much stronger statements have been made in regard to the applicability of the spontaneous nucleation model to predict vapor explosions. In 1979, Briggs, Fishlock, and Vaughan presented a review of molten fuel coolant interaction (MFCI) in fast reactors and concluded:

"The contention that UO_2 and sodium will not interact energetically on a large scale because of the interface temperature criterion is not proven. Theoretical work suggests that thermal detonation based on hydrodynamic fragmentation at rates observed experimentally is possible, hence the argument that spontaneous nucleation is necessarily involved in propagation of an interaction must be considered doubtful".

(p. 1509, Fast Reactor Safety Technology, Seattle, August 19-23, 1979).

The article by Herbst and Matthews refers to an experiment at Sandia National Laboratories which showed higher energetic fuel coolant interaction in a carbide systems than in an oxide system. The experiment was carried out in the power burst facility and the aim was to confirm an analytical model developed for FCI predictions. I examined this experiment more closely. The experimental results do suggest a greater FCI for carbide than for oxide pins. However, in my opinion, the results of these experiments are open to questions. Some of them are raised by the experimenters and authors Reil, Young and Jacobs of SNL.

In the PBE-SG2 experiment (carbide fuel pins), a single pulse heated up the fuel to 6200° K whereas in the oxide fuel experiment (PBE-9S), the fuel was heated up to only 5000° K. A comparison of critical parameters in both experiments is shown in Table 2.1. It could very well be that because of the fuel/coolant mass ratio of 8.2 in the carbide experiment, this caused a more energetic reaction than in the oxide fuel experiment with a substantially smaller ratio. In water-UO_2 experiments it was found that a maximum yield in the explosion was obtained when the water/fuel volume ratio was about 2 (see German Risk Study, translated by EPRI). Furthermore, the initial temperatures in the oxide experiment were uncertain because at the time of the interaction, some heat transfer between fuel and sodium in the post-pin failure geometry must already have occurred. The experimenters caution that any conclusions drawn from the experiments and their analysis are necessarily tentative because many of the important variables, like particle size, mixing time, and masses of interacting fuel and sodium, are unknown. It is also not clear how the oxide fuel response to a double pulse differs from the carbide fuel response to a single pulse.

Table 2.1: Critical Parameters in the PBE-SG2 and PBE-9S Experiments

	PBE-SG2	PBE-9S
Energy Deposition	2420 J/g	3520 J/g
Peak Fuel Temperature, ^{o}K	6200	5000
Initial Fuel/Sodium Temperature, ^{o}K	5600/920	unknown
Pulse Type	single	double
Interacting Zone		
Fuel	2.87 cc (30%)	6 g (10%)
Sodium	3.67 cc	2.2 g
Mass Ratio	8.2	2.73
Peak Pressure, MPa		
top	170	35
bottom	190	<10

Our review of the state of the art for steam/vapor explosions showed that even with years of extensive small and intermediate scale experiments and their analyses, there are still many questions about FCI, the prototypicality of experiments and the existing analytical models for LWRs. While the FCI concerns for LWRs are somewhat different (for example, they begin with part of a molten core dropping into a plenum filled with water), the interaction between molten fuel and coolant might very well depend on how the interaction was initiated.

To illustrate the degree of uncertainty that exists even today on steam explosions, some positions taken by NRC and IDCOR on FCI safety issues are listed below.

Issue	IDCOR	NRC
Maximum amount of fuel that can coarsely mix in-vessel	100 kg	5000 kg or more
Maximum amount of fuel that can coarsely mix ex-vessel	7 kg	16000 kg or more
Steam explosions may not occur at high ambient pressure	yes	maybe, but no data
Energetic steam explosions in reflood mode	doesn't occur	may occur
Energetic steam explosion in stratified mode (water above fuel)	doesn't occur	may occur
Multiple explosions and highly transient FCI phenomena	do not occur	may occur
In-vessel fuel dispersion due to a a steam explosion	doesn't occur	may occur

Because of those uncertainties in the phenomena and the ambiguity of the experimental data, it is in my view better not to assume a priori that there is energetic MFCI in carbide fuel systems but not in oxide fuel systems.

2.1.6 low pressure drop designs

For the same linear heat rate and operating conditions, carbide systems permit lower pressure drop designs than oxide designs. The higher fuel density of the carbide system permits to load the same number of heavy metal atoms in a smaller diameter rod. Because the coolant areas are the same (same number of sodium atoms) the carbide systems have a larger pitch-to-diameter ratio than oxide systems and therefore a smaller pressure drop.

This observation is important in many regards. For one, it has been largely obscured and just the opposite has been considered a characteristic of carbide systems. Using very high linear heat ratings for carbide fuel (twice the oxide rating) necessitates the use of very large fuel rod diameters to achieve the

same heavy metal/sodium atom ratio as in oxide systems. This in turn increases the pressure drop.

Secondly, the higher fuel density of the carbide fuel alone is an advantage over oxide fuel. By using smaller fuel rods at the same rating as an oxide pin, assembly sizes and core sizes are smaller than in comparable oxide designs. The safety advantage of the carbide fuel is then the improved natural convection capability coming from the reduced core pressure drop.

The pressure drop can also be reduced by exploiting the higher fission gas retention in carbide fuel, especially in sodium-bonded designs. This could result in a 20% reduction in core pressure drop. The uncertainty in this benefit lies, in my opinion, in the uncertainty in fission gas release under transient conditions. To my knowledge, we don't know at this time, how much of the stored fission products would be released under mild TOP conditions.

However, because of the compatibility of carbide fuel with sodium, the potential exists to design a vented fuel rod which would eliminate all discussions about the uncertainty in fission gas release fraction under steady-state and transient conditions as well as fuel rod failure due to excessive fission gas pressure.

2.2 Support Program to Demonstrate Advantage of Carbide Fuel Systems

In my view, we have currently a far better understanding of carbide fuel behavior than of carbide fuel designs.

The fuel performance has been investigated in some detail for the last 10 years, mostly as part of a base technology program where carbide fuel was viewed as a replacement fuel for oxide fuel. No attempts have been made in the past to utilize the characteristics of carbide fuel to determine meaningful design constraints and design a safe and economical carbide core. Instead, carbide cores were designed subject to design constraints developed for oxide cores and meant to be replacements for oxide cores. Oxide safety concerns were copied and applied to carbide fuel systems without knowing if the safety concerns were the same. An example is the application to carbide systems of the heterogeneous core concept that was first introduced to help oxide cores with small fuel rod diameters achieve a better breeding performance. Later it was discovered that the main advantage of the heterogeneous concept was the voiding incoherence that proved advantageous for oxide core energetics assessments. This concept was then applied also to carbide fuel cores even though the breeding performance of carbide fuel systems is far superior to that of oxide fuel systems. The need for voiding incoherence achieved by using a heterogeneous core configuration (and not another design concept) was never demonstrated.

Typically, carbide cores were designed for the highest achievable linear heat rating and the shortest possible doubling time. The designs were not constrained by safety considerations. The safe performance had to be confirmed, i.e. after

design completion, analyses were conducted to sketch out the expected performance during CDA transients. Despite of the wrong assumptions that a benign response to a CDA initiator means safety, no detailed CDA analysis was ever carried out for a carbide system. No attempts were made to trade off breeding performance for safety.

To justify carbide fuel system development as a viable alternative to oxide systems requires the demonstration, both analytically and experimentally, that carbide fuel systems are superior to oxide systems. This superiority has to be substantial and not only marginal. With uncertainties in cost predictions for nuclear power systems, a new fuel development program requires more than a fuel cycle cost advantage of a few tenth of a mil per kwh. System performance has to be far better than lowering the core pressure drop by a few psi and raising the breeding ratio and lowering the doubling time by a few percent. With the current de-emphasis of breeding, improvements in doubling time could not at all justify to embark on a new and expensive fuel development program. If carbide fuel is to be a viable option to oxide fuel, qualitative and not only quantitative advantages have to be demonstrated. As outlined earlier, the only qualitative difference between oxide and carbide fuel is the compatibility with sodium. While important, this difference alone could not justify a new fuel development program. Therefore, emphasis has to be placed on intelligent and creative use of the carbide fuel properties to develop systems that show a distinct qualitative difference to oxide systems. In other words, one must be able to point to essential features of a carbide system that cannot be obtained in an oxide system.

In my view, the design of a replacement core for a modular oxide design will not demonstrate carbide fuel advantages to a degree that one has to conclude that carbide fuel is a better fuel than oxide fuel and that its development costs are justified. The constraints coming from the small module size and the core internal geometry are too severe to conclude more from such a design activity than how a carbide replacement core for such a module performs.

In my view, it needs to be demonstrated that carbide fuel systems are safer than oxide systems. Furthermore, it must be shown that the results of the extensive testing of carbide fuel during the last 10 years can be directly applied in support of a newly designed carbide system. In my view, it weakens the case for carbide fuel if one has to start from scratch with, for example, a fuel rod size well above everything ever tested, arranged on a pitch much smaller than ever considered in design. The case for carbide fuel would be further weakened by selecting a rod diameter in a reference design that is far greater than ever tested when the trend obtained from experiments is toward more problematic performance as the rod size incraeses.

An analytical and experimental test program has therefore to focus on key issues that can demonstrate the safety advantages of carbide over oxide fuel.

2.2.1 analytical

In my view, before one embarks on extensive and detailed analysis efforts one
has to charter the course one wishes to follow. What has to be shown analytical-
ly is the safety advantage of carbide fuel over oxide fuel. Since fuel in itself
is neither safe nor unsafe, we have to determine the environment in which a
core/reactor with carbide fuel is safer than an oxide core/reactor. The follow-
ing is a brief discussion of the steps needed to achieve this goal. At least at
the early stages, no detailed analyses are required even though after a concept
has been defined in sufficient depth, detailed analyses are needed. The follow-
ing is a list of analysis complexes. To determine the safety advantages of
carbide fuel over oxide fuel, all of them should be addressed.

2.2.1.1 design ground rules

At the beginning of any design activity is the definition of the design ground
rules. Great care has to be exercised that those ground rules are flexible
enough not to bias the results, but sufficiently specific to permit drawing
meaningful conclusions. Nearly two years ago, I proposed to develop design
ground rules for carbide fuel, using oxide design ground rules as a starting
point and point of departure. Because design ground rules reflect what we know
about carbide fuel performance in a specific design (and this is very little)
those ground rules would have to be updated as designs evolve.

2.2.1.2 concept development

Concepts need to be developed that translate carbide fuel properties into safer
reactor/core designs. No detailed analyses are required at the early stage of
concept development. As an example, one design goal I proposed earlier to LANL
was to "design out" the transient over power event. This can be achieved in at
least two ways. One is to derate the fuel and use the larger Doppler reactivity
to compensate for reactivity additions to the core. The other design option is
to design a core with a near zero burnup swing so that an uncontrolled control
rod withdrawal adds only little reactivity to the system (no possibility for
super-promt criticality).

Next one needs to determine required module sizes to achieve the goal of elimi-
nating the TOP event from the list of severe accident initiators. Trade-off
studies have to be conducted to assess power output of the module, size of the
module (capital cost), degree of derating, available Doppler reactivity, control
rod worth needed or required and credible ramp rates depending on control rod
worth and withdrawal speed.

To counteract the consequences of the large sodium void reactivity typical of
carbide fuel systems, I proposed earlier to LANL a homogeneous core concept that
has the voiding characteristics of the heterogeneous core. This concept needs to

be assessed.

In those investigations, maximum use should be made of the rod diameters that have already been tested, namely the 0.31 in and 0.37 in rods.

Other concepts need to be developed that address the TUC event and hopefully help to eliminate it from the list of accident initiators.

A LOHS accident cannot be eliminated (because it is postulated based on power outage and diesel generator experience) but needs to be accomodated. Designs need to be developed that can effectively accomodate the LOHS accident utilizing carbide fuel assemblies. In a study for LANL, I identified the most promising design options to enhance natural convection flow.

Below, both TUC and LOHS accident prevention/mitigation design options will be discussed.

2.2.1.3 component designs

I developed a control rod/assembly design concept that has the potential for eliminating a core meltdown due to TUC or TOP events. The design uses an enhancement of control rod expansion so that any rise in sodium temperature above that permitted for normal power operation will add negative reactivity to the reactor and thus stabilize the power level and/or shut the reactor down. Because of the low heat capacity of carbide fuel, in case of a TOP event, sodium is heated up nearly instantaneously hence expanding the control rods into the core faster than in case of an oxide core that stores substantially more heat in the fuel.

The pressure drop in low pressure carbide designs can be further reduced by using grids instead of wire wrapping as spacer concept. Typically, grids have been considered for carbide cores whenever the spacer wire diameters would have to be very large (>80 mils) resulting from the use of large diameter rods and large p/d ratios (for example, a 0.40 in rod with a p/d ratio of 1.2). While grids are beneficial also to oxide rods as far as performance is concerned, cost comparisons have shown that gridded assemblies are more expensive than wire-wrapped assemblies. This cost penalty is smaller for carbide assemblies because less feet of fuel are required for the same power output.

Electro-magnetic pumps are very suitable for carbide designs because their short pump coastdwon matches very well the requirements for carbide core. As stated earlier, carbide fuels store very little heat when compared to oxide fuel. In case of a protected TUC event, a better power to flow match should be achievable for carbide fuel.

2.2.2 experimental

Because experiments are always more expensive than analytical efforts, experiments should be well prepared. Their definition should be based on the analytical efforts described above. The results of those analyses should allow to extract the needs for verification of calculational assumptions, and establish the behavior of fuel and components under certain operating conditions. Experimental efforts are therefore needed in the fuels and components area, the latter mostly addressing generic issues because of the absence of a specific design. This means, the latter effort is not a prototype testing but an effects testing.

2.2.2.1 fuels

It is common to test fuels under steady-state and transient conditions. We have sufficient knowledge to identify important fuel design parameters that need to be verified/determined, based on existing steady-state testing data. In my view, the range of rod diameters used in the past, namely 0.31 in to 0.37 in is probably well selected even for future applications. I personally favor the smaller end of the spectrum. What is not known today is the rating at which those fuels should be tested. In the past, emphasis was placed on ratings as high as possible to reduce the fissile inventory and with it fuel cycle cost. Today's emphasis is different. Safety considerations play a much more important role, and reliability is a close second. It is in my view quite conceivable that low-rated carbide fuel rods perform differently from high-rated carbide fuel rods. Temperature gradients across the rods are different and so are peripheral stresses and the diffusion of solids and gases through the pellet. What the ranges of ratings of interest are needs to be determined and then steady-state tests have to be performed.

Transient tests need a far better developed "needs" package because they are very design-specific. However, because of the lengthy process of designing an experiment, transient needs have to be addressed early in the analysis program so that test results can be most beneficial in the design development.

At this time, it is very difficult to specifically state what fuel rod test needs to be performed in order to support perceived safety advantages.

Generic problems for oxide and carbide fuels under CDA conditions can probably be defined today using the rod design parameters established for the steady-state testing during the last 10 years. In my view, a justification for those CDA tests can be derived from the fact that we know very little about the response of carbide fuel rods to those transients. The problem with the CDA data for oxide and carbide fuel systems, regardless what they are, has to do with their interpretation. If one develops designs that cannot undergo an event leading to core damage, then those data are "academic". One would then have to view those data as bounding the ultimate feasibility of the least conservative design.

Either as part of those CDA tests, or as a separate group of tests, we need a better understanding of MFCI for carbide rods. While those experiments are usually considered "licensing support experiments" there is some justification why DOE should be interested in those experiments, too. I support the current view that LMRs should be designed such that MCFI cannot occur. However, for future applications, it is of interest how far one can "push" the fuel. The centerline melting criterion might be too severe and unjustified. If some fuel melting is allowed, however, then one needs to know what happens when molten fuel comes in contact with the coolant. For those incidents, a data base must exist that allows to assess the potential for any energetic reaction.

2.2.2.2 components

Experimental support for component development is needed in three areas:

- nuclear performance assessment
- thermal-hydraulics assessment
- design and performance of specific components

Critical experiments would be needed to substantiate neutronics calculations for carbide cores in general, as well as the modified homogeneous core concept and the zero burnup swing core. None of these experiments are needed to establish the basic feasibility of the concept and to demonstrate the safety advantage coming from this specific design. However, no carbide fuel critical experiments for commercial size reactors have ever been performed, and therefore a data base is ultimately needed.

Thermal-hydraulics assessments are needed for particular fuel rod configurations with grids and spacer wires for a variety of p/d ratios. Flow distribution, pressure drop, and location of hot spots are a major concern. Later in this report, natural convection issues will be addressed which are important for an assessment of safety advantages.

Design of control assemblies (enhanced expansion, control with a control rod follower) should begin early and tests should be designed to determine the operational characteristics.

3.0 NATURAL CONVECTION ISSUES

The natural convection capability of a LMR is the most important inherent safety feature next to the Doppler reactivity. However, while Doppler reactivity/coefficient measurements and analyses were conducted extensively over the last two decades, very little attention has been given to natural convection flows and temperatures. Natural convection entered the lingo of reactor designers and analysts only when the IHX was placed at a higher elevation than the core because "this enhanced natural convection".

During the last three years more attention has been given to natural convection phenomena. However, the thrust of the investigation was to demonstrate that natural convection phenomena in a specific design are very beneficial and that with the help of natural convection, "everything was under control". Following is a listing of what I perceive as issues in the natural convection complex, an attempt to rank the issues and to define support programs to resolve the issues.

3.1 Technical Issues

In my view, natural convection phenomena are as important as they are complex. Natural convection flow is caused by a small density difference between the hot and cold sodium in the primary loop. Pressure drops under full flow conditions are typically in the 50+ psi range for the core. Under natural convection conditions, they are typically below 0.5 psi. At 3% flow conditions, those pressure drops would be below 0.1 psi if it were not for the rise in bundle friction factor at those low flows. The knowledge of the friction factor at these low flows (Re numbers below 3000, and sometimes below 1000) is very important.

Because the density difference between the hot and cold sodium creates buoyancy forces that cause the sodium to flow, anything affecting the temperature field in the reactor will also affect the convection flow. Heat losses not only change the energy balance but also affect convection flow because of the inseparability of flow and temperature. Furthermore, local geometry effects as compared to global bundle or assembly geometry effects, are very important at very low flow velocities.

These are just a few illustrations to show the complexity of natural convection flow in a LMR. Following is a brief discussion of technical issues.

The modelling of natural convection phenomena went a peculiar way. This capability was first added to reactor systems codes to marginally improve the temperature predictions for the reactor systems. Then more attention was focued on core performance and single channel core representations gave way to multi-channel representations hence allowing for some degree of flow redistribution. Interassembly heat transfer was added, more refined flow redistribution models were developed and incorporated, followed by better mixing models and approximate

two-phase flow models. In the past, development work for neutronics models, for example, followed a different path. After some exploratory calculations, models were developed to approximately describe the phenomena under investigation. Then models were developed that described phenomena as accurately as possible. After one could describe phenomena in detail then approximate models were developed that could be used for a variety of purposes. However, it was always possible to estimate the degree of approximation.

flow redistribution

Because the assemblies in the reactor are differently orificed and the non-fission power distribution is non-uniform, the flow through assemblies under natural convection conditions will redistribute to balance the pressure drops in the core assemblies. Some assemblies will receive relatively more flow than under full flow conditions, others will receive less. It has been argued by the applicant during the CRBR licensing proceedings that the hotter an assembly is, the more flow it will receive and that therefore natural convection phenomena will always ensure that hot spot locations will not change during the transition from full flow to natural convection flow and that the hot spot temperatures will not exceed those under full flow conditions.

It is correct that the hotter an assembly is the more flow it will receive because it creates the highest buoyancy forces. However, there is no assurance that the increase in flow will be just exactly right to avoid a temperature increase over steady-state temperatures. Flow redistribution is an effect coming from non-linearities in the friction factor vs Re number correlation. It needs to be determined how hot spot locations can change during a natural convection transient. Some analysis conducted at BNL showed that boiling in a medium (fission) power assembly can occur long before sodium boils in the peak assembly.

The flow redistribution in the core can be so severe that flow reversal can occur. The applicant denied during the CRBR licensing discussion that a flow reversal could ever occur. BNL, on the other hand, calculated flow reversal in low power CRBR assemblies during a natural convection transient. For EBR-II, flow reversal in some assemblies was inferred from entrance and exit flow measurements. Regardless if the applicant or BNL is correct with their prediction of flow reversal, it is an issue that has to be investigated. I do not agree with NRC's conclusion that natural convection analysis methods have been confirmed by "check-over" analyses because the predicted temperatures during a natural convection transient were not so far apart in WARD and BNL predictions. The fact that BNL calculates flow reversal and WARD concluded from their analyses that flow reversal cannot occur, raises questions in my mind as to the possibility of some form of cancellation of errors as far as temperature calculations are concerned. To make matters worse, ANL analysis with the COMMIX code showed no flow redistribution for the CRBR core during a natural convection transient. When I pointed this out, COMMIX results were investigated in more detail by ANL staff. It was then argued that the flow redistribution was invisi-

ble in the view graphs because of the way the data were plotted.

If one accepts flow reversal as a possiblity then the question is: how does the sodium flowing from the upper plenum to the lower plenum mix in the lower plenum. I asked this question repeatedly. It is accepted as an issue but no attempts are made to answer the question.

Another issue related to flow redistribution is flow recirculation inside an assembly. Again, this has been shown experimentally but the implications of this effect are largely not understood.

mixing and stratification

When the hot and cold fluids meet in the upper plenum, the fluid mixing is an important phenomenon. Various analyses by ANL and PNL have shown very complex flow patterns in the upper plenum. Detailed geometry representations are very important. At this time, however, one cannot go beyong the discussion of analysis results because of the scarcity of experimental data. An understanding of mixing in the upper plenum is very important because one needs to know at what temperature the sodium leaves the upper plenum and if it is possible that hot pockets develop in this region. This is an extremely important issue for pool designs because of difficulties in the design of the rotating plug and the upper support deck.

Flow stratification is another important effect related to flow mixing. It has been observed in the PHENIX reactor that substantial flow stratification occurred in the plenum region. The uppermost layer of sodium was nearly stagnant and at a very high temperature. Flow stratification has also been observed in loop-type LMRs, for example FTR. If stratification occurs, predictions are that the colder sodium will flow underneath the hotter layers which could be especially important for the flow in large diameter pipes.

ultimate heat removal capability

At this time we don't know how much heat can be removed from the reactor via natural convection flow. To my knowledge, no attempt has ever been made to determine the upper limit on power that can safely be removed from the core by natural convection flow. I view this as an issue of extreme importance.

two-phase-flow-effects

Experiments in Karlsruhe, Germany, have shown that natural convection flow is enhanced when sodium boiling occurs. This enhanced flow leads then to an enhanced cooling of the fuel/cladding and a collapse of the bubbles. At that time, the flow velocity decreases und after a while, boiling recurs, etc. To my

knowledge, no experiments of this type have been carried out in the U.S. and none of the computational tools can handle two-phase flow under natural convection conditions. Attempts have been made to expand the SSC code by adding a simplified two-phase flow capability for natural convection transient analysis. However, because of the nature of SSC, any of those modifications is aimed at an at-large description of the reactor and not a detailed modelling of core phenomena. A two-phase flow capability is also planned for COMMIX. However, I still view COMMIX as being in an early development stage.

pump coastdown vs onset of natural convection flow

This effect is largely not understood. The applicant for CRBR licensing claimed that the longer the pump coastdown the lower are the peak sodium and clad temperatures. This statement is wrong. Several years ago, the CEGB showed analytically that there are optimum halving speeds for the primary and secondary systems, in regard to sodium temperatures. If a pump coastdwon is extended too far then it takes a long time for natural convection flow to establish itself. The pumps would be pumping cold sodium from the inlet to the outlet plenum with only a very small temperature increase. It is this temperature increase, however, that develops the driving force for the flow. On the other hand, a virtually instantaneous stoppage of the pumps would create a very high power to flow ratio and could lead to sodium boiling, too.

heat losses through walls annd pipes

In the mid-70s those losses were viewed a panacea for decay heat removal problems. The French PHENIX relied on heat losses through the vessel wall and the German SNR-300 relies on heat losses through the pipes. However, both countries elected IRACS-type devices for their commercial plants.

There are some basic difficulties with reliance on those heat losses to remove decay heat. For one, those losses would occur also when the reactor is operating under full power conditions. Secondly, the larger the reactor the smaller is the surface to volume ratio hence the less feasible it becomes to remove heat effectively through vessel walls. Thirdly, whereever the heat is discharged from the core vessel or piping, it ultimately has to be removed to the atmosphere. This might require some active devices (blowers, fans) whose failure would require other passive devices to remove afterheat. In such an instance, one might as well go with a passive device like a IRACS in the beginning.

natural convection flow in deformed bundles

We have no knowledge as to how natural convection flow will evolve and perform in deformed bundles and/or blocked assemblies. We know that bundle distortion

occurs and take this is into account in full flow hot channel analyses. The effects of bundle deformation and assembly blockages on natural convection flow is not known yet. Westinghouse analyzed a blocked assembly under natural convection conditions and concluded that heat conduction would be sufficient to avoid sodium boiling. In my view, this is difficult to understand. CRBR analysis had shown that under natural convection conditions, hot channel sodium temperatures could be as close as $150^{\circ}F$ below the boiling point. These temperatures were achieved for free flowing sodium. If sodium flow were stagnant in such an assembly and this assembly were surrounded by identical assemblies, I would assume that boiling would occur.

hot channel analysis

At this time, there is no valid method to calculate hot channel flows and temperatures under natural convection conditions. The applicant for CRBR licensing used the full flow HCF method together with very conservative assumptions to calculate hot channel temperatures under natural convection conditions. However, this approach is incorrect. Under natural convection conditions, one cannot separate flow and temperatures anymore as one is justified to do under full flow conditions. In a report to LANL, I developed an outline for an approximate and exact method for hot channel analysis under natural convection conditions.

establishment of natural convection flow from refueling conditions

It is customary to look at the establishment of natural convection flow only immediately after a shutdown. However, one can develop a scenario where forced coolant flow is stopped during refueling conditions. The concern is then the freezing of the coolant in the reactor system and the possibility of cold trapping. This issue has been largely neglected in the past because of its low potential (if at all) for energetics.

Following is a list of issues that need to be addressed in addition to the issues listed above:

- means to enhance natural convection flow
- effect of cold bypass flow
- DRACS (flow path, shielding)
- IRACS (capacity limits)
- effect of overcooling
- effect of uncertainties in friction and form factors
- natural convection in wire-wrapped vs gridded assemblies
- perforated ducts vs natural convection flow
- pump coastdowns in the PHTS vs IHTS vs natural convection flow

- impact of fuel burnup on natural convection flow
- effect of interassembly heat transfer
- effect of rod length
- modelling of an integrated reactor vessel (lower plenum, core, upper plenum, upper internals strctures, etc.) vs modelling of core and plena separately
- needed degree of detail in the reactor modelling

All these issues have to be addressed ultimately if we ever want to understand natural convection and its significance in a LMR.

3.2 Ranking

The ranking of natural convection issues has to be very subjective. Some issues are important for the safe operation of the reactor, others are important in the licensing arena. Some issues deal with detailed phenomena inside an assembly, others deal with global issues. Following is my attempt to rank some of the issues listed above:

1. ultimate heat removal capability

It seems to me that we should know how much heat we can remove in a LMR when pumping power becomes unavailable. There are all indications that the decay heat can be safely removed, i.e. about 3% of the full power. However, I would not be surprised if it can be shown that we can actually remove safely 10% of the full power or even more via natural convection, especially when we design for it.

2. pump coastdown effect

The designer has control over the pump coastdown characteristic. Because this characteristic affects natural convection flow and temperatures we need to better understand the correlation between establishement of natural convection flow and the pump coastdown characteristic.

3. effect of heat losses

At a first glance, heat losses seem to be an effective means to remove after-heat. However, we also know that natural convection is heavily affected by the details in the design, tolerances and deviations from the normal/nominal in design and performance. The heat loss effect is particularly important for a modular system with integrated IHX where the possibility exists that the IHX can be heated up by the core directly via conduction.

4. mixing and stratification

Both effects are not well understood but have a significant impact on convection flow and temperatures.

5. effect of uncertainties in friction and form loss coefficients

Only nominal calculations have been carried out to determine the flow redistribution. Because the friction factor rises exponentially as the flow decays whereas the form factor rises slowly in a near linear fashion, the interaction between form and friction losses has a significant impact on flow allocations. If one could ignore form losses (no orificing) then blankets would receive relatively less flow than fuel assemblies in a flow coastdown. However, the presence of orifices changes this behavior drastically so that in CRBR, the blanket assemblies receive actually relatively more flow then the fuel assemblies at the beginning of a natural convection transient.

6. hot channel factor analysis

Temperature limitations for the core come from hot channel factor analyses. There is no methodology today to calculate hot channel temperatures under natural convection conditions.

7. establishment of natural convection flow from refueling conditions

No generic issues have yet been established for this effect. Only selected analyses have been performed for some existing designs. It was always concluded that freezing would not occur. However, we don't know what issues have to be addressed in the design of the reactor to ensure that freezing cannot occur and that natural convection flow can properly be established.

3.3 Support Programs

3.3 analytical

An analytical program to resolve the issues addressed above consists mostly of carrying out detailed analyses for loop and pool reactors. It needs to be assessed to what extend the issues affect the selection of the reactor type.

The selection of the reactor type could be very important. Analyses have to show if a certain problem is generic or design-dependent. In carrying out the analyses it needs to be assessed what models should be used (exact, near-exact, approximate) and how detailed the reactor geometry needs to be represented. The time step selection is important, especially for transients where both the performance immediately after reactor shutdown is important as well as so-called ultimate temperatures, i.e. temperatures hours after reactor shutdown.

Part of the analytical program has to be an assessment of the computational tools available for natural convection analysis. The most obvious choices are COBRA-WC (perhaps in conjunction with TEMPEST) and COMMIX for core analysis and SSC and DEMO for overall plant analysis. DEMO applications will be difficult for anything but CRBR analyses because many CRBR correlations and design features are built into the code.

In the hot channel analysis area, I suggest to follow one of our earlier proposals to develop a consistent methodology.

For the sequence of analyses, I suggest to follow the ranking presented above and complement the analysis by addressing the issues I listed above.

3.3.2 experimental

For the experimantal program the question of simulants needs to be addressed. In the absence of prototypical design, it is in my opinion best to address generic issue like

- flow redistribution
- two-phase flow effects
- effect of bypass flow
- effect of perforated ducts
- natural convection flow vs rod power
- recirculation
- effect of power gradients across an assembly
- friction-form loss interaction
- mixing and stratification
- deformed bundles and blocked assemblies
- wire-wrapped and gridded assemblies
- coastdown simulation
- effect of p/d ratio
- effect of rod length
- heat loss simulation
- local rod failure

Most of these experiments can be conducted in small experimental facilities. It is my understanding that some of the facilities available at LANL would be well suited for some of the generic experiments.

4.0 CONCLUSIONS

The current U.S LMR program emphasizes two major issues: safety and economics. Economic advantages for carbide systems are difficult to assess at this time because of the lack of carbide fuel system designs. Carbide systems' economics cannot be assessed from knowledge gained in the design of a replacement core for an oxide fuel system.

To my knowledge, carbide fuel system safety (and safety advantages) have not been addressed in any degree of depth. As discussed in this report, carbide fuel provides the designer with far greater flexibility than oxide fuel. Carbide fuel systems can be designed to eliminate major accident initiators. They allow to turn quantitative advantages into a qualitative advantage. We proposed to LANL a series of core design and component concepts that would greatly the safety of carbide over oxide systems. To my knowledge, LANL carbide fuel design activities concentrated on the design of a reload core for a LMR module design. This activity will not permit to establish a basis from which to judge safety advantages of carbide fuel over oxide fuel systems. At best, this activity which is constrained by oxide design ground rules and an oxide core geometry, will show marginal advantages of a carbide system but it cannot be expected that substantial advantages can be identified for the reasons cited above. In my opinion, it will be difficult to use this activity as the basis to justify the development of a new fuel type.

This report cites a series of safety advantages which potentially exist for a carbide fuel system. In my view, carbide fuel systems have the potential for being safer than oxide fuel systems. However, to demonstrate safety advantages would require to address the issues outlined in this report and to creatively use carbide fuel, both in fuel rod/assembly design as well as in the design of the core concept.

At this time, the basic question, namely "Why carbide fuel", has not been answered.

Natural convection issues have not been given much attention in the past. Only during the last few years has this issue been addressed in some detail. Despite of the claims to the contrary by some of the LMR contractors, I do not think that we fully understand natural convection phenomena. Some of the approximations made in natural convection transient analyses (for example, choice of the number of core channels) have probably a greater impact on calculated transient temperatures than the effects under investigation. Only integral in-pile experimental data and single assembly out-of-pile detailed data are available for comparisons with analytical models and correlations. In my view, this is an unsatisfactory situation. If we cannot confirm integral experimental data then we are certainly unable to calculate detailed core performance data. On the other hand, if we calculate integral data well then we cannot claim to be able to calculate also detailed performance data.

Note: if a SSC calculation shows that a single subchannel that represents the average performance of over 20 fuel assemblies, does not experience sodium boiling during a natural convection transient, this says very little about the "worst" actual subchannel for those 5000+ fuel rods that are represented by this single channel. The concern about sodium boiling in the core is not only the fear of bulk boiling but sodium boiling in a subchannel from where it can spread.

Especially for derated cores, the natural convection capability of a LMR should be far superior to that of a LWR. I rank the natural convection capability of the LMR as the most important inherent safety feature. Regrettably, we know very little about this safety feature. We need far more experimental and analysis data. In my view, it is possible to design out the TOP and TUC event and ensure that the LMR can always be brought to a shut-down state. Decay heat removal is then the major safety concern that needs to be addressed. This report tried to list the issues that need to be addressed.