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EXPERIMENTS

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THE ROLE OF SIMILITUDE IN THE DESIGN OF LMFBR
SAFETY-RELATED SIMULATION EXPERIMENTS

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ABSTRACT

In this paper we examine the implications of scaling in the design of simulation experiments for two major areas of fast reactor safety research -- the transition phase and postdisassembly energetics. Specific scaling requirements and compatible experimental designs are formulated and compared with ongoing programs having similar objectives. Suggestions are also outlined for future out-of-pile experimental research.

INTRODUCTION

A key feature of liquid metal fast breeder reactor (LMFBR) hypothetical core-disruptive accidents (HCDAs) is the extreme thermophysical environment generated during the postulated accident sequence.¹ Because these harsh environments usually can be generated only in-pile at considerable expense, simulant materials at modest temperatures and pressures are often used to model accident progressions. In this paper we develop and apply a rationale for designing "optimum" simulant-material experiments for LMFBR safety research in the areas of transition phase and post-disassembly energetics.

BACKGROUND

Any simulation experiment that qualitatively exhibits phenomena similar to those present in an accident sequence can be useful in an analytical or numerical model if that model can be validated, verified, or have parameters set by such an experiment. An extrapolation to prototypic conditions (i.e., the hypothetical accident) can then be made with some confidence. Frequently, however, the validity of models used in LMFBR

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accident analysis must be questioned because the physical conditions under which the models were validated are significantly different than the corresponding prototypic conditions.

This distinction can be quantified by the concept of similitude. Briefly, a model experiment employing simulant materials is said to exhibit similitude to the prototypic case if, and only if, the relative magnitude is the same for all corresponding terms in the energy, momentum, and mass-conservation equations and boundary conditions describing both the accident sequence and the model experiment. A model experiment exhibiting similitude thus ensures that the relative strength of all physical phenomena in the experiment will duplicate that in the accident sequence. The major advantages of such an experiment are:

(1) The experimental results can be used by themselves to infer the behavior of the accident progression, and

(2) Analytical or numerical models validated by an experiment exhibiting similitude gain credibility for accident analysis applications.

Unfortunately, it is usually impossible (except in the most simple situations) to design an experiment that rigorously fulfills the requirements of similitude. A more realistic goal is to insure that any imbalances in the appropriate equations are relatively small (i.e., much less than an order-of-magnitude discrepancy).

SCALING REQUIREMENTS

Scaling requirements derived from considerations of similitude can be obtained by examining all terms in the relevant equations and boundary conditions, as listed in Table I. These equations describe multiphase, multicomponent, chemically inert flow past solid boundaries and as such are applicable to both transition-phase dynamics and postdisassembly energetics (assuming, of course, that terms modeling all phenomena of importance have been included). For simplicity of notation, homogeneous flow has been assumed.² Upon averaging these equations over flow area (perpendicular to flow direction), we obtain more convenient forms for the viscous stress terms involving the friction factor and Nusselt number. It is assumed in the following that the Nusselt number and friction factor can be expressed as functions of the time-dependent Reynolds numbers, Prandtl numbers, concentrations, or other dimensionless scaling parameters as developed in the next two sections.

TRANSITION-PHASE APPLICATIONS

Consider first the problem of designing a simulant-material experiment for a transition-phase situation - that is, a situation where the active-core geometry begins to differ from its original state. The scaling requirements obtained from enforcing similitude suggest two significant problems. First, an accurate simulation of sodium's

TABLE I
Governing Equations^a

Mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (\text{fluid field})$$

Momentum

$$\rho \frac{\partial u_i}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \underbrace{\frac{\partial \tau_{ij}}{\partial x_j}}_{\rho f u_i^2 / a} + \rho B_i \quad (\text{fluid field})$$

Energy

$$\rho \frac{\partial e}{\partial t} + \rho u_i \frac{\partial e}{\partial x_i} = -p \frac{\partial u_i}{\partial x_i} + \underbrace{\tau_{ij} \frac{\partial u_i}{\partial x_j}}_{\rho f u_i^2 / a} - \underbrace{\frac{\partial q_i}{\partial x_i}}_{(Nu)k\Delta T/a^2} \quad (\text{fluid field})$$

$$\frac{\partial T}{\partial t} = \kappa_{sn} \frac{\partial^2 T}{\partial x_i^2} + \frac{Q}{\rho_{sn} c_{sn}} \quad (\text{solid field})$$

Boundary condition: continuity of heat and mass transfer between fluid and solid fields, where

$$\begin{aligned} e &= \sum_n \Gamma_{gn} e_{gn} + \Gamma_{ln} e_{ln} \\ e_{ln} &= c_{sn} T_{mn} + L_{fn} + c_{ln} (T - T_{mn}) \\ e_{gn} &= e_{ln} + L_{vn} - R_n T \quad (\text{if liquid and vapor in equilibrium}), \\ &= c_{gn} T \quad (\text{otherwise}), \text{ and} \\ P &= \rho \sum_n \Gamma_{gn} R_n T / \alpha \\ &= \sum_n P_n^* e^{-T_n^*/T} \quad (\text{if liquid components immiscible}). \end{aligned}$$

^aSee Appendix for nomenclature.

phase-transition characteristics appears unattainable; and second, sodium's Prandtl number can be preserved only if other liquid metals are employed as the sodium simulant. Such problems have prompted experimentalists to divide the entire transition phase into the more easily characterized areas of cladding relocation, fuel crust formation,³ and boiling pool experiments.

In some cladding-relocation experiments, a gas designed to simulate sodium vapor is blown vertically past a melting cladding simulant while the relocation of the cladding is traced. Most experiments have employed argon and Wood's metal;^{4,5} we have attempted to identify other simulants that might better satisfy the requirement of similitude. Table II

presents the results of this study for three pairs of simulants. All applicable scaling requirements derived from Table I are shown, along with an indication of how closely the simulant pairs satisfy those requirements. The requirement for coolant thermal diffusivity is omitted because diffusivity is roughly proportional to kinematic viscosity for a gas. Likewise, the requirement of equal ratios of specific heats for the sodium vapor and its simulant has not been included because of the weak dependence of this ratio on the particular simulant gas employed. Note that phenomena associated with fuel-cladding interaction (e.g., wetting) are not examined in this class of experiments.

Of the three simulant pairs, helium-lithium appears to most closely satisfy similitude. Lithium is about a factor-of-two larger than the ideal for cladding thermal conductivity; however, this is still quite good compared to the other simulant pairs, where more than an order-of-magnitude discrepancy is observed in several categories.

Boiling-pool LMFBR safety experiments have traditionally focused on steady-state internally heated boiling, where the principle concern is the dispersive nature of the flow.^{6,7} Simple calculations suggest that if heat transfer and certain viscous effects are unimportant, the Kutateladze scaling parameter should be related to the flow-regime character.⁸ Under these assumptions, any liquid could be used to determine the onset of dispersive behavior. Although this paper does not specifically address uranium dioxide/steel boiling-pool experiments, many of the scaling requirements and simulant materials derived in the next section are also applicable to these experiments.

POSTDISASSEMBLY ENERGETICS APPLICATIONS

The postdisassembly energetics problem begins with a highly disrupted active core region consisting of a two-phase (liquid and gas) mixture of uranium dioxide, steel, and perhaps gaseous sodium under high pressures and temperatures.¹ As this mixture expands and progresses through the intact upper-core structure (UCS), the mixture tends to flash and interact with the steel structure and any liquid sodium films that may be present. Finally, the mixture interacts with the sodium pool above the UCS, driving a liquid sodium slug against the containment vessel.

Simplified simulation experiments of this accident progression have been carried out at both SRI International⁹ and Purdue University,¹⁰ where a single two-phase component (usually water) is allowed to flash through a simulated UCS. Because of the difficulty in simulating two-phase sodium behavior, we restricted our attention to the case where only gaseous sodium is present. Thus, the model experiment described here could be identified better as an upper-core injection experiment, the latter stages of the accident sequence (interaction with the sodium pool) having been ignored temporarily.

In Table III we present the scaling requirements derived from enforcing similitude together with the degree that selected simulant materials actually meet these requirements. With primary emphasis placed on the vaporization characteristics of uranium dioxide (UO₂) and steel, the best simulants we have identified are an n-propyl alcohol, ammonia, and

TABLE II

Scaling Requirements for Cladding Relocation Experiments

Scaling Requirement ^a	Description	Steel, Sodium Value	Prototypic System	Lithium, Helium Value	Wood's Metal, Argon Value	Water, Helium Value
1. $c_s T_{ms}/L_{fs}$	Ratio of internal steel to latent energy	5.0		4.4	1.1	3.4
2. $\rho_c c_{fs}$	Ratio of coolant gas to clad internal energy	4.4		4.0	1.6	4.0
3. $Re_c \propto \rho_s L_{fs} l/m_c$	Coolant vapor Reynolds number	250.1		92.0	27.7	135.2
4. $(L_{fs})^{3/2}/\kappa_s$	Clad thermal diffusivity	1.3×10^4		5.2×10^3	3.1×10^2	4.9×10^5
5. $(L_{fs})^{3/2}/\nu_s$	Clad Reynolds number	7.2×10^4		1.1×10^5	1.6×10^4	7.2×10^4
6. $\sigma_s/\rho_s L_{fs}^2$	Clad surface tension	2.9×10^{-3}		3.0×10^{-3}	2.0×10^{-2}	6.4×10^0
7. $Q/\rho_s \sqrt{L_{fs}}$	Sets volumetric energy deposition	$Q=Q_p$		$Q=0.1Q_p$	$Q=0.5Q_p$	$Q=0.2Q_p$
8. l/L_{fs}	Sets experimental length scale	$l=l_p$		$l=1.6l_p$	$l=0.2l_p$	$l=1.24l_p$
9. $u_c/\sqrt{L_{fs}}$	Sets vapor velocity	$u_c=u_{cp}$		$u_c=1.26u_{cp}$	$u_c=0.45u_{cp}$	$u_c=1.11u_{cp}$
10. $P/\rho_s L_{fs}$	Sets pressure	$P=P_p$		$P=0.12P_p$	$P=0.22P_p$	$P=0.18P_p$
11. l/D	Sets geometric similarity	NA		NA	NA	NA

^aThe listed parameters should be the same under both model and prototypic conditions to preserve similitude. The subscripts s and c designate steel and coolant (sodium) respectively. The subscript p stands for prototypic value. All scaling requirements can be made dimensionless by multiplying by suitable powers of the gravitational acceleration.

TABLE III

Scaling Requirements for Postdisassembly Energetics Simulation Experiments^a

Scaling Requirement ^b	Description	UO ₂ Steel, Na, Value	Prototypic System	Propyl Alcohol, NH ₃ , He, Value	Ethlene Glycol, NH ₃ , He, Value	Water, Steel Value
1. $c_{ff}T_f^*/L_{vf} \propto m_f c_{ff}$	Ratio of fuel internal to latent energy	32.5		33.8	34.9	18.0
2. $c_{ss}T_s^*/L_{vs} \propto m_s c_{ss}$	Ratio of steel internal to latent energy	10.5		17.9	17.9	NA
3. m_s/m_f	Ratio of steel to fuel molecular weight	0.21		0.28	0.27	NA
4. m_c/m_f	Ratio of coolant to fuel molecular weight	0.09		0.07	0.07	NA
5. T_{mf}/T_f^*	Ratio of fuel melt to vaporization temperature	0.05		0.03	0.04	0.06
6. T_{ms}/T_s^*	Ratio of steel melt to vaporization temperature	0.03		0.07	0.07	NA
7. $P_f^*/\rho_f L_{vf}$	Ratio of static to dynamic fuel pressures	$10^2-5 \times 10^3$		6×10^3	4×10^2	2×10^2
8. $P_s^*/\rho_s L_{vs}$	Ratio of static to dynamic steel pressures	1.8×10^2		1.3×10^2	1.3×10^2	NA
9. L_{vf}/L_{ff}	Ratio of latent fuel energies	6.1		9.0	4.4	6.8
10. L_{vs}/L_{fs}	Ratio of latent steel energies	27.7		4.1	4.1	NA
11. L_{vf}/L_{vs}	Ratio of fuel to steel latent energies	0.3		0.6	0.6	NA

TABLE III (cont)

Scaling Requirement ^b	Description	UO ₂ , Steel, Na, Value	Prototypic System	Propyl Alcohol, NH ₃ , Re, Value	Ethlene Glycol, NH ₃ , Re, Value	Water, Steel, Value
12. ρ_s/ρ_f	Ratio of steel to fuel density	0.81		0.86	0.64	NA
13. $Re_{fv} \propto \rho_f L_{vf} v_f / \mu_f$	Fuel vapor Reynolds number	1.2×10^3		3.2×10^2	3.8×10^2	8.8×10^2
14. $Re_{sv} \propto \rho_s L_{vf} v_f / \mu_f$	Steel vapor Reynolds number	8.0×10^2		3.0×10^2	4.3×10^2	NA
15. $Re_{fl} \propto (L_{vf})^{3/2} / \nu_f$	Fuel liquid Reynolds number	1.9×10^7		1.0×10^6	1.5×10^5	1.0×10^7
16. $Re_{sl} \propto (L_{vf})^{3/2} / \nu_s$	Steel liquid Reynolds number	1.3×10^7		6.0×10^6	6.3×10^6	NA
17. $(L_{vf})^{3/2} / \kappa_f$	Fuel thermal diffusivity	1.6×10^7		2.6×10^7	2.6×10^7	7.4×10^7
18. $(L_{vf})^{3/2} / \kappa_s$	Steel thermal diffusivity	2.2×10^7		2.5×10^7	1.0×10^7	2.2×10^7
19. $\sigma_f / \rho_f L_{vf}^2$	Fuel surface tension	1.3×10^{-5}		4.8×10^{-5}	6.8×10^{-5}	1.4×10^{-5}
20. $\sigma_s / \rho_s L_{vf}^2$	Steel surface tension	5.0×10^{-5}		4.8×10^{-5}	3.3×10^{-5}	NA
21. $c_{ff} T / L_{vf}$	Sets temperature scale	$T = T_p$		$T = 0.08 T_p$	$T = 0.08 T_p$	$T = 0.13 T_p$
22. $P / \rho_f L_{vf}$	Sets pressure scale	$P = P_p$		$P = 0.04 P_p$	$P = 0.04 P_p$	$P = 0.13 P_p$
23. l / L_{vf}	Sets experimental scale	$l = l_p$		$l = 0.4 l_p$	$l = 0.4 l_p$	$l = l_p$
24. l / D	Sets geometric similarity	NA		NA	NA	NA

^aProperties of prototypic materials were taken from "Properties for LMFBR Safety Analysis," ANL-CEN-RSD-76-1, March 1976. Nominal values of all quantities were used except in Requirement 7 where an uncertainty band was employed.

^bThe listed parameters should be the same under both model and prototypic conditions to preserve similitude. The subscripts s, c, and f designate steel, coolant (sodium), and fuel (UO₂) respectively. The subscript p stands for prototypic value. All scaling requirements can be made dimensionless by multiplying by suitable powers of the gravitational acceleration.

helium system, which is representative of UO_2 volatility near the high end of its uncertainty band, and an ethylene glycol, ammonia, and helium system, which is representative of UO_2 volatility near the low end of its uncertainty band (note the large range of uncertainty for Requirement 7 in Table III). Also listed in Table III is a water-steel system for comparison with ongoing experimental work.^{9,10} None of the steel simulants can model steel's rather large ratio of vaporization latent heat to fusion latent heat (Requirement 10). In addition, propyl alcohol's melting point is lower than ammonia's, thus precluding the modeling of UO_2 freezing and crust formation with the propyl alcohol system. However, the propyl alcohol system reasonably matches all other requirements, except for the liquid fuel Reynolds number (Requirement 15), which may not be important in a flashing situation when the fuel vapor is expected to dominate the frictional flow properties. The surface tension and viscous properties of the ethylene glycol system are slightly poorer than the propyl alcohol system. Note that it is possible to change the length scale of the experiment by ignoring gravitational similitude (Requirement 23) thus making the heat-transfer comparisons agree more closely.

The water-steel system designed to fulfill the requirements of similitude in a pure UO_2 blowdown case would consist of a roughly full-scale system (Requirement 23) at reduced temperatures and pressures (Requirements 21 and 22). Most scaling requirements are reasonably well satisfied for this system. The fact that Requirement 1 is not satisfied implies that the vapor-pressure behavior of the system will be incorrect. In particular, the initial pressures and temperatures given by Requirements 21 and 22 would have to be violated to reflect the actual behavior of water.

The Purdue experiments in this area appear to be more in agreement with similitude considerations than do the SRI experiments.⁹ However, the modeling of the inertial effect of the sodium pool above the upper-core structure does not satisfy similitude in either the SRI or Purdue studies, where water also was used to model the sodium pool. Here, similitude requires a much lighter fluid with a density around 125 kg/m^3 .

CONCLUSIONS AND RECOMMENDATIONS

Several recommendations can be made from this study. First, we believe that the feasibility of a helium-lithium system should be investigated for cladding relocation experiments, particularly if heat transfer and viscous effects are of interest. Problems could arise because of the difficulty in working with lithium and the size of the experiment (1.6 times larger than prototypic length scale). However, the helium-lithium system offers a substantial improvement over the argon-Wood's metal system.

Postdisassembly simulation experiments could be designed to approximately satisfy similitude. In place of the flashing-water source used in current fluid-dynamics experiments, a propyl alcohol source would be somewhat better at modeling phase-transition phenomena. In addition, the

scale size required for a propyl alcohol experiment is more than a factor-of-two smaller than the scale size of the corresponding water experiment, which is approximately full scale.

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APPENDIX

Nomenclature used in scaling analysis of Table I

<p>ρ = density of two-phase mixture</p> <p>u_i = velocity of specific component</p> <p>p = system pressure</p> <p>g_i = gravitational acceleration</p> <p>q_i = heat-flux vector</p> <p>τ_{ij} = shear stress</p> <p>e = total energy of the liquid and gas mixture</p> <p>f = friction factor</p> <p>a = radius of equivalent flow area</p> <p>Re = Reynolds number</p> <p>Nu = Nusselt number</p> <p>k = thermal conductivity</p> <p>T = temperature</p> <p>κ_{sn} = thermal diffusivity of the n^{th} solid</p> <p>Q = volumetric heat-generation rate</p> <p>ρ_{sn} = density of the n^{th} solid</p> <p>Γ_{gn} = ρ_{gn}/ρ = density ratio between n^{th} gas component and mixture</p> <p>Γ_{ln} = ρ_{ln}/ρ = density ratio between n^{th} liquid component and mixture</p> <p>e_{gn} = energy of the n^{th} gaseous component</p> <p>e_{ln} = energy of n^{th} liquid component</p> <p>c_{gn} = specific heat at constant volume of n^{th} gaseous component</p>	<p>c_{jn} = specific heat of n^{th} solid component</p> <p>c_{ln} = specific heat of n^{th} liquid component</p> <p>T_{mn} = melting temperature of n^{th} component solid</p> <p>L_{fn} = latent heat of fusion of the n^{th} component</p> <p>L_{vn} = latent heat of vaporization of n^{th} liquid component</p> <p>R_n = R/m_n = universal gas constant/molecular weight of n^{th} component</p> <p>α_v = fraction of total space occupied by vapor</p> <p>P_n = vapor-pressure parameter for n^{th} component</p> <p>T_n = vapor-temperature parameter for n^{th} component</p> <p>σ = surface tension</p> <p>ν = kinematic viscosity</p> <p>l = arbitrary vertical-length scale</p> <p>D = arbitrary radial-length scale</p> <p>Σ = collision cross section</p>
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