**LMFBR Aerosol Release and Transport
Program—Quarterly Progress Report for
July–September 1975**

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OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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**LMFBR AEROSOL RELEASE AND TRANSPORT PROGRAM --
QUARTERLY PROGRESS REPORT FOR JULY-SEPTEMBER 1975**

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FOREWORD

This report summarizes progress made under the LMFBR Aerosol Release and Transport Program (sponsored by the Nuclear Regulatory Commission's Division of Reactor Safety Research) for the period July-September 1975.

Work on this program was previously reported as Volume III of a four-volume series. Prior reports are:

<u>Report No.</u>	<u>Period Covered</u>
ORNL-TM-4655	April-June 1974
ORNL-TM-4729	July-September 1974
ORNL-TM-4805	October-December 1974
ORNL-TM-4914	January-March 1975
ORNL-TM-5021	April-June 1975

Copies of the reports are available from the Technical Information Center, Oak Ridge, Tenn. 37830.

SUMMARY

1. AEROSOL RELEASE AND TRANSPORT PROGRAM

The LMFBR Aerosol Release and Transport (ART) Program at CRNL, one of the Nuclear Regulatory Commission's lead programs for LMFBR safety, is designed to investigate radionuclide release and transport from LMFBRs as a result of reactor events of varying severity up to and including a hypothetical core-disruptive accident (HCDA).

A capacitor discharge vaporization (CDV) technique is being developed for generating electrical energy directly in LMFBR fuel so that HCDA-like fuel disassemblies can be produced. The scoping tests for this technique, which are being conducted at the Arnold Engineering Development Center (AEDC), were continued this quarter with one additional set of experiments consisting of five tests. The results and analyses of these tests are reported. We believe that the scoping tests have demonstrated the feasibility of using this technique for creating HCDA-like energy states in fuel, and, consequently, we are now assembling a CDV system to use as a nonnuclear tool for studying the response of fuel to HCDA-like energy depositions and the behavior of the resultant aerosols under sodium and in containment vessels.

The U_3O_8 aerosol experiments (Cold Proof Tests), which are being conducted in the 5-m³ vessel (CRI-II), were continued. These tests serve to calibrate and check out the system and instrumentation and have provided useful information on aerosol characteristics and transient behavior. The induction furnace used for producing the U_3O_8 aerosol has proved to be limited in capacity. Consequently, we are assembling a dc electric arc furnace that will produce aerosol by direct vaporization of a pool of UO_2 ; construction is about 90% complete.

Conceptual design for the modifications to the Nuclear Safety Pilot Plant (NSPP) has been completed, and the authorizations necessary to initiate final design, start construction, and procure equipment have been requested. The large-vessel UO_2 and sodium aerosol tests will be conducted in this facility.

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Conceptual design of the facility for conducting the HCDA, under-sodium, fuel-bubble simulation task, designated the Fuel-Aerosol Simulant Test (FAST), is about 70% complete. A low-pressure water tank, which is to be used for exploratory studies of bubble behavior under water in support of FAST, has been installed and is undergoing checkout.

Analytical requirements for the ART Program appear to fall into four general categories: (1) use of existing models and computer programs for the predisassembly and disassembly stages of the HCDA to determine initial conditions and rates of energy deposition for CDV experiments, (2) analyses of fuel response to high rates of energy deposition to establish the effectiveness of the CDV system for producing aerosols and modeling the HCDA and to interpret the experimental results, (3) analysis of the expansion and transport behavior of the energetic fuel material under sodium, and (4) analyses of aerosol evolution and behavior at high concentrations under dynamic confinement within the bubble, in the cover-gas region, and in the containment building. Progress is reported in three of these categories.

2. STRUCTURAL INTEGRITY OF EQUIPMENT CELL LINERS

The behavior of a plane wall segment of a prototype LMFBR cell was studied analytically under postulated conditions of a massive sodium spill. Sodium-concrete reaction calculations were performed assuming the existence of an initial flaw in the liner which allowed high-temperature sodium to penetrate to the concrete underneath.

The results are preliminary and are intended primarily to outline the scope of the problem. Additional follow-up studies are identified to resolve uncertainties involved. A detailed report will be issued shortly.

KEY-WORD LIST

Aerosol, hypothetical accident, LMFBR, fuel, fission product release, fission product transport, ex-reactor experiment, safety, radionuclide transfer, plutonium, cell liner, inelastic analysis, high-temperature design, high-temperature concrete, high-temperature carbon steel, sodium spill, sodium-concrete reaction.

1. AEROSOL RELEASE AND TRANSPORT PROGRAM

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1.1 INTRODUCTION

The LMFBR Aerosol Release and Transport (ART) Program at ORNL is one of the Nuclear Regulatory Commission's lead programs for LMFBR safety in the area of radionuclide release and transport. The scope of the program includes radionuclide release from fuel; transport to, and release from, the primary containment boundaries; behavior within containments; and escape to the environment. The overall goal of the program is to provide the analytical techniques and experimental data necessary to assess the transient behavior and amounts of radionuclides released from LMFBR cores as a result of postulated events of varying severity up to and including a hypothetical core-disruptive accident (HCDA).

The program is divided into several related experimental and analytical activities, as detailed and summarized in other reports.^{1,2} These efforts can be briefly categorized as follows:

1. Development of a capacitor discharge vaporization (CDV) system for generating electrical energy internally in simulated (UO₂) and real (mixed oxides) LMFBR fuel that will provide a nonnuclear technique for studying the fuel (core) behavior at HCDA-like energy states.
2. Development of alternative techniques for generating fuel-simulant aerosols on a relatively continuous basis.

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3. Identification and qualification of appropriate fuel-simulant aerosols (e.g., UO_2).

4. Study of the characteristics and transient behavior of fuel and fuel-simulant aerosols within several small vessels, including effects of radiation and of the simultaneous vaporization of small amounts of sodium.

5. Production and study of fuel-simulant and sodium aerosols in large vessels for scaleup to containment size and development of possible engineered source reductions.

6. Study of the fuel interactions and expansion behavior within the sodium pool as the resultant bubble is transported through the overlying sodium to the cover-gas region.

Varying levels of effort are anticipated within these broad categories, with analytical modeling accompanying each phase of the experiment program. The analytical requirements appear to fall into four general categories: (1) predisassembly analyses, (2) fuel response to high rates of energy deposition, (3) fuel-bubble dynamic behavior and transport characteristics under sodium, and (4) dynamic aerosol behavior at high concentrations in the bubble and containment atmospheres.

Scoping calculations using simple models are being made early in the program. More sophisticated models will be developed as the program progresses and the controlling processes are identified. An attempt will be made to consolidate the models and data and to present them in a manner that will facilitate direct assessment of the radiological hazard associated with arbitrary hypothetical accident sequences.

1.2 EXPERIMENT PROGRAM

1.2.1 Introduction

During this quarter, efforts continued to improve the vaporization efficiency of the CDV method of producing aerosols from simulated LMFBR fuel. Previous quarterly reports^{2,3} have summarized the results of four separate test series at Arnold Engineering Development Center (AEDC) in which UO_2 test assemblies were subjected to high-voltage energy depositions from a 2- to 3-kV capacitor storage bank.

During the present quarter, another test series of five shots was completed in which methods were investigated for (1) producing a more uniform radial temperature gradient in the UO_2 pellets during preheat, (2) adding stainless steel to the resultant aerosol, and (3) determining the fraction of aerosol produced from the powder packing in the test assembly. Several mechanical difficulties were encountered, making this test series only partially successful.

Examination of the behavior of cold uranium-fuel aerosols has continued for the purpose of comparing the attenuation mechanisms (agglomeration and deposition) of electrically generated UO_2 aerosols from the AEDC tests and the pyrophorically generated U_3O_8 aerosols from the CRI-II tests. Characterization methods have included (1) primary particle size distribution by electron microscopy, (2) airborne aerosol concentration as a function of time by volumetric filter sampling, (3) and aerodynamic agglomerate size measurement by inertial cascade impactor or by measurement of aerodynamic mobility in a charged field. These measurements provide useful information for understanding the attenuation processes and also supply directly measured input values for aerosol behavioral codes.

Necessary preparations for initiating the large vessel UO_2 and sodium aerosol study and the HCDA bubble simulant study are continuing. Final design, site and facility preparation, and material and equipment procurement will begin early in the next quarter.

1.2.2 Capacitor Discharge Vaporizer (CDV) Development

Scoping tests are being conducted at AEDC to provide guidance in developing the CDV system to be used for depositing energy in LMFBR fuel in a manner that simulates HCDA conditions. Early tests have demonstrated the feasibility of the technique, and later tests have investigated various test sample designs and electrical parameters with the intent of maximizing the aerosol yield. Test parameters and results of the current test series are summarized in Tables 1.1 to 1.3.

Table 1.1. Physical data for AEDC tests 17 through 21.

Test No.	Quartz sleeve ID-OD (mm)	Load length (mm)	Pellet mass (g)	Packing mass (g)			Total mass (g)
				Spheres	Powder	Stainless steel	
17	11-15	44	10.08			0.66 ^a	10.74
18	11-15	44	10.05	20.02		0.73 ^a	20.93
19	14-18	57.5	14.08		32		46.08
20	14-18	57.5	13.2		35	2.0 ^b	48.20
21	11-15	49.0	9.7		12.7 ^c		22.40

^aStainless steel tubing surrounding pellet stack.^bStainless steel filings mixed in powder pack.^cThorium dioxide.

Table 1.2. Prefire conditions for AEDC tests 17 through 21.

Test No.	Low preheat resistance (Ω)	Prefire resistance (Ω)	Indicated surface temperature (K)	Capacitor bank voltage (V)	Bank energy (J)
17	1.42	1.42 ^a	1618	2600	61,000
18	0.18	0.18 ^b		2600	61,000
19	4.0	0.32 ^c		3000	80,000
20	8.2	0.44 ^c		3000	80,000
20A		2.2 ^c	1643	3000	80,000
21	2.9	0.39 ^c	1698	2600	61,000
21A	2.9	0.37 ^c	1623	2600	61,000

^aPreheat at 240 W.^bPreheat at 200 W.^cHigh preheat power at 1000 W for 50 sec.

Table 1.3. Summary of test results - EDC tests 17 through 21

Test No.	Energy deposited before arcing (J)	Load resistance at arcing (Ω)	Time to arcing (msec)	Prearcing average power rate (MW)	Energy deposited after arcing (J)	Prompt pressure rise ^a (psi)	Aerosol yield (determined from filter samples) (g/m ³)
17	2,200	0.040	0.8	2.8	13,800	N11	0.64 UO ₂ 0.01 N1 0.07 Fe <0.01 Cr
18	30,300	0.054	b	b	0	N11	0.08 UO ₂ <0.01 N1 0.03 Fe <0.01 Cr
19	6,800	0.29	1.4	4.9	4,000	N11	
20	Capacitor bank energy divided between test assembly and preheater power supply						
20A	Tried to fire test assembly 20; attempt unsuccessful						
21	Capacitor bank did not fire upon command						
21A	7,500	0.068	1.6	4.7	42,200		0.45 UO ₂ 0.06 ThO ₂

^a All tests during this series were conducted with the test vessel at an initial pressure of 1 atm of argon.

^b Power break at 0.8 msec is assumed to be the end of initial stainless steel vaporization.

Tests conducted at AEDC

AEDC test 17. This test was designed to investigate the effects of using external stainless steel cladding to preheat the UO_2 pellets and to provide the initial path for the capacitive discharge current. The assembly consisted of a UO_2 pellet stack contained in a stainless steel tube which was, in turn, contained within a quartz tube. No powder or microsphere packing was used between the stainless steel tube and quartz tube.

During the preheat cycle, it was intended that the stainless steel tube would serve as the power acceptor and function as an external heater for the pellet stack, thereby producing a radial temperature profile within the pellets that is more uniform than that produced if the pellets are internally heated. (When UO_2 pellets alone are used as the preheat power acceptor, the center temperature is much higher than the surface temperature.) Upon discharge of the capacitor bank, the stainless steel tube should vaporize, thereby adding additional heat to the outer surface of the UO_2 pellets and consequently lowering the electrical resistance of the outer surface compared to interior regions. Upon disappearance of the stainless tube by vaporization, the electrical current should then be preferentially deposited in the outer portion of the pellets, with surface melting and vaporization of the UO_2 progressing inwardly.

During the 240-W preheat phase, partial melting of the stainless steel tube was observed. Upon discharge of the capacitor bank, the stainless steel tube vaporized, the quartz containment tube ruptured, and some aerosol was produced; however, the pellet stack remained in place between the electrodes. Subsequent examination indicated that some surface melting and vaporization had occurred. Measurements indicated that an energy deposition of 2.2 kJ was achieved before arcing.

Filter samples indicated that 0.64 g/m^3 of UO_2 aerosol and about 0.09 g/m^3 of stainless steel aerosol were produced.

AEDC test 18. The objective of this test was similar to that of test 17. The test assembly was identical to that for test 17 except for the addition of microsphere packing between the stainless steel tube and the quartz containment tube.

The power level during the preheat phase was reduced to 200 W to preclude preheat melting of the stainless steel tube. During discharge of the capacitor bank, the energy deposition totaled about 30 kJ. Only a small amount of aerosol was produced; the quartz tube was fractured but not pulverized, and the UO_2 pellets did not melt. Considering the level of energy deposition and the lack of disassembly, one must suspect that vaporized (and possible recondensed) stainless steel served as a continuous-phase shunt for dissipation of the discharge current to ground.

Filter samples indicated a production of only 0.08 g/m^3 of UO_2 aerosol and less than 0.05 g/m^3 of stainless steel aerosol.

AEDC test 19. The test assembly for test 19 was very similar to those used in several earlier tests which had resulted in high yields of aerosol. The assembly consisted of a 6-cm stack of UO_2 pellets surrounded by UO_2 powder and contained in a quartz tube. The duration of the 1000-W preheat phase was 50 sec, and the capacitor bank charged to 3000 V and 80 kJ.

At 1.4 msec after initiation of capacitor bank firing, arcing at the high-voltage end of the test assembly terminated the energy deposition into the UO_2 pellets, and no disassembly was produced. Measurements indicated that a deposition of about 6.8 kJ occurred prior to arcing. Visual observation indicated that virtually no aerosol was produced and filter samples were not taken.

Subsequent examination revealed that hot UO_2 powder had penetrated through an area of excessive clearance between a lavite electrical insulator and the quartz containment tube into a gap between the upper lavite insulators, which provide insulation between the high-voltage electrode and the grounded outer stainless steel pipe. The hot (and electrically conductive) UO_2 powder thus provided a lower resistance pathway bypassing the UO_2 assembly. This mechanical defect will be eliminated in future test assemblies by reducing the clearances and using one-piece insulators.

AEDC test 20. The conditions for this test were the same as those for test 19 except for the addition of 2 g of stainless steel filings to the UO_2 powder pack as a method of simulating fuel cladding in the resultant aerosol.

The test proceeded normally until an unexplained safety circuit malfunction resulted in premature capacitor bank firing while the preheater power supply was still connected to the test assembly. As a result, the bulk of the energy was deposited in the preheater power supply. The resulting damage to the power supply required considerable field repair. However, with the cooperation of AEDC personnel, the preheater power supply was essentially rebuilt on the site, and a second run on this test assembly was attempted the next day.

AEDC test 20A. The second try was also unsuccessful. During the preheat phase, it was noted that the quartz containment tube had cracked and that the electrical resistance through the pellet stack was abnormally high. Nevertheless, capacitor discharge was initiated and energy deposition was achieved; however, no disassembly occurred.

AEDC test 21. The objective of this test was to determine if a significant fraction of the aerosol is produced from the powder packing around the pellet stack. The test assembly was similar to that used in test 19, except that the powder packing was ThO_2 rather than UO_2 so that chemical analysis could be used to determine the fractional yield from pellets and powder pack.

The capacitor bank was charged and a 1000-W preheat was applied for 50 sec; however, the capacitor bank did not fire upon command. All relays and electrical connections were checked, but no reason for this malfunction was found.

AEDC test 21A. A second trial was made under identical conditions, and a successful firing of the capacitor bank occurred. Disassembly was achieved, and considerable aerosol was generated. Analysis of the filter samples indicated yields of 0.45 and 0.06 g/m^3 for UO_2 and ThO_2 , respectively. The results from this one test indicate that about 88% of the aerosol comes from the UO_2 pellets and about 12% from the powder packing.

Pictorial highlights

This section highlights some of the visual observations made and recorded in connection with the current (5th) series of CDV tests at AEDC.

Figure 1.1 shows the condition of the UO_2 pellets recovered from test 17. This test was an attempt to initiate UO_2 vaporization from the outer surfaces of the pellets by utilizing the heat supplied by vaporizing stainless steel cladding to produce an inverse temperature gradient. Although only limited success was achieved, it is obvious that there was

PHOTO 2390-75

Fig. 1.1. Postshot condition of pellets from test 17.

no center melting, and the appearance of the pellets suggests that some surface melting and vaporization occurred.

Figure 1.2 shows the inner surface of the quartz containment tube after capacitor bank firing in test 18. Note the large amount of friable deposit, probably a mixture of UO_2 and stainless steel, on the interior surface of the quartz. This evidence lends support to the thesis that evaporated and recondensed stainless steel probably provided a continuous-phase shunt for the capacitor bank discharge current.

Figure 1.3 shows the postshot condition of the surfaces between the upper two lavite electrical insulators from test assembly 19. Arcing between these surfaces through hot UO_2 powder is believed to have caused early termination of power delivery to the test assembly. This possible electrical pathway will be eliminated in future test assemblies.

Figure 1.4 shows the postshot condition of the assembly after tests 20 and 20A. During test 20, the capacitor bank fired prematurely, and an unknown amount of energy was deposited in the assembly. In test 20A, an attempted retest, disassembly did not occur, and no aerosol was generated, although considerable energy (~ 36 kJ) was delivered into the assembly. Evidence of an extrusion of molten UO_2 can be seen around the spring-loaded electrode. Figure 1.5 is a photograph of the solidified UO_2 mass recovered from the interior of the quartz containment tube shown in Fig. 1.4. Note that the UO_2 pellets melted and disappeared. The pictured shells were apparently formed from the melting and sintering of the UO_2 powder pack.

Discussion of tests 17 through 21

Tests 17 and 18 represented a continuation of the effort to perfect a method of producing an aerosol consisting of both fuel material and cladding material. Management of energy deposition in a two-component test assembly, where one component is an electrical insulator and the other is an electrical conductor, continues to be a difficult, but not insoluble, problem. Design of future test assemblies will incorporate features which, hopefully, will discourage short circuiting of the discharge current.

PHOTO 2392-75

Fig. 1.2. Postshot condition of quartz containment from test 18.

Fig. 1.3. Postshot condition of upper insulators from test 19.

PHOTO 2386 75

Fig. 1.4. Postshot condition of quartz containment from tests 20 and 20A.

Fig. 1.5. Postshot condition of UO_2 powder-pellet loading from tests 20 and 20A.

The aerosol produced in test 17 contained both UO_2 and stainless steel and appeared to be composed of two types of particles with differing characteristics of deposition. One aerosol seemed to be composed of UO_2 only, and the other contained both stainless steel and UO_2 . The UO_2 aerosol disappeared from the atmosphere of the test vessel much faster than did the one containing UO_2 and stainless steel. Test 18 produced an

aerosol at a much lower concentration than test 17. This aerosol appeared to be similar in deposition characteristics to the UO_2 plus stainless steel aerosol produced in test 17.

The problems encountered with tests 19 and 20 are characteristic of problems which occur in any experimental program. The experience gained will be useful in future tests. Both experiments will be repeated.

Test 21, although plagued with some experimental difficulties, achieved its primary objective of demonstrating that most of the aerosol produced originates from the UO_2 pellets and not from the powder packing.

Thermal end-loss measurements at ORNL

As a part of the CDV optimization process, a series of specific tests was completed at ORNL this quarter to measure the thermal end losses from the UO_2 pellet stack during the preheat cycle.

To determine the thermal end losses, experimental measurements were obtained for the axial voltage drop along a UO_2 test assembly. Tungsten wires were inserted into the test assembly through the quartz containment tube at measured axial locations. A typical preheat cycle was initiated, and voltage measurements were made at these locations.

The voltage profile was found to be uniform along the UO_2 pellet stack, but with marked discontinuities at the two electrode-pellet interfaces. It was assumed that the end losses were proportional to the electrical resistance changes at the interfaces. A typical voltage profile and calculated end losses are shown in Fig. 1.6. The end losses are larger than had been previously estimated.

As a result of these measurements, we plan to increase the capability of our preheater power supply for future AEDC tests.

Figure 1.7 shows the condition of the UO_2 pellets and the UO_2 powder or microsphere packing following two preheating tests. In each case, the length of the pellet stack was 5.4 cm, and total power input was about 120 W/cm. The UO_2 pellet- UO_2 microsphere sample, on the right, did not exhibit gross pellet melting, although the center of the pellets had been molten during the preheat cycle. The UO_2 pellet- UO_2 powder sample, on the left, apparently underwent complete pellet melting. The

Fig. 1.6. Data and results from an experiment to determine preheater power lost through the electrodes.

PHOTO 2766 75

Fig. 1.7. Condition of posttest samples from preheater experiments.

radical sintering of the UO_2 powder over such a short period of time was surprising. We suspect that this sintering adversely changed the thermal properties of the powder packing in such a manner that the pellet material, initially molten, probably resolidified during the peak power phase of the preheat cycle.

Preheater power supply

The Q-5220 constant-power regulator used for preheating in the AEDC experiments is presently being upgraded from a full-range power of 1000 W to a full-range power of 5000 W. The short-circuit current will be boosted from 60 to 100 A.

Capacitor bank

The vaporization experiments conducted at AEDC have indicated that 2500 V is about the optimum capacitor bank voltage rating for HCDA-like energy deposition rates. This voltage has proved more than adequate for supplying a 6-cm fuel pin segment with 10^6 W/g. In addition, 2500 V is low enough that troublesome arcing directly across the fuel pin or across insulators can be controlled with reasonable assembly designs.

Present plans call for the ORNL capacitor bank to be constructed using a modular concept with a maximum capacity of 60,000 J per module. Each module will be completely self-sufficient and independent of other modules, thus allowing simultaneous or sequential firing of multiple fuel pins (one pin per module).

Each module will consist of 20 capacitors rated at 2500 V and 3000 J storage. Specifications for these capacitors have been prepared and submitted to several manufacturers. Procurement and delivery of enough units to fabricate two bank modules is expected within the next quarter.

The average energy deposition rate delivered by an ORNL module will be selectable over at least a 10 to 1 range (from 10^5 to 10^6 W/g) by the use of a series inductance choke to limit the average current delivered to each fuel pin. (The design current range is presently 3 to 12.2 kA per pin.) For one of the modules, the choke will probably be fabricated

using the ORMAK iron core obtained from the Thermonuclear Division. Chokes for other modules will be similar to those used with the AEDC capacitor bank.

1.2.3 Small-Vessel Fuel and Fuel-Simulant Aerosol Studies (Cold Proof Tests)

The examination of cold uranium fuel aerosols has continued for the comparison of the attenuation behavior (agglomeration and deposition) of the electrically generated UO_2 aerosols from the AEDC tests and the pyrophorically generated U_3O_8 aerosols from the CRI-II tests. To date, our tests have been limited to rather dilute, low-temperature aerosols; these tests are preliminary to future aerosol tests to be conducted at higher concentrations and elevated temperatures.

As part of the comparison program, electron microscopy has been used to determine the size distribution of the primary particles and the related sigma functions for the U_3O_8 aerosol from CRI-II tests and the UO_2 aerosol from the CDV tests. It was noted that values for geometric mean diameter (d_{50}) and for sigma differ for the two aerosols.

	d_{50}	Sigma
	(μ)	(σ)
U_3O_8 aerosol, CRI-II	0.011	2.05
UO_2 aerosol, AEDC-CDV	0.0056	2.75

The CDV aerosol, being generated from a more energetic system and of a different chemical form, contained primary particles of a smaller average size but a larger distribution of sizes (larger sigma value). Figure 1.8 displays graphically the primary particle size distribution³ for the aerosol produced in AEDC test 9. Surface scanning electron photographs of this same aerosol, as recovered from vertical plate-out samples, are shown in Fig. 1.9. In these photographs, the presence of some rather large (several microns in diameter) primary particles can be seen, together with agglomerates consisting of smaller primary particles. This evidence suggests that aerosols produced by evaporating and condensing

Fig. 1.8. UO_2 primary particle size distribution in CDV aerosol from test 9.

UO_2 at high concentrations and elevated temperatures will contain agglomerates composed of very small primary particles as well as larger spheres formed by droplets of liquid UO_2 . The U_3O_8 aerosol, which is produced by the burning of uranium metal, has been observed to be composed entirely of agglomerated primary particles with no "droplet" particles.

Upon completion of the do-arc hearth furnace, which is about 90% complete, we will be able to produce CRI-II aerosol by direct evaporation of UO_2 . Consequently, the physical characteristics of the CRI-II aerosol and the CDV aerosol should then become more comparable.

Evaluation of methods for the characterization of aerosols has continued. The methods evaluated have included (1) primary particle size distribution as measured by electron microscopy, (2) change in airborne

Fig. 1.9. Four successive magnifications of a plate-out sample from test 9 showing both large droplets and submicron agglomerates.

aerosol concentration as a function of time by volumetric filter sampling, and (3) the aerodynamic agglomerate size distribution as measured by inertial cascade impactor or by measurement of aerodynamic mobility as determined by the Whitby particle analyzer (Thermosystems Company). From each of these measurements, information is obtained which is useful to the understanding of the aerosol attenuation processes and which provides directly measured input values for use with aerosol behavioral codes.

Particle classification by the Whitby aerosol analyzer is done as follows: Entering aerosol (drawn in by vacuum pump) is given a unipolar negative charge by a special diffusion charger. It then passes through an aerosol flow meter into a mobility analyzer where it is introduced into a long vertical chamber in a thin annular region around a core of clear (filtered) dilution air. The charged aerosol is drawn inward through the core of dilution air by a positive potential on a collector rod along the axis of the vertical chamber. If the collector rod is operated at constant potential, then the aerosol is classified along the rod according to electrical mobility; however, if the collector voltage is varied in a systematic manner, all particles having a mobility less than a given value will miss the end of the collector rod and be collected by the current-collecting filter at the bottom of the chamber. Then the number-particle size distribution curve of the aerosol may be calculated from the filter current vs collector-rod voltage curve. The analyzer covers a particle diameter range of from 0.015 to 1.0 μ divided into 14 increments.

The results of the analysis of a typical CRI-II U_3O_8 aerosol test are illustrated by plotting the percent of particles having diameters less than a stated value against the log of the diameter on a probability scale, as in Fig. 1.10; the geometric mean diameter d_g and the geometric standard deviation σ are determined graphically. These values are compared with values computed from relations given by Smith and Jordan⁴ and listed in Table 1.4 for various time increments following the generation of the aerosol. As the aerosol ages in the vessel, the agglomeration process proceeds and leads to a particle size increase and also to a change in the particle size distribution.

The effect of aging on the agglomeration process may be illustrated by processing the data from the Whitby analyzer in a different manner. As noted earlier, the Whitby analyzer covers a particle diameter range of 0.015 to 1.0 μ . This range is divided into 14 increments, and the number of particles in each increment is determined by means of successive ionizer current differences. Figure 1.11 gives values of $nd/\Delta d$ obtained by multiplying the number of aerosol particles in a size increment by the average diameter of the particles within that increment and

Fig. 1.10. Distribution of number sizes of U_3O_8 aerosol in CRI-II test as measured by means of the Whitby electrical mobility technique.

dividing this product by the increment width plotted vs the log of the average diameter. This graph illustrates both the drastic decrease in the number of very small particles (diameter $\sim 0.02 \mu$) through agglomeration and the significant decrease in the number of particles approximately 0.1μ in diameter through plate-out or further agglomeration as a function of aging time.

Samples of the same U_3O_8 aerosol were also taken with a pair of inertial cascade impactors arranged in series (an Andersen impactor followed by a low-pressure impactor). The U_3O_8 collection plates from the two inertial cascade impactors are shown in Fig. 1.12. In the lower row of plates, the six stages of a conventional Andersen impactor are shown with very little material on the first two stages and an increasing quantity on the last four stages. In the upper row are six plates from

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Fig. 1.11. Apparent numerical distribution after successive intervals for U_3O_8 aerosol in the CRI-II tests, as measured by means of the Whitty aerosol analyzer.

Table 1.4. CRI run 10-2-75 - data from Whitby aerosol analyzer

Aerosol aging time (min)	Number of particles per cubic centimeter ($\times 10^6$)	Geometric mean diameter d_g		Geometric standard deviation σ_g	
		Computed ^a	Graphic ^b	Computed ^a	Graphic ^b
2	6.87	0.044	0.049	2.6	2.2
15	8.4	0.038	0.006	2.4	1.9
45	2.1	0.087	0.093	2.1	1.9
50	2.3	0.057	0.063	2.5	2.2
108	1.6	0.079	0.085	2.2	2.0
113	1.8	0.061	0.068	2.3	2.1
118	1.4	0.071	0.078	2.3	2.0
137	1.05	0.074	0.079	2.3	2.2
192	0.69	0.081	0.079	2.2	2.0
207	0.69	0.07	0.093	2.7	1.9

^aValues computed from relations given by Smith and Jordon in Ref. 4.

^bValues obtained by plotting data. (See Fig. 1.11c.)

a special low-pressure impactor which was operated in tandem with the depleted aerosol stream exhausted from the Andersen impactor. The range of the low-pressure impactor extends to very small diameters approaching 0.005μ , with the midstages (3 and 4) collecting particles between 0.1 and 0.15μ . The calibration of the Andersen impactor is presently known only for particle of unit density, so that a heavier material would appear to have a larger size distribution. The lower cutoff diameter of stage 6 is about 0.2μ at unit density. For U_3O_8 , with density $\sim 8 \text{ g/cc}$, this value would be significantly lower and in substantial agreement with the Whitby analysis in Fig. 1.11 which indicates a peak number concentration around 0.1μ .

In comparing the number or count-size distribution data from the Whitby analyzer with mass distribution data from the impactor analysis, it is convenient to convert number distribution from the Whitby analyzer to mass distribution.

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Fig. 1.12. Appearance of the collection plates from two cascade impactors operated in series. The standard Andersen plates are shown in the lower row (stages 1 to 6 from right to left) and the low-pressure impactor plates are in the upper row, arranged similarly.

The Whitby analyzer data give the number of particles n_i within a given diameter range around diameter d_i .

Assuming the particles are spherical, then

$$W_i = (0.5236 d_i^3) (n_i) (\rho) (10^{-12}) = 5.236 \times 10^{-13} n_i \rho d_i^3, \quad (1)$$

where

$$\text{cm}^3/\mu^3 = 10^{-12},$$

n_i = number of particles of average diameter d_i within a standard range,

ρ = density of $\text{U}_3\text{O}_8 = 8.2 \text{ g/cm}^3$,

W_i = weight of n_i particles of U_3O_8 having an average diameter of d_i .

Using relationship (1), the weight distribution of the different size particles was estimated and plotted in Fig. 1.13. The upper curve

Fig. 1.13. Whitby analyzer numerical size distribution for U_3O_8 aerosol compared to mass distribution, using theoretical density of 8.3. Data taken 118 min after formation.

($d_{50} = 0.309 \mu$, $\sigma = 1.91$) was plotted using percent of total weight [$d_{50} = \text{mass mean diameter (mmd)}$], and the lower curve ($d_{50} = 0.078 \mu$, $\sigma = 2.0$) resulted from using numbers of particles. The mmd of 0.309μ appears to be in good agreement with the Andersen impactor analysis.

A new optical density measuring device

A very small detector for particulate concentration is currently being evaluated for use inside the CRI-II. The sensitive element is mounted on the end of a 12-in. section of 1/4-in.-OD sealed stainless steel tubing and is inserted through a tube fitting several inches inside the vessel. The heart of the unit consists of a commercially available solid-state light-emitting diode (LED) and a phototransistor in a single subminiature housing. The LED and phototransistor are mounted side by side, separated by a thin wall, with their optically sensitive axes parallel. The phototransistor thus measures backscattered light at a very narrow angle. Emission from the gallium arsenide LED is centered fairly sharply at 900 nm; the phototransistor is very broadly responsive to light, but peaks in the 800- to 900-nm region. Fairchild FPA-105 and Optron ORB-730 units have both proved very sensitive for this service.

This type of detector has been used successfully on tobacco smoke in concentrations from 2.5×10^7 to 5×10^9 particles/cc in several applications in bio-organic analysis. The signal output from the sensor has proved to be linear, within a few percent, over this wide range of smoke concentration. While tobacco smoke consists primarily of aerosols in the 0.1- to 0.4- μm range, it is hoped that this detector will also prove sensitive and proportional over the much wider size range of the U_3O_8 aerosols. To date, the results have been encouraging, but inconclusive, due mainly to instrument problems associated with sensor mounting and output recording.

CRI-III vessel

Work continues on construction of the CRI-III vessel; a schematic of the vessel is shown in Fig. 1.14. Aerosol experiments at elevated

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Fig. 1.14. Schematic of CRI-III aerosol vessel and discharge chamber as redesigned.

pressures and at the design temperature of 1000°F will be conducted in this vessel to develop the "upper-limit" source term.

1.2.4 Large-Vessel Aerosol Studies

Conceptual design for the modifications to the Nuclear Safety Pilot Plant (NSPP) has been completed, and the authorizations necessary to initiate final design, start construction, and procure equipment have been requested. The test vessel ($\sim 38 \text{ m}^3$), some of the associated piping, and some of the instrumentation from a prior aerosol study conducted in the NSPP will be utilized. A preliminary equipment layout plan and engineering flowsheet for the NSPP are shown in Figs. 1.15 and 1.16, respectively.

At present, the facility modifications are scheduled to begin during the next quarter, with experimental operations beginning about 8 months later.

In conjunction with this program, the HAARM-1 version of the aerosol behavior code (HAA-3B), the aerosol behavior code (PARADISEKO-III), and the sodium fire code (SOFIRE-II), have been obtained and made operational on the ORNL computer system.

1.2.5 HCDA Bubble Simulant Tests

Preliminary design of the Fuel Aerosol Simulant Test (FAST) has been completed, and the authorization necessary to initiate final design and start procurement of materials and equipment has been requested.

This facility will make use of the CDV system to electrically generate fuel-simulant bubbles under a pool of sodium at representative reactor conditions within a small-scale vessel that models the primary reactor vessel. A preliminary process flowsheet of the facility appears in Fig. 1.17.

Low-pressure water vessel

While the under-sodium facility is being prepared, exploratory bubble experiments will be made in a low-pressure water tank, 35 in. in

Fig. 1.16. Nuclear Safety Pilot Plant engineering flowsheet.

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Fig. 1.17. Fuel-Aerosol Simulant Test (FAST) process flowsheet.

diameter by 72 in. high. A high-pressure gas-injection system is installed at the bottom surface of the tank; this "bubble injection" system allows the sudden injection of a known volume of high-pressure gas into the column of water. The behavior of the bubble, as it rises to the surface of the water, will be recorded with a high-speed motion picture camera. Installation of this facility is essentially complete, and check-out procedures are under way.

Simulant materials for bubble experiments*

To aid in the planning of bubble-behavior experiments to bridge the transition between the exploratory study of gas bubbles in the low-pressure water vessel and the final study of sodium-fuel aerosol bubbles in the FASI facility, a survey was made of various simulant materials and methods for generating vapor bubbles of (1) noncondensable gas, (2) condensable vapor of the same composition as the containing liquid, and (3) condensable vapor of a composition different from the containing liquid.

1.3 ANALYTICAL PROGRAM

1.3.1 Introduction

Analytical requirements for the Aerosol Release and Transport Program appear to fall into four general categories: (1) use of existing models and computer programs for the predisassembly and disassembly stages of the HCDA to determine initial conditions and rates of energy deposition for CDV experiments, (2) analyses of fuel response to high rates of energy deposition to establish the effectiveness of the CDV system for producing aerosols and modeling the HCDA and to interpret the experimental results, (3) analysis of the expansion and transport behavior under sodium of the energetic fuel material, and (4) analyses of

*This work was performed in cooperation with A. B. Reynolds and S. Rao, Nuclear Engineering Department, University of Virginia, Charlottesville.

aerosol evolution and behavior at high concentrations under dynamic confinement within the bubble, in the cover-gas region, and in the containment building.

In the early phases of the program, simplified analyses are being made to provide bases for designing the experiments, to interpret exploratory experiments, and to make sensitivity assessments.

1.3.2 Fuel-Simulant Response to CDV Electrical Energy Deposition

Analytical modeling of the CDV system requires consideration of three different phases: a low-power preheat stage that brings the UO_2 sample to its melting temperature, a zero-power temperature leveling period (zero to several seconds duration) that will allow the internal UO_2 temperature profile to flatten, and a short period (a few milliseconds) of energy deposition from capacitor discharge that produces disassembly. Separate analytical studies are being directed toward each of these stages.

Finite-element computer simulation code

This code was developed as an experiment design tool for use with the CDV development tests. It describes the effects of various design and experimental parameter changes so that value judgments can be made on potential improvement in aerosol yield resulting from such changes. The code incorporates the preheat stage and the capacitor discharge period up to disassembly. Temperature changes during the zero-power waiting period are not included.

The simulation code treats a representative cylindrical geometry fuel sample contained in a quartz tube. The cross section is subdivided into 50 concentric finite-element rings, and a forward marching in time procedure is used with small time increments ($\sim 10^{-5}$ sec). The basic code has been discussed in a previous quarterly.³

Figure 1.18 is a graph of theoretical aerosol yields for various fractions of pellet melt as computed by the finite-element code. These calculated values, even though dependent on estimated input values for

Fig. 1.18. Aerosol yields calculated by the finite-element CDV simulation code at various pellet-melt fractions compared to maximum theoretical aerosol yield.

physical properties, are descriptively adequate for use in making value judgments and are reasonably consistent with experimental results.

The computed curves in Fig. 1.18 indicate that three factors are involved in maximizing the aerosol yield.

1. The UO_2 pellets should be melted as completely as possible before discharge of the capacitor bank.
2. The radial temperature gradient in the molten UO_2 should be as small as possible.
3. The yield pressure of the containment tube should not be much lower than ~ 5000 psi.

Achievement of full pellet melting will require sufficient energy input during preheat and adequate thermal insulation (powder packing) between the pellets and the quartz containment. One parameter related to the powder packing which can be varied in the computer code is the void fraction. Figure 1.19 shows the calculated effect of varying the void

Fig. 1.19. Effect of varying void fraction on power required for pellet melting.

fraction in the powder packing on the power required to achieve full pellet melting during preheat.

Also shown in Fig. 1.19 are experimental data from two of our most successful AEDC tests to date (shots 14 and 16) each corrected for thermal end losses (see Section 1.2.2). After the end-loss correction, the preheat power input for test 14 was found to be 149 W/cm, and the extent of pellet melting was estimated to have been 35%; for test 16, the values were 124 W/cm and 43%. The experimental points for these two tests fall within the curve envelopes for representative void fractions.

This exercise indicates that UO_2 powder will probably be superior to UO_2 microspheres in achieving better thermal insulation and that the capacity of the preheat power supply should be increased to overcome the effect of thermal end losses. (See Section 1.2.2.)

Figure 1.20 illustrates the effect of varying the thickness of the UO_2 powder pack around the pellets, at constant void fraction, on the preheat power required to achieve full pellet melting. As expected, increasing the packing thickness at constant power results in increased pellet melting because of the added thermal insulation provided by the packing. The labels on the curves in Fig. 1.20 refer to the internal diameter of the quartz containment tube; at a constant pellet diameter, a larger tube would provide a thicker powder packing.

Additional calculations at various preheat power levels indicate that complete pellet melting could probably be achieved by using an 11-mm-ID quartz containment tube and a powder packing with a void fraction of 0.5 or greater. The preheat input power should be within the capacity of our new preheat power supply, and the temperature produced at the containment-powder pack interface should not exceed the softening point of quartz ($\sim 1940^\circ\text{F}$) or other potential containment materials (Al_2O_3 , BeO , etc.).

We plan to incorporate the results of this analytical study into the design of future test shots at AEDC.

Fig. 1.20. Effect of varying thickness of pellet packing at fixed void fraction (0.5) on power required for pellet melting.

Analytical description of CDV process

A preliminary analysis was performed to predict temperature distribution in fuel pellets during the three phases of the CDV process.*

Preheat phase. The temperature distribution in the UO_2 pellets at the end of the preheat phase can be characterized as steady-state heat conduction with heat generation. An analytical model was developed by describing the problem as steady-state, one-dimensional, two-region heat conduction in cylindrical geometry, with temperature-dependent thermal

*This work was performed in cooperation with M. N. Ozisik, Mechanical and Aerospace Engineering Department, North Carolina State University, Raleigh.

conductivity and temperature-dependent heat generation in the inner region, and subject to convective heat transfer at the outer surface. The effect of radiation losses from the outer surface is incorporated in the analysis by the proper adjustment of the surface heat transfer coefficient. One result of this analysis yielded an integral equation for the temperature distribution that could be solved with a digital computer. A special case of this solution - for uniform thermal conductivity and heat generation - resulted in a closed-form solution, which provided good insight into the effects of various parameters on the temperature distribution.

To calculate the temperature distribution from this model, the electrical resistivity and the thermal conductivity of the UO_2 pellet assembly are needed as functions of temperature. Expressions are available for the electrical resistivity of UO_2 in the temperature range $1200 \text{ K} < T < 2800 \text{ K}$; therefore, it was necessary to extrapolate this expression for liquid UO_2 for temperatures up to 4000 K .

No data were available for the thermal conductivity of the UO_2 microsphere packing; therefore, an estimate of the value was made by reducing the value for solid UO_2 by the void fraction present in the microsphere packing (i.e., 60% of the thermal conductivity of solid UO_2).

The first series of computations was performed for an average CDV test assembly using experimentally determined preheat power deposition and assuming that all the current passed through the UO_2 pellets. Calculated temperatures for the UO_2 pellets were high and inconsistent with the experiments, and it was concluded that some of the current must have passed through the UO_2 microsphere packing.

Since no exact experimental information was available on what fraction of the current passed through the microsphere packing, a parameter study was made by performing the calculations with different rates of heat generation in the UO_2 pellets. It appears that 60 to 70% of the current must have passed through the UO_2 pellets and the remainder through the UO_2 spherical beads. For example, taking the outer surface temperature of the assembly to be 1800 K and assuming about 60% of the current passed through the UO_2 pellets, we calculated that temperatures

at the center and the outer surface of the UO_2 pellets were 3500 and 3000 K, respectively.

Although the above results appear to be reasonable in comparison with the experimental data, there are numerous uncertainties involved in the input data on the physical properties of UO_2 pellets and UO_2 microspheres. For example, the calculated temperatures are very sensitive to the choice of the value of the thermal conductivity for the UO_2 microspheres. The value of thermal conductivity chosen as 60% of the thermal conductivity of UC_2 is probably an overestimation because of the presence of thermal contact resistance. Calculations performed using the closed-form solution for uniform generation showed that, for a power input of 700 W/cm^3 , the center temperature of the UO_2 pellet would be increased from 3512 to 4400 K by merely reducing the thermal conductivity of the microspheres from 60 to 40% of the thermal conductivity of UO_2 . Therefore, an accurate determination of the thermal conductivity of the UO_2 microspheres is needed.

In order to establish what fraction of the total current passes through the UO_2 pellets, the electrical resistivity of the UO_2 microspheres must be known.

Finally, in order to predict the temperature distribution in the liquid- UO_2 region, the electrical resistivity and thermal conductivity of liquid UO_2 in the temperature range from 3200 to 4000 K must be known.

Zero-power phase. Experimental requirements necessitate a delay of several seconds duration between the preheat phase and the capacitor discharge phase. During this period, some cooling of the test assembly occurs. It is of interest to predict the temperature change during this short period of time. A transient analysis was performed, but no satisfactory numerical results could be obtained because of difficulty associated with the convergence of the solution. However, an estimate of the temperature change was made with the following considerations. The whole assembly is treated as a single UO_2 region initially at a nearly uniform temperature and subjected to convective cooling at the outer surface. If the governing equations for this problem are expressed in

dimensionless form, it can be shown that the center temperature T_c of the UO_2 pellet is a function of two dimensionless parameters ξ and Bi , as follows:

$$\frac{T_c(\xi) - T_\infty}{T_{\text{initial}} - T_\infty} = f(\xi, Bi),$$

where

$$\xi = \frac{r_2^2}{4d_1t},$$

$$Bi = \frac{r_2 h_\infty}{k_1}.$$

d_1 = thermal diffusivity (cm^2/sec),

r_2 = overall radius of UO_2 region (cm),

h_∞ = surface heat transfer coefficient ($\text{W cm}^{-2} \text{ sec}^{-1}$),

k_1 = thermal conductivity [$\text{W cm}^{-1} (\text{°C})^{-1}$],

T_∞ = temperature of the surroundings (K).

If it is assumed that most of the heat transfer from the outer surface takes place by radiation and that immediately after the termination of the preheat phase the surface temperature is about 1000 K, then the effective heat transfer coefficient at the outer surface, due to radiation, is

$$h_\infty = 5 \times 10^{-3} \text{ W cm}^{-2} \text{ sec}^{-1}.$$

The other properties are taken to be

$$\alpha_1 = 0.636 \times 10^{-2} \text{ cm}^2/\text{sec},$$

$$r_2 = 0.9 \text{ cm},$$

$$k_1 = 0.026 [\text{W cm}^{-1} (\text{°C})^{-1}].$$

We find

$$\frac{1}{Bi} = 5.8, \quad \xi = 0.78 \times 10^{-2} \times t = \begin{cases} 0.78 \times 10^{-2} & \text{for } t = 1 \text{ sec} \\ 0.078 & \text{for } t = 10 \text{ sec} \end{cases}$$

Using transient temperature charts,⁵ we find that even for a period as long as 10 sec,

$$\frac{T_c(\xi) - T_\infty}{T_{\text{initial}} - T_\infty} > 0.95,$$

or the temperature drop is less than a few percent. This amount will be even less if one considers the fact that the center portion of the UO_2 pellet is melted and that some of the heat will be given out as latent heat during the solidification.

Capacitor discharge phase. A rapid deposition of electrical energy in the amount of 10^6 W/g will be applied to the fuel assembly within a short period of 2 to 3 msec. Assuming that the conduction losses are negligible in this short time interval, the temperature rise ΔT ($^{\circ}\text{C}$) at any location in the fuel assembly can be computed from the relation

$$\Delta T(\eta) = \frac{g[T(\eta)]}{w[T(\eta)]C_p[T(\eta)]},$$

where

$$g(T) = \frac{V^2}{\rho(T)}, \text{ total energy input (W sec}^{-1} \text{ cm}^{-3}\text{),}$$

$$V = \text{voltage drop (V/cm),}$$

$$\rho(T) = \text{electrical resistivity (}\Omega\text{-cm),}$$

$$w(T) = \text{density (g/cm}^3\text{),}$$

$$C_p(T) = \text{specific heat [W sec}^{-1} \text{ g}^{-1} \text{ (K)}^{-1}\text{],}$$

$$\eta = r/r_1,$$

$$r = \text{radial position from center of } UO_2 \text{ pellet (cm),}$$

$$r_1 = \text{radius of the pellet (cm).}$$

The temperature $T(r)$ can be taken as the temperature distribution ($^{\circ}\text{C}$) in the fuel assembly prior to the capacitor discharge phase.

Clearly, to determine the resulting temperature distribution in the fuel assembly by the above relations, an accurate knowledge of the electrical resistivity of liquid UO_2 in the temperature range above 3200 K as a function of temperature is needed.

Dissassembly and extended expansion model

This model will cover the disassembly process of a CDV fuel assembly and a short period of extended expansion following disassembly. The general approach is to utilize existing computer codes with appropriate modifications for the FAST experiments under consideration. During the disassembly phase, we plan to use either the VENUS II code or the PAD code. These are coupled neutronics-hydrodynamics codes that calculate the energy deposited and the subsequent temperatures, pressures, and motions of various core regions for short time steps during a power excursion. The neutronics in the codes will be replaced by a procedure whereby the CDV test fuel pin assembly will be divided into mesh cells and calculations made for short time steps to determine the spatial energy deposition resulting from the electrical discharge. The equations of state and the hydrodynamics of the code will be retained to calculate material motion, and internal temperatures, pressures, and vapor fractions.

The calculations based on VENUS II or PAD will be assumed to apply up to the time when the calculated pressure on the outer container of the fuel pin assembly has reached some preestablished failure level. This failure criterion will be based on stress considerations but will require experimental verification and possible modification resulting from successive comparisons with the experiments.

Results of the disassembly calculations will then be used to obtain input conditions for extended expansion calculations. We would expect to predict the sequence of thermodynamic states experienced by the expanding fuel simulant and obtain information on the bubble size, vapor flashing, and effects of shock waves on the bubble interface. We plan

to consult with staff members at Argonne National Laboratory to investigate the feasibility of using REXCO or ICECO codes to assess the bubble expansion behavior for the configuration of the FAST experiments.

This modeling effort will help provide a fundamental understanding of the disassembly process and will allow us to interpret experimental data and make suggestions for possible modifications of the experimental configurations. These modifications would allow experimental assessment of the different conditions that are postulated to exist under various core disruptive accident (CDA) assumptions.

1.3.3 Bubble Shape and Rise Behavior*

In a core-disruptive accident, a large bubble may be produced at the core level during and immediately after disassembly. There is no clear agreement on the early motion of the bubble under constraints imposed by the core, the blanket and shielding assemblies, and the structural members. However, regardless of this early movement, a large bubble would be formed eventually near the top of the fuel assemblies. It is of interest to predict the shape of this bubble and its rate of rise through the sodium to the cover-gas region.

A literature search revealed several articles⁶⁻⁹ that contained definitive experimental information on bubble shape and rise behavior. It should be noted that these articles deal with experiments with "large" bubbles of not more than 20 cm in diameter; experimental verification that the reported bubble behavior extends to bubbles of much larger diameter will be required.

The references cited generally agree that a spherical bubble, starting from rest, initially rises at a constant acceleration, $U = 2g$. After a short time, liquid moves upward from the bottom of the sphere and transforms the bubble into a shape which is spherical on top and flat on the bottom⁶ [see Fig. 1.21(a) for illustration of spherical-cap

*This work was performed in cooperation with A. B. Reynolds and S. Rao, Nuclear Engineering Department, University of Virginia, Charlottesville.

Fig. 1.21. Shape of gas bubbles rising through columns of liquid.⁶
 (a) Spherical-cap, $\theta = 53^\circ$. (b) Slug shape: Spherical cap of radius a on top; cylindrical slug of radius a below.

shape]. Under some conditions, the spherical bubble may change into two bubbles — one with a spherical-cap shape and one below it with a toroidal shape.⁹ After the lapse of a time period obtained from the relation $t = 0.8(g/a_0)^{-1/2}$, where a_0 is the radius of the initial spherical bubble, the bubble velocity changes to a constant value. This constant rate of rise of bubbles in an infinite pool U_∞ seems to be fairly well established as

$$U_\infty \approx 0.67(ga)^{1/2}$$

where "a" is the radius of the spherical cap of the bubble. The cap-shaped bubble has an angle θ of about 53° .

In terms of the volume V the rate of rise in an infinite pool is

$$U_\infty = 2.5(V)^{1/6},$$

where U_∞ is in meters/sec and V is in cubic meters.

The rate of rise of a bubble in a finite pool is less than U_∞ ; a finite pool is defined as a cylindrical tank of radius b in which the bubble radius is similar in magnitude to the tank radius. For this case, the bubble takes on a cylindrical-slug shape with a spherical top [see Fig. 1.21(b)], and the rate of rise U_s is

$$U_s = 0.5(gb)^{1/2}.$$

A preliminary method for making the transition from one domain to another, that is, from U to U_∞ and from U_∞ to U_s , is proposed.

Transition from U to U_∞

It is assumed that the initial acceleration of the spherical bubble is constant at $2g$ until $t = 0.8(g/a_0)^{-1/2}$, where a_0 is the initial radius; $U = 2gt$ until this time. At $t = 0.8(g/a_0)^{-1/2}$, the bubble changes shape to a spherical-cap form with $\theta = 53^\circ$ which results in a spherical-cap radius "a" of $2.1a_0$. The rise velocity also changes at this time to $U_\infty = 0.67(ga)^{1/2}$.

Transition from U_∞ to U_s

Although the relations for U_∞ and U_s are simple, an appropriate transition from one to the other is surprisingly tricky. One desires a plot of U/U_∞ vs a/b such that U limits to U_∞ for a small a/b and to U_s at some higher value of a/b . At this higher value of a/b , the bubble is still considered to be of spherical-cap shape; if the bubble has more volume than a spherical-cap bubble of that a/b , then the bubble assumes a slug shape, with the same spherical cap as the spherical-cap

bubble but with a cylindrical body. The rise velocity remains constant, however, for the slug-shaped bubble; it remains the value for the maximum size spherical-cap bubble. This limiting value is the slug velocity U_s .

Proposed method for determining bubble shape and rise velocity

Assume a spherical-cap-shaped bubble with $\theta = 53^\circ$ whenever $a/b < 0.8$.

For bubble volumes which give $a/b > 0.8$ for a spherical-cap shape, assume a slug shape with a spherical cap and cylindrical body, and with $a/b = 0.8$.

Calculate U/U_∞ from the relation

$$\frac{U}{U_\infty} = \left(1 - \frac{a}{b}\right)^{0.1} \text{ for } 0 < \frac{a}{b} \leq 0.8 .$$

For slug-shaped bubbles, assume U equals the velocity for $a/b = 0.8$. This guarantees the correction limit for U_s for the following reasons:

$$U = (1 - 0.8)^{0.1} U_\infty ,$$

$$U = (0.85)(0.67)(ga)^{\frac{1}{2}} ,$$

$$U = 0.5(gb)^{\frac{1}{2}} ,$$

$$U = U_s .$$

2. STRUCTURAL INTEGRITY OF EQUIPMENT CELL LINERS

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The behavior of a plane wall segment of a prototype LMFBR cell was studied under postulated conditions of a massive sodium spill. Sodium-concrete reaction calculations were performed assuming the existence of an initial flaw in the liner which allowed high-temperature sodium to penetrate to the concrete underneath. Based on existing sodium-concrete reaction rate data, bounding values were established for the maximum energy release per unit volume of concrete. The potential effect of this energy release on the deformation of the liner material was determined. The temperature buildup in the liner and the pressure differential across the flaw in the liner were also studied.

The transient thermal and structural responses of the steel liner and the backup concrete were studied in detail, using the inelastic computer code ANSYS. The conditions studied were a ramp temperature change in the liner surface away from the concrete of 65.6 to 537.8°C in 1 sec, an isothermal steady-state period at 537.8°C, and an isothermal cooldown back to 65.6°C. Stresses, strains, and displacements were calculated for each condition.

The results are preliminary and were intended primarily to outline the scope of the problem. Additional follow-up studies are identified to resolve uncertainties involved in assessing cell liner behavior during a sodium spill.

A detailed report covering this study will be issued in the near future ¹⁰

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