ANNUAL TECHNICAL PROGRESS REPORT
NUCLEAR SAFETY
CHARACTERIZATION OF SODIUM FIRES
AND
FAST REACTOR FISSION PRODUCTS
GOVERNMENT FISCAL YEAR 1975

ERDA Research and Development Report

Prepared for the United States
Energy Research and Development Administration,
Division of Reactor Research and Development,
under Contract Number AT(04-3)-824

Rockwell International
Atomics International Division
8900 DeSoto Avenue
Canoga Park, California 91304
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $5.45 Microfiche $2.25
ANNUAL TECHNICAL PROGRESS REPORT
NUCLEAR SAFETY
CHARACTERIZATION OF SODIUM FIRES
AND
FAST REACTOR FISSION PRODUCTS
GOVERNMENT FISCAL YEAR 1975

The preceding Progress Report was AI-ERDA-13148.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Rockwell International
Atoms International Division
8900 DeSoto Avenue
Canoga Park, California  91304

CONTRACT: AT(04-3)-824
ISSUED: AUGUST 15, 1975
DISTRIBUTION

This report has been distributed according to the category, "LMFBR Safety," as given in the Standard Distribution for Unclassified Scientific and Technical Reports, TID-4500.
CONTENTS

<table>
<thead>
<tr>
<th>Program</th>
<th>ERDA Task No.</th>
<th>Project Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterization of Sodium</td>
<td>10</td>
<td>Characterization of Sodium Fires and Fission Products</td>
<td>5</td>
</tr>
<tr>
<td>Fires and Fission Products</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLES

1. LSM JET TEST DATA ......................................................... 9
2. Stationary Drop Burning Test Summary .................................. 20
3. Aerosol Leakage Test Results ........................................... 38
4. Test Summary ..................................................................... 43

FIGURES

1. Schematic of Laboratory Spray Modeling Test Apparatus .......... 7
2. Water Jet Test at 6 m/sec .............................................. 11
3. 5 vol % Alcohol-Water Jet Test at 6 m/sec ......................... 11
4. 34 vol % Alcohol-Water Jet Test at 6 m/sec ......................... 12
5. Sodium Jet Test at 8 m/sec ............................................. 12
6. Summary of Mean Drop Diameters for Various Test Liquids and Strike Plate Materials ..................................... 14
7. Determination of $K$ .................................................... 16
8. Determination of $K_H$ .................................................. 16
9. Determination of $K_V$ .................................................. 16
10. Schematic of Stationary Drop Test Apparatus ...................... 18
11. Stationary Sodium Drop ................................................ 21
12. Time Lapse Photograph of Burning Stationary Sodium Drop .......... 22
13. Schematic of Falling Drop Test Apparatus ........................... 22
14. Falling Sodium Drop Test ............................................. 24
15. Schematic of Gas Recirculation Test Apparatus .................... 24
<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.</td>
<td>Pressure Rise in 20 by 40 ft Vault When Injection Rate = (2 \times 10^5) cm Na/sec</td>
<td>28</td>
</tr>
<tr>
<td>17.</td>
<td>Schematic of HCDA Source Term Scoping Test Apparatus</td>
<td>28</td>
</tr>
<tr>
<td>18.</td>
<td>Aerosol Buoyant Bubble Rise Test Apparatus</td>
<td>30</td>
</tr>
<tr>
<td>19.</td>
<td>Noncondensible Bubble Rise</td>
<td>31</td>
</tr>
<tr>
<td>20.</td>
<td>90% Condensible Bubble</td>
<td>32</td>
</tr>
<tr>
<td>21.</td>
<td>Iron Powder (~44(\mu)) Used in Aerosol Buoyant Bubble Rise Tests</td>
<td>34</td>
</tr>
<tr>
<td>22.</td>
<td>Iron Powder Aerosol Collected After Buoyant Bubble Rise Test</td>
<td>34</td>
</tr>
<tr>
<td>23.</td>
<td>Aerosol Leakage Test Vessel</td>
<td>35</td>
</tr>
<tr>
<td>24.</td>
<td>Aerosol Leakage Sample Manifold</td>
<td>35</td>
</tr>
<tr>
<td>25.</td>
<td>Fall-Out Chamber</td>
<td>36</td>
</tr>
<tr>
<td>26.</td>
<td>Gas Volume Through Capillary Until Plugging Occurred</td>
<td>40</td>
</tr>
<tr>
<td>27.</td>
<td>Aerosol Fallout from Capillary Leakage Test</td>
<td>41</td>
</tr>
<tr>
<td>28.</td>
<td>Photograph of Induction Melting Furnace</td>
<td>46</td>
</tr>
<tr>
<td>29.</td>
<td>Diagram of Induction Furnace</td>
<td>46</td>
</tr>
<tr>
<td>30.</td>
<td>Crucible Being Heated by Induction Coil</td>
<td>47</td>
</tr>
<tr>
<td>31.</td>
<td>Crucible and Crucible Cover for Melting (\text{UO}_2)</td>
<td>47</td>
</tr>
<tr>
<td>32.</td>
<td>Exploding Wire Experiment</td>
<td>49</td>
</tr>
<tr>
<td>33.</td>
<td>Tilt Pour Skull Furnace</td>
<td>50</td>
</tr>
<tr>
<td>34.</td>
<td>Fragmentation of (\text{UO}_2) by Jets</td>
<td>50</td>
</tr>
</tbody>
</table>
I. PROJECT OBJECTIVES

1) Develop a computer program for calculating two-dimensional, transient natural convection phenomena, such as those arising from various postulated sodium spill accidents in LMFBR heat transfer vaults, head compartments, containment buildings, and secondary heat transfer systems.

2) Develop experimental programs and conduct tests that will characterize the behavior of sodium, sodium oxide, fuel, fission product, and other aerosols as they might be generated by various postulated LMFBR accidents.

3) Determine by analysis and experiment the generation and transport of these aerosols with respect to source (location, type, and configuration) release dispersal, agglomeration attenuation, and removal for the entire course of events associated with real and hypothetical accident conditions.

II. TECHNICAL PROGRESS DURING FISCAL YEAR 1975

The preliminary version of the SOMIX-1 Code was developed and is now under test. Computer runs showed that the code performance was satisfactory for all routines. The conversion of SOMIX-2 to cylindrical geometry was completed and excellent agreement was achieved with SOMIX-1 for low Grashof number cases.

*Consultant
A series of tests were conducted which provided verification of the analytical models used in SOMIX. These tests also provide fundamental principles for LMFBR heat transfer vault pipe rupture studies. Correlations were developed for the mean drop size and spatial distribution of drops resulting from an open-ended pipe jet, 2.38 cm ID, impinging on the bottom of a flat horizontal surface that is four pipe diameters above the nozzle. During this test series several different test fluids, including sodium, were used.

The burning characteristics of stationary and falling sodium drops were determined in tests conducted in 21 vol % O₂ in air, and at various water vapor concentrations.

The buoyant bubble rise test were conducted in two phases: (1) scoping tests to determine the characteristics of noncondensible and condensible bubbles rising in a column of water, and (2) aerosol tests to determine the attenuation of aerosols in condensible-noncondensible bubbles.

A series of tests were conducted in the STV using capillaries representative of the largest single straight-through leak paths for gas and particulates in an LMFBR reactor containment building. (This capillary would leak gas at the design rate of 0.1 vol % day at 10 psig.) Capillaries ranging in size from 0.053 to 0.157 cm ID were used during this test series. Aerosols of typical concentration (e.g., up to 18 μg/cc) were passed through the capillary to the outside environment to determine the aerosol attenuation factors due to capillary plugging.

UO₂ was melted by induction heating in a tungsten crucible. An apparatus for exploding UO₂ and U wires was set up and operated.

A series of preliminary tests were conducted of the release of uranium from burning sodium. Sodium uranate was dissolved in sodium which was ignited as a pool fire in air. The fraction of uranium released was <2.6 x 10⁻⁴.

A. SUBTASK A - SODIUM JET DISPERSAL TESTS

Liquid jet dispersal tests were conducted in the Laboratory Spray Modeling test apparatus (LSM) to determine the drop size and spatial distribution of drops resulting from an open jet impinging vertically on a horizontal surface. The LSM is an acrylic plastic chamber having the cubic dimension of 1,2 m.
test apparatus was fitted with a stainless steel bottom, an interchangeable lid (acrylic plastic, mild or stainless steel), an antichamber for sample removal, an atmosphere control system, and a jet column. The jet column consisted of a 30 l gas reservoir which was prepressurized to expel the test fluid, a 9.5 l liquid reservoir, and a U-tube which penetrated the LSM and was oriented vertically. The open end of the U-tube extended to an elevation of four pipe diameters below the strike plate (LSM lid). The LSM is shown schematically in Figure 1.

Figure 1. Schematic of Laboratory Spray Modeling Test Apparatus

Drop size and spatial distribution were determined at jet velocities ranging from 3 to 8 m/sec for water, mixtures of 5 and 34 vol % alcohol and water, and liquid sodium. During each of these tests a liquid sheet was formed by the jet upon impingement of the test liquid with the strike plate. Drops were then formed as the rim of the liquid sheet departed from the strike plate. Drop size was determined by sieve screening frozen droplets collected in liquid nitrogen (LN₂) filled dewars positioned radially within the LSM. Still photography was used to measure radial sheet formation, drop formation, and radial drop distribution.
The liquids under test in the LSM test series included water, 5 and 34 vol % alcohol-water mixtures, and liquid sodium at 150°C. These test fluids were chosen on the basis of their respective physical properties. The density and viscosity of each fluid were within 12% of each other, whereas the surface tension varied from 31 dyne/cm for 34 vol % alcohol-water mixture to 195 dyne/cm for Na. During the test series the jet velocity was varied from 3 to 8 m/sec and the effect on liquid sheet formation, drop size, and spatial distribution was determined for each of the test fluids. A summary of the jet dispersal test data is presented in Table 1. Summary discussions of each fluid test series are presented in the following subsections.

1. Water Jet Test Series

Water jet tests were conducted in the LSM with nozzle velocities of 3.0, 4.3, 5.2, and 6.0 m/sec. Throughout the test series it was observed that the mean drop size $D_{50}$ was not appreciably velocity dependent; $D_{50}$ ranged from 0.60 to 0.61 cm ±10%. As the velocity was increased from 3.0 to 6.0 m/sec, the radius of the liquid sheet increased by a factor of 1.45 (observed through an acrylic plastic lid). At a nozzle velocity between 5.2 and 6.0 m/sec, a portion of the vertical jet sheared away from the liquid jet at impact on the strike plate resulting in a spray of droplets, 0.27 cm mean diameter, which were ejected tangentially along the under surface of the strike plate. These sheared droplets had sufficient horizontal velocity to spray over a mean radius of 2.0 to 3.0 m. Similar jet shearing was observed in previous experiments. Figure 2 shows a typical view of the liquid sheet formed under the acrylic plastic lid at a nozzle velocity of 6.0 m/sec.

2. 5 vol % Alcohol-Water Mixture Tests

A mixture of 5 vol % alcohol and water was used as the second LSM test fluid. Nozzle velocities of 3.0, 4.3, 5.2, and 6.2 m/sec were used to determine sheet formation of the fluid and drop size upon impaction with an acrylic plastic strike plate. The mean drop size, $D_{50}$, observed with this test fluid varied from 0.63 to 0.73 ±10% cm diameter. As the jet velocity was increased from 3.0 to 6.2 m/sec, the radius of the liquid sheet formed under the strike plate increased from 46 to 79 cm, or a factor of 1.7. Again, as observed in the
<table>
<thead>
<tr>
<th>Test Liquid</th>
<th>Nozzle Velocity (m/sec)</th>
<th>Sheet Velocity at Edge (cm/sec)</th>
<th>Sheet Radius R (cm)</th>
<th>Maximum Mass Splash Radius R (cm)</th>
<th>Maximum Mass Fraction at R (cm)</th>
<th>D$_{\text{50}}$ at R (cm)</th>
<th>$\bar{D}_{\text{50}}$ Average (cm)</th>
<th>Lid Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>3.04</td>
<td>42.1</td>
<td>38</td>
<td>60</td>
<td>0.50</td>
<td>0.61</td>
<td>0.60</td>
<td>Lucite</td>
</tr>
<tr>
<td>Water</td>
<td>3.04</td>
<td>42.1</td>
<td>38</td>
<td>60</td>
<td>0.46</td>
<td>0.81</td>
<td>0.57</td>
<td>Lucite</td>
</tr>
<tr>
<td>Water</td>
<td>4.27</td>
<td>50.3</td>
<td>42</td>
<td>68</td>
<td>0.58</td>
<td>0.59</td>
<td>0.55</td>
<td>Lucite</td>
</tr>
<tr>
<td>Water</td>
<td>5.18</td>
<td>55.7</td>
<td>45</td>
<td>74</td>
<td>0.41</td>
<td>0.56</td>
<td>0.58</td>
<td>Lucite</td>
</tr>
<tr>
<td>Water</td>
<td>6.09</td>
<td>52.2</td>
<td>55</td>
<td>82</td>
<td>0.41</td>
<td>0.54</td>
<td>0.64</td>
<td>Lucite</td>
</tr>
<tr>
<td>Water</td>
<td>6.09</td>
<td>46.4</td>
<td>55</td>
<td>79</td>
<td>0.48</td>
<td>0.86</td>
<td>0.77</td>
<td>Lucite</td>
</tr>
<tr>
<td>+5 vol % Alcohol</td>
<td>3.04</td>
<td>16.9</td>
<td>37</td>
<td>46</td>
<td>0.53</td>
<td>0.76</td>
<td>0.86</td>
<td>Lucite</td>
</tr>
<tr>
<td>Alcohol</td>
<td>4.27</td>
<td>40.4</td>
<td>42</td>
<td>62</td>
<td>0.31</td>
<td>0.65</td>
<td>0.69</td>
<td>Lucite</td>
</tr>
<tr>
<td>Alcohol</td>
<td>5.24</td>
<td>44.8</td>
<td>48</td>
<td>71</td>
<td>0.42</td>
<td>0.82</td>
<td>0.74</td>
<td>Lucite</td>
</tr>
<tr>
<td>Alcohol</td>
<td>6.19</td>
<td>47.3</td>
<td>55</td>
<td>79</td>
<td>0.38</td>
<td>0.74</td>
<td>0.75</td>
<td>Lucite</td>
</tr>
<tr>
<td>Alcohol</td>
<td>6.19</td>
<td>30.1</td>
<td>55</td>
<td>71</td>
<td>0.37</td>
<td>0.80</td>
<td>0.68</td>
<td>Lucite</td>
</tr>
<tr>
<td>+34 vol % Alcohol</td>
<td>3.07</td>
<td>48.1</td>
<td>30</td>
<td>54</td>
<td>0.64</td>
<td>0.54</td>
<td>0.52</td>
<td>Lucite</td>
</tr>
<tr>
<td>Alcohol</td>
<td>4.32</td>
<td>55.9</td>
<td>34</td>
<td>62</td>
<td>0.42</td>
<td>0.67</td>
<td>0.63</td>
<td>Lucite</td>
</tr>
<tr>
<td>Alcohol</td>
<td>5.23</td>
<td>64.2</td>
<td>38</td>
<td>71</td>
<td>0.48</td>
<td>0.62</td>
<td>0.63</td>
<td>Lucite</td>
</tr>
<tr>
<td>Alcohol</td>
<td>6.34</td>
<td>53.4</td>
<td>43</td>
<td>71</td>
<td>0.27</td>
<td>0.54</td>
<td>0.59</td>
<td>Lucite</td>
</tr>
<tr>
<td>Test Liquid</td>
<td>Nozzle Velocity (m/sec)</td>
<td>Sheet Velocity at Edge (cm/sec)</td>
<td>Sheet Radius R (cm)</td>
<td>Maximum Mass Splash Radius R (cm)</td>
<td>Maximum Mass Fraction at R (cm)</td>
<td>D50 at R (cm)</td>
<td>D50 Average (cm)</td>
<td>Lid Material</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------</td>
<td>---------------------------------</td>
<td>--------------------</td>
<td>----------------------------------</td>
<td>-------------------------------</td>
<td>---------------</td>
<td>------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>+34 vol % Alcohol Water</td>
<td>6.34</td>
<td>53.4</td>
<td>43</td>
<td>71</td>
<td>0.41</td>
<td>0.72</td>
<td>0.63</td>
<td>Lucite</td>
</tr>
<tr>
<td>+34 vol % Alcohol Water</td>
<td>5.18</td>
<td>-</td>
<td>52</td>
<td>-</td>
<td>-</td>
<td>0.81</td>
<td>0.77</td>
<td>Mild Steel</td>
</tr>
<tr>
<td>+34 vol % Alcohol Water</td>
<td>5.23</td>
<td>-</td>
<td>45</td>
<td>-</td>
<td>-</td>
<td>0.72</td>
<td>0.71</td>
<td>Mild Steel</td>
</tr>
<tr>
<td>+34 vol % Alcohol Water</td>
<td>5.18</td>
<td>-</td>
<td>50</td>
<td>-</td>
<td>-</td>
<td>0.86</td>
<td>0.84</td>
<td>Stainless</td>
</tr>
<tr>
<td>+34 vol % Alcohol Water</td>
<td>5.23</td>
<td>-</td>
<td>38</td>
<td>-</td>
<td>-</td>
<td>0.73</td>
<td>0.75</td>
<td>Stainless</td>
</tr>
<tr>
<td>Na at 150°C</td>
<td>6.70</td>
<td>-</td>
<td>10-12*</td>
<td>1.9-2.5 m*</td>
<td>1.0</td>
<td>-</td>
<td>1.28</td>
<td>Mild Steel</td>
</tr>
<tr>
<td>Na at 150°C</td>
<td>6.90</td>
<td>-</td>
<td>10-12*</td>
<td>1.9-2.5 m*</td>
<td>1.0</td>
<td>-</td>
<td>1.27</td>
<td>Mild Steel</td>
</tr>
<tr>
<td>Na at 150°C</td>
<td>8.00</td>
<td>-</td>
<td>10-12*</td>
<td>1.9-2.5 m*</td>
<td>1.0</td>
<td>-</td>
<td>1.28</td>
<td>Mild Steel</td>
</tr>
<tr>
<td>Na at 150°C</td>
<td>8.05</td>
<td>-</td>
<td>10-12*</td>
<td>1.0-2.5 m*</td>
<td>1.0</td>
<td>-</td>
<td>1.32</td>
<td>Mild Steel</td>
</tr>
</tbody>
</table>

*Calculated minimum and maximum splash radius — average of all tests.
Figure 2. Water Jet Test at 6 m/sec

Figure 3. 5 vol % Alcohol-Water Jet Test at 6 m/sec
Figure 4. 34 vol % Alcohol-Water Jet Test at 6 m/sec

Figure 5. Sodium Jet Test at 8 m/sec
water jet tests a fraction of the liquid jet sheared from the strike plate upon impact at the higher velocities but the mass fraction involved in this tangential spray increased from 4 to 10% with an average drop size of 0.27 cm diameter. Figure 3 shows a typical view of the liquid sheet formed on the underside of an acrylic plastic strike plate with a 5 vol % alcohol-water mixture at 6.2 m/sec nozzle velocity.

3. 34 vol % Alcohol-Water Jet Tests

To determine the effect on drop size using a test fluid of very low surface tension, a mixture of 34 vol % alcohol and water was used in the LSM at nozzle velocities of 3.0, 4.4, 5.3, and 6.4 m/sec. The sheet formed by the jet upon impaction increased from a mean radius of 54 cm at 30 m/sec to 71 cm at 6.4 m/sec. The mean drop diameter, $D_{50}$, ranged from 0.52 to 0.63 cm ±10% during these tests. Tangential ejected drops from the jet impaction point increased from a mean fraction of 4% (water) to ~35% as a result of the decreased surface tension of the test fluid. Figure 4 shows the radial distribution of the sheet formed on the underside of the strike plate.

4. Sodium Jet Tests

Sodium jet tests were conducted in the LSM in a 0% $O_2$ atmosphere to determine the drop size and sheet formation of a sodium jet of velocities ranging from 6.5 to 8.0 m/sec impinging on a mild steel strike plate. Due to the high surface tension of the test fluid and the nonwetting characteristics of sodium at test temperatures (150°C), the liquid sheet formed by the jet traveled approximately 15 cm before departure of the fluid from the strike plate. Consequently the drops formed upon departure maintained substantial horizontal velocity (3.6 m/sec to 4.8 m/sec). The mean drop diameter, $D_{50}$, observed on these tests ranged from 1.28 to 1.32 cm diameter ±10%. Figure 5 shows the sodium drops formed in the LSM at a nozzle velocity of 8.0 m/sec.

5. Summary of LSM Test Data

Both water and the 34 vol % alcohol-water mixture fluids were used with different strike plate materials to determine the effect on drop size as a function of increased drag coefficient on the liquid sheet by various strike plate materials, (e.g., lucite, stainless steel, cold rolled mild steel, and nonwettable lucite.) Each strike plate material yielded drops of increasing diameter at identical
Figure 6. Summary of Mean Drop Diameters for Various Test Liquids and Strike Plate Materials
nozzle jet velocities, thus indicating the presence of a drag coefficient (wetting factor) on drop size. The drop size measured on the above materials for water was 0.56, 0.84, 0.64, and 1.16 cm diameter respectively. A summary of mean drop diameter for various test liquids and strike plate materials is shown in Figure 6.

6. Theoretical Correlation of LSM Test Data

Theoretical correlations which may be used to predict the drop size resulting from a vertically oriented jet impinging on a flat horizontal surface have been derived. These correlations require the experimental determination of empirical constants. These correlations are presented as follows:

Heisler Correlation —

\[ \bar{D}_{50} = K_D \left( \frac{\sigma}{\eta U_0} \right)^a \left( \frac{\rho}{\rho_g} \right)^{1/6} \left( \frac{\eta_L}{\eta_R} \right)^{1/6} Re^{b} \text{pipe}, \] ...

or

\[ \bar{D}_{50} = K_H D \left( \frac{\sigma}{\eta U_0} \right)^c \left( \frac{\rho}{\rho_g} \right)^{1/6} \left( \frac{\eta_L}{\eta_R} \right)^{1/6} Re, Re, \] ...

Vaughan Correlation —

\[ \delta = K_V (1/8) \left( \frac{D^2}{r} \right) \left( \frac{\bar{U}_o}{U} \right) \] ...

where

\[ \bar{D}_{50} = \text{mean drop diameter (cm)} \]
\[ \sigma = \text{surface tension (dyne/cm)} \]
\[ \eta, \eta_L, \eta_R = \text{viscosity of fluid or reference fluid (cP)} \]
\[ U_0, \bar{U}_o = \text{nozzle velocity (m/sec)} \]
\[ U = \text{velocity at liquid sheet at departure from strike plate (m/sec)} \]
\[ r = \text{radius of liquid sheet at departure from strike plate (cm)} \]
Figure 7. Determination of $K_H$

$K_H = \text{constant (Heisler)}$

$\delta_{50} = K_H \frac{D}{(\sigma/\eta L u_0)^{1/4}} \left( \frac{\rho L}{\rho C} \right)^{1/6} \left( \frac{\eta L}{\eta R} \right)^{1/6} Re$

Figure 8. Determination of $K_V$

Figure 9. Determination of $K_V$

AL-ERDA-13155

16
K, K_H, K_V = empirical constant

δ = thickness of liquid sheet at departure from
strike plate [assumed = to D_{50} (cm)]

The respective values of K, a, b, K_H, c, and K_V were experimentally
determined to be 1.6 \times 10^{-4}, 0.25, 0.75, 2.47, 0.25, and 4.06 respectively.
The variance of K, K_H, and K_V were respectively ±5%, ±5%, and ±16%. Figures 7 and 8 and 9 show these functions vs mean drop diameter.

B. SUBTASK B - STATIONARY SODIUM DROP TESTS

Burning characteristics of stationary sodium drops were determined in the
Laboratory Drop Modeling test apparatus (LDM). This test apparatus consists
of an acrylic plastic pipe 30 cm ID by 1.8 m long with aluminum end plates. A
clam-shell heater is connected to an extension rod which extends through the
lower plate and is provided with an argon purge line. The loop that suspends
the sodium drop is constructed of a 0.68 mm diameter Alumel wire formed into
a 0.55 cm diameter loop. This wire, along with a thermocouple, is positioned
into a ceramic insulator and mounted in the LDM. Test samples were prefabricated in a dry box and retained for use during the test series. A schematic
of the stationary drop test apparatus is shown in Figure 10.

During a stationary drop burning test, a drop sample was positioned in the
LDM, covered with the clam-shell heater and maintained in an inert atmosphere
during the preheat stage. As the temperature of the drop approached test conditions (e.g., 430 or 540°C), the heater was removed and the drop allowed to
ignite spontaneously in a 21 vol % O_2 atmosphere. Observations and measurements made during each test included: (1) liquid sodium drop temperature, (2)
flame temperature, (3) aerosol release fraction, (4) species of aerosol, (5) type
of ignition, (6) surface burning phenomena, (7) burning time, and (8) humidity.

A total of 24 stationary sodium drop burning tests were conducted in the
2-m LDM test apparatus. From these tests it was observed that the burning rate
of stationary sodium drops was relatively constant (0.008 gm/sec) for both high
and low humidity 21 vol % O_2 environments. A slight dependency of combustion product release fraction as a function of humidity was observed, 88.5% release
at water vapor content of >10,000 ppm and 76.1% release at <1,000 ppm. When
Figure 10. Schematic of Stationary Drop Test Apparatus
air circulation was provided around the burning sodium drop (produced by an upward directed fan), the burning rate increased by a factor of 40. Three drop burning tests conducted with water vapor content <1,000 ppm exhibited low burning rates which were attributed to inert gas buildup in the LDM column, see Table 2. Figure 11 (a, b, c, d, and e) show front and back views (taken at 5 sec intervals) of a stationary burning sodium drop in air.

Figure 12 is a sequence of three photos of a single sodium drop taken through a macro lens at 6 cm distance. The top view shows burning ignition, the second view (middle) shows the formation of sodium oxides on the surface of the drop which provide a localized cold surface. As the sodium drop is at the boiling point, 888°C, during its burning period, the cold surfaces caused by the formation of sodium oxides produce localized hot spots on other surface areas of the drop. The protrusions shown on the right side of the middle photo and the front-top of the lower view are a result of these hot spots lowering the surface tension of the sodium.

1. **Falling Sodium Drop Tests**

The falling sodium drop tests were conducted in an air-filled (21 vol % O₂) chamber also designated the LDM, except this apparatus is 30 cm ID by 5.4 m long. The drop generating device consists of a 0.46 cm ID tube, 7.6 cm long. Approximately 0.2 gm of solid sodium is loaded into each drop chamber and preweighed. The drop chamber is loaded into a 2.5 by 30 cm long preheat tube. A pressure-vacuum manifold is connected to the top of the drop chamber for external control of the atmosphere above the sodium and to provide pressure exchange to discharge the drop. The preheat tube is surround with a clamshell heater to heat the drop chamber tube by radiation. An argon purge is also provided to the preheat tube at the bottom and atmospheric venting through the top lid. A photocell transmitter-receiver is positioned ~13 cm below the bottom of the preheat tube, in the path of the falling sodium drop, to actuate strobe lights.

Preparations required to conduct a falling drop test are: (1) connect the drop chamber to the atmosphere control manifold, (2) initiate an argon purge in the preheat tube, (3) insert the drop chamber into the preheat tube (the lower end of the tube is closed with a removable cap), and (4) preheat the drop chamber to 430 or 540°C. As test temperatures are approached, still cameras
<table>
<thead>
<tr>
<th>Test Number</th>
<th>LDM Humidity (ppm)</th>
<th>Sodium Drop Weight Initial (gm)</th>
<th>Initial Preheat Temperature (°C)</th>
<th>Sodium Drop Volume at 888°C (cc)</th>
<th>Theoretical Diameter at 888°C (cm)</th>
<th>Release Fraction (wt %)</th>
<th>Na O2 in Released Aerosol (%)</th>
<th>Burning Rate (gm/sec x 10^-3)</th>
<th>Surface Temperature during Burning (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>11,200</td>
<td>0.174</td>
<td>427</td>
<td>0.235</td>
<td>0.766</td>
<td>87.3</td>
<td>-</td>
<td>8.5</td>
<td>1358</td>
</tr>
<tr>
<td>9</td>
<td>12,000</td>
<td>0.113</td>
<td>427</td>
<td>0.153</td>
<td>0.664</td>
<td>87.8</td>
<td>-</td>
<td>7.2</td>
<td>1302</td>
</tr>
<tr>
<td>11</td>
<td>12,000</td>
<td>0.129</td>
<td>427</td>
<td>0.176</td>
<td>0.695</td>
<td>87.6</td>
<td>-</td>
<td>8.3</td>
<td>1302</td>
</tr>
<tr>
<td>12†</td>
<td>14,000</td>
<td>0.130</td>
<td>427</td>
<td>0.175</td>
<td>0.695</td>
<td>90.7</td>
<td>-</td>
<td>36.5</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>14,000</td>
<td>0.146</td>
<td>427</td>
<td>0.197</td>
<td>0.723</td>
<td>88.4</td>
<td>-</td>
<td>313.0†</td>
<td>888</td>
</tr>
<tr>
<td>14†</td>
<td>13,800</td>
<td>0.128</td>
<td>427</td>
<td>0.174</td>
<td>0.692</td>
<td>89.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>3,600</td>
<td>0.087</td>
<td>427</td>
<td>0.118</td>
<td>0.609</td>
<td>44.3</td>
<td>100</td>
<td>3.6</td>
<td>1140</td>
</tr>
<tr>
<td>16</td>
<td>2,100</td>
<td>0.128</td>
<td>427</td>
<td>0.174</td>
<td>0.692</td>
<td>79.9</td>
<td>-</td>
<td>0.05</td>
<td>1225</td>
</tr>
<tr>
<td>17</td>
<td>620</td>
<td>0.223</td>
<td>427</td>
<td>0.301</td>
<td>0.832</td>
<td>79.0</td>
<td>-</td>
<td>1.3</td>
<td>1181</td>
</tr>
<tr>
<td>18</td>
<td>620</td>
<td>0.186</td>
<td>427</td>
<td>0.251</td>
<td>0.783</td>
<td>79.6</td>
<td>-</td>
<td>0.95</td>
<td>1245</td>
</tr>
<tr>
<td>19</td>
<td>620</td>
<td>0.166</td>
<td>427</td>
<td>0.225</td>
<td>0.755</td>
<td>68.5</td>
<td>-</td>
<td>6.8</td>
<td>1245</td>
</tr>
<tr>
<td>20</td>
<td>620</td>
<td>0.124</td>
<td>427</td>
<td>0.169</td>
<td>0.686</td>
<td>74.3</td>
<td>-</td>
<td>6.1</td>
<td>1100</td>
</tr>
<tr>
<td>21</td>
<td>620</td>
<td>0.092</td>
<td>538</td>
<td>0.125</td>
<td>0.620</td>
<td>-</td>
<td>71.2</td>
<td>4.3</td>
<td>1100</td>
</tr>
<tr>
<td>22</td>
<td>620</td>
<td>0.125</td>
<td>538</td>
<td>0.169</td>
<td>0.686</td>
<td>75.6</td>
<td>85.2</td>
<td>7.9</td>
<td>1217</td>
</tr>
<tr>
<td>23</td>
<td>620</td>
<td>0.099</td>
<td>538</td>
<td>0.133</td>
<td>0.634</td>
<td>-</td>
<td>86.3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Surface temperature measured with optical pyrometer
†Forced convection supplied by fan.
Figure 11. Stationary Sodium Drop

a. At 1 sec  
b. At 6 sec  
c. At 11 sec  
d. At 16 sec  
e. At 21 sec
Figure 12. Time Lapse Photograph of Burning Stationary Sodium Drop

Figure 13. Schematic of Falling Drop Test Apparatus
(2 each) are actuated and the preheat tube cover removed. As the drop is released, the strobe lights are actuated providing a photo of the drop as it leaves the preheat tube. The second camera views the drop during the entire fall period (1.06 sec) and provides a streak image indicating initiation of combustion as a function of test apparatus height. Post-test analysis is made of the sodium to determine a mass balance (e.g., sodium retained in the drop tube, and that captured in a liquid-nitrogen-filled dewar). From these data, time to ignition, burning time, and rate are determined. A schematic diagram of the falling drop test apparatus is shown in Figure 13.

The falling sodium drop tests were conducted in the LDM having an overall height of 3.6 and 5.5 m to determine the burning rate of sodium drops in a 21 vol % air atmosphere containing a water concentration ≥10,000 ppm. Still photographs were taken of the sodium drop as it was released from the preheat tube to determine the initial drop size (at ∼430 to 480°C). Still streak photography was used to determine the point in flight at which ignition first occurred and where complete surface burning occurs. Figure 14 shows these burning characteristics during the free fall period in the 5.5 m high test apparatus. Although analysis is incomplete, initial indications show that when full ignition occurs the burning rate is ∼0.17 gm/sec.

2. Sodium Jet Air Recirculation Tests

The sodium jet air recirculation tests are to be conducted in FY 1976 providing experimental data on the magnitude of gas recirculation resulting from a 3 cm diameter jet of sodium impinging vertically on a horizontal surface. The tests will be conducted in the LTV which will be modified to conform to a right circular cylinder having the dimensions 3.0 m OD by 3.0 m high. Modifications to the LTV to support this test series include adding flat circular plates to form a floor and ceiling in the LTV.

The sodium preheat and injection system is located external to the LTV and consists of a 40 cm diameter by 2 m high, 100 psig at 593°C pressure coded vessel which can contain 136 kg of sodium. The outlet of the preheat tank penetrates the LTV, and expands to a vertical 50 cm diameter tube. This tube is positioned on the vertical centerline of the LTV and becomes the jet nozzle. The gas recirculation test apparatus is shown schematically in Figure 15.
Figure 14. Falling Sodium Drop Test

Figure 15. Schematic of Gas Recirculation Test Apparatus
A gas recirculation test will be initiated by preheating sodium in the preheat tank, then transferring ~25 kg of 540°C sodium into the test vessel at a nozzle velocity of 3 m/sec. The jet velocity is obtained by pressurizing the preheat tank and maintaining the drive pressure during the transfer period. Recirculation flow patterns will be measured during each test at various positions in the LTV with fast response thermocouples. The radial distribution of sodium drops formed as the sheet departs from the ceiling and the respective size will also be measured. All gas recirculation tests will be conducted at a test velocity of 3 m/sec and in nitrogen atmospheres containing 0 and 2 vol % \( \text{O}_2 \).

C. SUBTASK C – SOMIX CODE DEVELOPMENT

In the first quarter of this fiscal year, the hydrodynamics portions of SOMIX-1 were completed. Computer comparisons were then made with the experimental and calculational results of Torrance. The comparisons were taken up to incipient turbulent flow \( (N_{Gr} = 4 \times 10^8) \). Good agreement was achieved for all cases studied.

During this same period, optimization studies of code running times were completed. The optimization studies proceeded along two directions. First, a second order extrapolation procedure was applied to the elliptic stream function equation. A substantial reduction in the number of iterations required for convergence to a final solution was obtained, typically one-half to one-third as many iterations as were required without optimization. A 30% reduction in running time was achieved. Second, the recently developed Fast Fourier Transform method was applied to the solution of the elliptic stream function equation. With the Fast Fourier Transform method an additional 40% decrease in computer running time was achieved as compared to the second order extrapolation procedure.

During the second quarter, code development activities were directed toward the sodium spray breakup and droplet combustion routines.

A literature search indicated that, in general, the breakup of sheets into drops is due to the formation of wavelike perturbations on the surface of the sheet under the action of turbulent eddies, pipe vibrations, and the like. These wavelike perturbations grow under the action of aerodynamic forces as they
move down the sheet, resulting in violent flapping of the leading edges, much as a flag flaps in a breeze, with subsequent disintegration of the sheet into drops.

A combination of dimensional and theoretical analysis of sheet breakup suggested that the factors which affect drop diameter can be collected into a single relationship of the following form:

\[
\frac{d}{D} \propto \frac{\sigma}{\eta_L U} \delta \left( \frac{\rho_L}{\rho_g} \right)^{1/6} \left( \frac{\eta_L}{\eta_r} \right)^{1/6} f(Re_{\text{pipe}}) \quad \ldots (4)
\]

where

- \( \sigma \) = liquid surface tension
- \( \eta_L \) = liquid viscosity
- \( U \) = liquid discharge velocity
- \( \rho_L \) = liquid density
- \( \rho_g \) = gas density
- \( \eta_r \) = reference viscosity (e.g., of the test fluid)
- \( Re_{\text{pipe}} \) = Reynolds number based on the pipe diameter and liquid discharge velocity.

The function \( f(Re_{\text{pipe}}) \) correlates with the viscous drag exerted by the fluid on the ceiling. \( D \) is a suitable characteristic dimension of the opening.

For fan sprays, theory and test show that \( \delta = 1/3 \); for two jets impinging on each other at an angle of 180°, \( \delta = 1/4 \). For the pipe rupture studies, the constant of proportionality and the exponent \( \delta \) have been determined experimentally for one set of jet splash tests using jets of varying velocity and liquids with surface tension equal to or less than that of water. The results of the initial sodium spray breakup studies correlated against Equation 1 in the form.

\[
\frac{d}{D} = 1.6 \times 10^{-4} \left( \frac{\sigma}{\eta_L U} \right)^{1/4} \left( \frac{\rho_L}{\rho_g} \right)^{1/6} \left( \frac{\eta_L}{\eta_r} \right)^{1/6} (Re_{\text{pipe}})^{3/4} \quad \ldots (5)
\]

A literature review of droplet combustion in low oxygen atmospheres indicated that sodium drop burning can be expressed in terms of Frossling's equation.
\[ \dot{M}_M = \dot{M}_S (1 + A \text{Re}^{1/2} \text{Pr}^{1/3}) \]  \hspace{1cm} \ldots (6)

where

\begin{align*}
\text{Re} & = \text{Reynolds number based on drop diameter and gas properties} \\
\text{Pr} & = \text{Prandtl number based on gas properties}
\end{align*}

Frossling's equation shows that the burning rate of a moving drop, \( \dot{M}_M \), is expressible in terms of the burning rate of a stationary drop, \( \dot{M}_S \), augmented by a function which takes into account the increased burning due to forced convection flow. The burning rate, \( \dot{M}_S \), of a stationary drop can be calculated from fundamental mass transfer principles. The augmentation factor is a function of drop diameter and velocity.

In the following quarter, the sodium drop drag and low oxygen (<2%) combustion models were completed. The drop drag routine, using an offset chopped cosine drop distribution, was programmed into SOMIX-1 and checked on the timeshare computer. It was found to work satisfactorily.

During this same period, an approximate conversion of SOMIX-2 to cylindrical geometry was obtained. Computer runs were made with a Grashof number \( (N_{\text{Gr}}) \) of \( 10^{-5} \) as a trial problem. The runs were numerically stable, but the results did not correspond to those obtained with SOMIX-1. Work was started on a more rigorous conversion of SOMIX-2 to cylindrical geometry.

During the final quarter, the oxygen mass transport equation was incorporated into SOMIX-1, signalizing completion of the preliminary version of the program. A number of computer runs of the entire SOMIX-1 program were completed with indication of satisfactory performance of all the routines. One of these runs comprised a relatively large sodium injection rate (200,000 cc/sec) in a relatively large vault (20 ft high by 40 ft wide). The results of this run are shown in Figure 16. In all cases, the code performed satisfactorily. Work has been started on programming SOMIX-1 for the ERDA computer center at Berkeley. The program will then be accessible to various ERDA contractors concerned with LMFBR safety analysis.
Figure 16. Pressure Rise in 20 by 40 ft Vault When Injection Rate = $2 \times 10^5$ cm Na/sec

Figure 17. Schematic of HCDA Source Term Scoping Test Apparatus
D. SUBTASK D - BUOYANT BUBBLE RISE TESTS

The Buoyant Bubble Rise Tests were conducted in two phases: (1) scoping tests to determine the characteristics of condensible and noncondensible bubbles rising in a water column, and (2) aerosol tests to determine the attenuation of aerosols in condensible and noncondensible bubbles. The test apparatus used in the scoping tests consisted of a 30-cm diameter by 2 m high acrylic plastic tube. The bottom plate of the test apparatus was fitted with inlet gas tubes through which gas could be introduced into a balloon. Still and motion pictures were taken of the buoyant bubble during its rise to the surface of the column. A schematic drawing of the scoping test apparatus is shown in Figure 17. The test apparatus used with the aerosol buoyant bubble test series was comprised of a 25-cm ID acrylic plastic tube (2.5 cm wall thickness) by 40 cm long (see Figure 18). A 2.5-cm ID tube, containing a rupture diaphragm is mounted on the bottom plate of the water column assembly. The aerosol generator, water check valve, and associated piping to the solenoid valve is filled with air at atmospheric pressure. Upstream from the solenoid valve is a pressure relief valve, rupture diaphragm, and a steam reservoir. The ratio of condensible and noncondensible gases introduced into the test chamber is controlled by increasing the time the solenoid valve is open, maintaining constant steam pressure on the upstream side.

Aerosols are introduced into the bubble as the gas mixture passes through a screen containing 40 μ diameter metal oxides. Preliminary tests were conducted to determine the quantity of aerosols that would be introduced into the bubble as a function of pressure and valve actuation time.

Buoyant noncondensible bubbles released in a 2 m water column exhibited a quick transformation from a spherical geometry to a turbulent surface configuration. After a short period of bubble rise, the bubble formed a hemispheric dome top surface area with a flat turbulent bottom. The bubble shown in Figure 19 sheared into two bubbles, each of which exhibits the above characteristics. As the bubble broke the surface, small jets were observed rising from the underside of the bubble and jetting into the cover gas space. The above tests were performed with noncondensible gases released at ambient temperatures.

AI-ERDA-13155
Figure 18. Aerosol Buoyant Bubble Rise Test Apparatus

AI-ERDA-13155

30
Figure 19. Noncondensible Bubble Rise
Figure 20. 90% Condensible Bubble
Further tests were conducted in the scoping bubble test apparatus with various ratios of condensible to noncondensible gas mixtures as shown in Figure 20. These photos show the history of a 20-cm diameter bubble containing ~ 90% condensible steam (at 175°C) and 10% noncondensible air. Results of these tests show that the condensible gases condensed within 32 msec.

Reduction of the test data from the buoyant bubble aerosol tests is incomplete, but preliminary indications show substantial aerosol attenuation results from collapse of the bubble. Figure 21 is a photomicrograph of the iron powder (~44μ diameter) used in these tests. Figure 22 is the aerosol collected in the gas region after release of a steam-air bubble in the buoyant bubble test apparatus.

High speed photography was used to show the time history of a bubble.

E. SUBTASK E - AEROSOL LEAKAGE

The first series of preliminary tests were conducted using a 61-cm ID by 148-cm high test vessel to contain the required aerosol and environment. As shown in Figure 23, nozzles have been installed in the vessel for atmospheric control and sampling. Inside the vessel is a sodium burn pot to produce the required aerosol concentration. Also attached to the vessel is an optical device which indicates the start of burning and aids in estimating the quantity of aerosol produced during the test.

For this series of tests, the capillaries* were initially installed vertically at the upper portion of the vessel where the particulates had to pass upward through a 0.5 cm tube and a ball valve before entering the capillary. The gas flow rate and total volume of gas passing through the capillary is monitored by the sampling manifold. The aerosol concentration in the vessel is determined by periodically passing a known volume of gas through a filter and analyzing the collected material.

The sampling manifold which is attached to the capillary, as shown in Figure 24, is composed of a differential pressure gauge, differential pressure

*Representative of the largest single, straight through leak in the reactor containment building. This capillary would leak gas at the design leak rate, (i.e., 0.1 vol %/day at 10 psi).
Figure 21. Iron Powder (~44μ) Used in Aerosol Buoyant Bubble Rise Tests

Figure 22. Iron Powder Aerosol Collected After Buoyant Bubble Rise Test
Figure 23. Aerosol Leakage Test Vessel

Figure 24. Aerosol Leakage Sample Manifold

1. GAUGE, PRESSURE DIFFERENTIAL
2. TRANSDUCER, PRESSURE
3. FILTER
4. FLOWMETER
5. WET TEST METER
6. CAPILLARY
Figure 25. Fall-Out Chamber
transducers, filters, flowmeter, and wet test meter. The differential pressure
gauge is used to calibrate the pressure transducer which is mounted across the
filters and to provide visual observation of the filter condition during the testing
period. In view of the possibility of a plugged filter, a backup filter is mounted
in parallel with the No. 1 filter. Should filter plugging occur, that particular
filter is isolated from the flow system and the second filter brought into ser-
vice. All valves from the vessel to the filters are of the ball valve type to
reduce plugging between the capillary and filter.

The pressure transducer mounted between the flowmeter and wet test meter
is used to measure the gas flow rate. The flowmeter is used to visually observe
the flow rate, and the wet test meter to obtain the total volume of gas passing
through the capillary.

In later tests, a fallout chamber was used as an aid in observing the parti-
culates which penetrated the capillary. Such a device is shown in Figure 25. The
chamber body and tray are made of Plexiglas. Microscope cover slips are
mounted on the tray and are used to collect a portion of the fallout particulates
for analysis. A filter or an impactor can be installed at the chamber outlet to
collect the particulates which do not settle on the tray or plate-out on the
chamber wall.

The test articles are made from capillary tubing and mounted in 0.58 cm
steel tubing 7.6 cm in length. The 0.053- and 0.081-cm ID tubing are mounted
in pairs inside the 0.58 cm tubing for increased initial flow. All capillaries
greater than 0.081 cm ID were mounted individually.

All tests were conducted in an air atmosphere containing 8000 ppm water
vapor or greater, except those tests as noted in Table 3. Excluding one test,
25 gm of sodium were placed in the pot and burned to completion to produce the
aerosol. Periodically, aerosol samples were taken to determine the aerosol
concentration in the vessel. The pressure in the vessel varied from ~28 to
35 cm water, and the pressure differential across the capillaries from 0 to
28 cm water. The vessel pressure was maintained constant by adding air to the
vessel as air was removed during sampling.

AI-ERDA-13155
37
<table>
<thead>
<tr>
<th>Capillary ID (cm)</th>
<th>Length (cm)</th>
<th>Aerosol Concentration (g/cc)</th>
<th>Flow Through Capillary (l)</th>
<th>Plug Mass (mg)</th>
<th>Time to Plug (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.052</td>
<td>4.9</td>
<td>15 to 11</td>
<td>~0.06</td>
<td>0.65 to 0.9</td>
<td>0.1 to 0.15</td>
</tr>
<tr>
<td>0.052</td>
<td>4.9</td>
<td>12.5 to 9.5</td>
<td>0.12</td>
<td>1.3 to 1.5</td>
<td>2.2 to 2.9</td>
</tr>
<tr>
<td>0.052</td>
<td>4.9</td>
<td>10 to 7</td>
<td>0.14</td>
<td>1.0 to 1.4</td>
<td>1.5 to 3.1</td>
</tr>
<tr>
<td>0.052</td>
<td>4.9</td>
<td>4.2 to 2.8</td>
<td>0.25</td>
<td>0.7 to 1.0</td>
<td>2.9 to 4.3</td>
</tr>
<tr>
<td>0.052</td>
<td>4.9</td>
<td>1.3 to 0.9</td>
<td>1.5</td>
<td>1.4 to 1.9</td>
<td>~25</td>
</tr>
<tr>
<td>0.052</td>
<td>4.9</td>
<td>1.9 to 0.047</td>
<td>163</td>
<td>(did not plug)</td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td>7.6</td>
<td>~5.8</td>
<td>0.16</td>
<td>~0.93</td>
<td>~0.3</td>
</tr>
<tr>
<td>0.08</td>
<td>7.6</td>
<td>~4.4</td>
<td>0.20</td>
<td>~0.88</td>
<td>1.1 to 1.5</td>
</tr>
<tr>
<td>0.08</td>
<td>7.6</td>
<td>1.5 to 1.25</td>
<td>1.07</td>
<td>1.5</td>
<td>6.5 to 7.5</td>
</tr>
<tr>
<td>0.08</td>
<td>7.6</td>
<td>0.26 to 0.17</td>
<td>5.55</td>
<td>1.3</td>
<td>21 to 31</td>
</tr>
<tr>
<td>0.08</td>
<td>7.6</td>
<td>0.13 to 0.0001</td>
<td>57</td>
<td>(did not plug)</td>
<td></td>
</tr>
<tr>
<td>0.107</td>
<td>3.8</td>
<td>2.1 to 3</td>
<td>5.5</td>
<td>14.3</td>
<td>10 to 14</td>
</tr>
<tr>
<td>0.107</td>
<td>7.6</td>
<td>0.75 to 1.6</td>
<td>17</td>
<td>19.4</td>
<td>33 to 36</td>
</tr>
<tr>
<td>0.107</td>
<td>3.8</td>
<td>0.4 to 0.7</td>
<td>19.75</td>
<td>9.5</td>
<td>~39</td>
</tr>
<tr>
<td>0.107</td>
<td>7.6</td>
<td>20 to 2.5</td>
<td>29</td>
<td>(did not plug)</td>
<td></td>
</tr>
<tr>
<td>0.107</td>
<td>7.6</td>
<td>0.14 to 0.0001</td>
<td>1550</td>
<td>(did not plug)</td>
<td></td>
</tr>
<tr>
<td>0.132</td>
<td>3.8</td>
<td>9 to 9.8</td>
<td>10</td>
<td>92</td>
<td>23 to 24</td>
</tr>
<tr>
<td>0.132</td>
<td>7.6</td>
<td>1.3 to 6.2</td>
<td>30.5</td>
<td>95</td>
<td>39 to 41</td>
</tr>
<tr>
<td>0.157</td>
<td>7.6</td>
<td>15 to 18</td>
<td>3.5</td>
<td>58</td>
<td>4</td>
</tr>
<tr>
<td>0.157</td>
<td>7.6</td>
<td>8 to 21</td>
<td>68</td>
<td>(did not plug)</td>
<td></td>
</tr>
</tbody>
</table>

*Initial water vapor in the vessel atmosphere was 1300 ppm. Other tests conducted in atmospheres containing 8000 ppm H₂O and greater.*
The results of the tests are shown in Table 3. The data in the table are listed as to the capillary size, the aerosol concentration in the vessel during the period the gas from the vessel was flowing through the capillary, the quantity of gas which passed through the capillary prior to plugging, the mass of particulates which entered the capillary prior to plugging, and the time to plug. The aerosol concentration in the vessel was determined by analyzing the particulates collected on "metrical" filter paper. The quantity of gas passing through the capillary was read directly from the wet test meter. Values of the plug mass were obtained analytically since a mass balance was not attempted at this time. The plug mass was obtained by plotting the vessel aerosol concentration and gas flow rate through the capillary for the sample time period involved and integrating the volume of gas passing through the capillary and the aerosol concentration with time. The time data shown in the table indicates the periods in which 90 to 95% of the total gas volume had passed through the capillary and when the flow rate had reduced to zero.

A plot was made of the total gas volume which passed through the capillary prior to plugging vs the vessel aerosol concentration. This plot is shown in Figure 26. Although the data are incomplete, the plot indicates that the gas volume vs aerosol concentration is predictable for various capillary diameters in air atmospheres of $\geq 8000$ ppm $H_2O$ vapor.

Visual observations of the capillary indicated that plugging occurred primarily at the entrance of the 0.053 to 0.107 diameter capillaries when the aerosol concentration was 1 $\mu g/cc$ and greater. Observations also showed that the majority of the particles which penetrated the capillaries remained in the vertical 0.63 cm tubing adjacent to the capillary, thus indicating that the particles were too large to be carried along with the air stream to the filter.

In order to observe the particulates which penetrate the capillaries, additional tests were conducted with the capillaries installed in one of the lower vessel ports. In these tests, the capillaries were installed with the capillary entrance mounted flush with the vessel wall. Figure 25 shows the mounting of the fallout chamber to the capillary. The results of a test using a 0.107 capillary are shown in Figure 27. This cover slip had been installed 13 cm from the capillary exit. Viewing the cover slip through a microscope at 40x shows that the particles range from $\sim 50$ to 1350 $\mu$. The particulate concentration in the
Figure 26. Gas Volume Through Capillary Until Plugging Occurred
vessel during this time period ranged from \( \sim 1 \) to 6 \( \mu g/cc \). Data from previous tests have shown that the average aerodynamic diameter of the aerosol in the vessel would be between 3 and 5 \( \mu m \).

Tests conducted in an atmosphere containing 1300 ppm H\(_2\)O (relative humidity of \( \sim 5\% \)) produced no visible capillary plugging over the time period of the test. However, work done by others at Atomics International has shown that the 0.635 cm OD tubing exhibited entrance plugging as a result of sampling sodium aerosols produced in 2 vol \% O\(_2\) atmospheres containing 1000 ppm H\(_2\)O. The aerosol sampling was performed at 0.6 \( \ell/min \) gas flow through tubes ranging from 15 to 61 min length. During these tests, the entrance plugging time ranged from 10 to 180 min.

It appears, from the Reynolds numbers of these experiments, that the flow may be either laminar or turbulent, and hence that theories of diffusional deposition based on laminar flow may have limited applicability. Observations of what appeared to be inertial deposition at the leak entrances suggested making estimates of the Stokes parameter for representative aerosol particles, this being a dimensionless number that measures the effect of particle inertia in causing particle trajectories to depart from streamlines. Since the values found were moderate or large (of the order of 1 to 10), there is no manifest anomaly in the observations.
F. SUBTASK F - FUEL AND FISSION PRODUCT RELEASE FROM BURNING SODIUM

I. Experimental

A Test Plan (TP 707-130-014) was prepared which described the proposed experiments for determining the release of radionuclides from the oxidation of sodium. These tests are designed to evaluate the amount and mechanism for the release of radiologically significant isotopes in the primary coolout of an LMFBR when postulated spills or leakage of molten sodium occur.

A series of preliminary tests have been conducted in which 10 to 20 gm quantities of sodium containing ~1 wt % U as sodium uranate* were ignited in a 7.4-ft air-filled test chamber. The fraction of sodium released was <0.1 in these preliminary tests, probably because there was not sufficient O₂ to oxidize all the sodium. The small combustion vessels utilized (1 to 2 in. diameter) may also have contributed to the low fraction of sodium released. The extent of uranium released was determined by isolation of settled and plated material from the floor and walls of the vessel. The collected material was analyzed for uranium by x-ray fluorescence. The sensitivity of this technique was shown to be 5 μg U (L αc peak at 13.6 kev). However, the sensitivity is not constant because the background increases due to gamma scattering in the sodium oxide which accompanies the released uranium. In all cases the extent of uranium release was low, pressing the sensitivity of the technique. For all tests run to date, the fraction of uranium released was <2.6 x 10⁻⁴ (Table 4). If one considers the possibility that accident conditions may foster larger sodium released fractions than were observed in the present studies, and if one assumes that the release ratio is invariant, then the fraction $U_F$ of uranium released will increase. However, assuming 0.15 Na release results in uranium release fractions no higher than 10⁻³ for all tests to date.

$$U_F = \frac{U}{Na} \frac{Na}{U_T}$$

where Na is the sodium released and $U_T$ is the amount of uranium initially in the pool.

*Na₃UO₄ has been synthesized using a method described by O'Hare, et al (1) in which stoichiometric mixtures of Na₂O and UO₂ are heated in liquid sodium for 48 hr at 800°F. X-ray diffraction techniques have been employed to verify the face centered cubic structure previously reported by ANL.
TABLE 4
TEST SUMMARY

<table>
<thead>
<tr>
<th>Test</th>
<th>Sodium Burned (gm)</th>
<th>Fraction Oxide Released</th>
<th>Uranate In Sodium (gm)</th>
<th>Fraction Uranium In Uranate</th>
<th>Fraction Uranium Released</th>
<th>Fraction Uranium Released Normalized*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>0.09</td>
<td>0.23</td>
<td>0.59</td>
<td>&lt;2.6 x 10^-4</td>
<td>&lt;4.3 x 10^-4</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>0.07</td>
<td>0.33</td>
<td>0.59</td>
<td>&lt;1 x 10^-4</td>
<td>&lt;2 x 10^-4</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>0.06</td>
<td>0.26</td>
<td>0.59</td>
<td>1.5 to 2 x 10^-4</td>
<td>3.7 to 5 x 10^-4</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>0.035</td>
<td>0.21</td>
<td>0.59</td>
<td>&lt;2.5 x 10^-4</td>
<td>1 x 10^-3</td>
</tr>
</tbody>
</table>

*Normalized to 0.15. Assumes that (µgm U/gm oxide) released is constant and that if 0.15 of oxide is released then the total uranium release fraction increases.

2. Modeling Development

Review of the literature has verified that sodium metallates are stable under potential LMFBR operating conditions (1-4). The thermodynamic properties of the metallate [(Na₃U₃(1-x)Pu₂O₄)] formed during interaction of mixed fuel [(U₃(1-x)Pu₂O₂)] with sodium closely resemble those of the homogeneous uranate Na₃UO₄. Thus, sodium uranate provides a convenient chemical model system for the heterogeneous metallates. Mass spectrometric studies of the thermal vaporization of Na₃UO₄ have shown no release of uranium nuclei (3). Extrapolation of the preliminary results to large scale combustion of sodium laden with PuO₂ at CRBRP allowable levels of 0.1 ppm suggests that Pu release will not contribute appreciably radiologically relative to those of other radionuclides (such as I¹³¹) when ordinary spills occur. Furthermore, if one wishes to model the experiments at levels which exist in typical LMFBR's (~1 ppm by weight) and if the release fractions are of the order of 10^-3 or less, there are no economical chemical methods for detecting the released materials. This occurs because the released radionuclide is associated with 10 to 15% of the oxide which is also released (10^-6 gm Na/gm) (10^-3/0.20 gm Na₂O = 5 x 10^-9 gm M/gm oxide, where M = Pu or U. Even the use of high specific activity isotopes of uranium (U²³³ is 9.5 x 10^-3 µ Ci/µgm) will result in only 2 dps/gm of oxide released. One could perhaps use U²³⁵ and place some of the released

AI-ERDA-13155
43
material in a neutron flux. About 200 gm of released oxide will contain 1 \( \mu \)gm of uranium. A 2 hr experimental irradiation of 1 \( \mu \)gm in a flux of \( 10^{13} \) n/s/cm\(^2\) will produce 1400 gammas/sec of Ba\(^{140}\).

G. SUBTASK G – HEAT-TEMPERATURE PROPERTIES OF FUEL MIXTURE

1. Introduction

Experimental methods were devised for characterizing the aerosol source term and identifying factors which would tend to minimize the aerosol production due to a HCDA. A number of hypothetical accident scenarios were studied and various experiments devised to test the validity of assumptions made for the scenarios.

It appears that common to all the scenarios are two processes, which will minimize the aerosol source term on limit the HCDA size. These are summarized in the following listing.

1) Molten Fuel - Stainless Steel Interaction — A hypothetical core disassembly accident (HCDA) will melt fuel which may then interact with the considerable amount of stainless steel present. Since the temperature of molten fuel (2850°C or more) is more than is needed to vaporize stainless steel, there will be enough vapor pressure to prevent rapid motions of high-density fuel which might otherwise initiate a recriticality accident. The stainless steel vapor will tend to foam up any fuel in contact with it. The formation of foamed fuel will also fill voids which otherwise would be filled with aerosol.

2) Fuel Aerosol - Sodium Interaction — Any fuel aerosol which reaches the cover gas region will have considerable amounts of sodium vapor and aerosol mixed with it since the vapor bubble carrying the fuel aerosol must rise through the sodium pool. The sodium and fuel particulates will agglomerate mechanically and chemically react to form larger particles than would otherwise form. These larger particles will tend to fall out more rapidly and are also less hazardous biologically.

Of particular interest is the formation of sodium uranates and plutonates. The finer the fuel particle, the more rapidly this chemical
reaction will proceed. If the plutonates are slightly soluble in sodium or agglomerate easily, a mechanism will be present for preferential fine particle abatement. This is important since the finer (<1µ) particles are considerably more hazardous biologically than larger particles.

2. **UO₂ - SS Interaction Experiments**

Experimental work has been directed toward study of the aerosol source term as modified by the fuel-sodium and stainless steel interaction listed previously. The first requirement is to have a source of molten and/or vaporized UO₂. UO₂ will be used as a fuel simulant since mixed oxide fuel can be expected to be similar in physical and chemical behavior to UO₂. An induction melting furnace has been constructed for melting UO₂ and a capacitor discharge apparatus has been put into operation for the sudden vaporization of uranium or UO₂ wires.

The induction melting furnace is shown in Figures 28 and 29. The UO₂ is melted in a tungsten crucible surrounded by multilayers of tungsten heat shielding foil. The induction coil is water-cooled copper tubing of eight turns powered by a 10 kw "Lepel" high-frequency current generator. A photograph of the shielded crucible while being heated is shown in Figure 30.

A considerable amount of experimentation was needed to reach UO₂ melting temperature (2850°C). At its melting temperature, UO₂ has a high vapor pressure (20 torr) and one of the dissociation products, monatomic oxygen, has a vapor pressure of 0.05 torr.

Figure 31 shows the result of one melting experiment. As shown in this figure, UO₂ in powder form was placed in the tungsten crucible. A special lid with a tantalum tube forming a black body cavity was placed in the crucible. After heating for some time, some of the molten UO₂ ran into the cavity tube, and destroyed the effectiveness of the black body cavity. The remaining UO₂ melted, vaporized, and then collected on the top shield of the crucible near the black body cavity tube. (This region was coolest because of heat conduction through the shield along the cavity tube.)
Figure 28. Photograph of Induction Melting Furnace

Figure 29. Diagram of Induction Furnace
Figure 30. Crucible Being Heated by Induction Coil

Figure 31. Crucible and Crucible Cover for Melting UO₂
The crucible is thick-walled tungsten surrounded by several layers of tungsten foil for radiation shielding. The cover (shown upside down) consists of several tungsten disks penetrated by a tantalum tube. Most of the UO₂ has vaporized and deposited on the tantalum tube, where it penetrates the cover.

Because of the high vapor pressure of UO₂, it will be necessary to suppress transpiration by using an argon cover gas over the UO₂. This will be accomplished by hanging the tungsten crucible from above by means of a thin-walled tungsten tube. Argon introduced within the tube wall will suppress the UO₂ evaporation. Planned experiments include introduction of stainless steel into the crucible and measurement of density, viscosity, surface tension, and vapor pressure of UO₂ - SS mixtures.

3. UO₂ Aerosol - Sodium Interaction Experiments

Fuel-sodium interactions may be classified as either chemical or physical. The chemical reactions take place most readily in the presence of excess oxygen to produce sodium plutonates or uranates. For example, UO₂ and Na₂O react to form Na₃UO₄. There are several species of uranates (⁵) – NaUO₃, NaUO₄, Na₂U₂O₇, and Na₄UO₅. The reactants produced by condensation from high-temperature vapor are likely to be a complex mixture of these and others.

The physical reactions are the result of agglomerations of sodium and fuel particles. It has been previously noted (⁶) that long chains or filaments form which may contain small droplets of sodium in the chain. Such agglomeration is, of course, favorable to rapid agglomeration of the fine aerosols and subsequent depletion due to fallout.

Since there are several processes taking place – chemical reaction, mechanical agglomeration, condensation of sodium droplets, etc, it may not be possible to separately measure the importance of each effect. The general procedure must be to simulate high temperature and pressure conditions expected during a HCDA. The reaction products will then be examined to determine the overall effect of variation of any parameter. For example, the amount of sodium present will be varied to show that the presence of sodium vapor results in a larger average size particulate than without sodium.

The variation of particulate size with energy input will also be measured. Higher energy input will tend to divide the fuel into smaller particles and higher
pressure will spread the particles over a greater region before agglomeration takes place. However, if the vaporized fuel is confined to a fixed volume, energy input may have less effect.

The experiments are in an early stage of development. A capacitor discharge apparatus (diagramed in Figure 32) has been constructed. Capacitors with a capacity of \( \sim 75 \) kJ are available for this experiment. Initial exploratory work has been carried out with lesser amounts.

Since \( \text{UO}_2 \) is insulator at room temperature, it cannot be electrically heated directly, but must be preheated first. This could be done with an auxiliary heater. However, initial experiments will be performed using uranium metal wires exploded in a dilute oxygen atmosphere. Sodim vapor and liquid will be provided by evaporating sodium in a small oven. The chamber walls must be heated somewhat to provide the desired vapor pressure.

Figure 32. Exploding Wire Experiment
A high current (10,000 amp) arc melts UO₂. After melting, the trunnion is rotated to pour the melt.

Figure 33. Tilt Pour Skull Furnace

Figure 34. Fragmentation of UO₂ by Jets
Experiments will be performed both with and without sodium present. Particulate size will be measured using impactor and electron microscope techniques. It is expected that a difference in particle size distribution will be found, depending on the presence of sodium. The effect of pressure and energy input on aerosols will also be investigated.

4. Aerosol Production from Molten Fuel – Coolant Interaction (MFCI)

The LMFBR molten fuel – coolant interaction (MFCI) may, in principle, be capable of providing copious amounts of finely divided particulate fuel. Observations of interactions between liquids, one of which was much hotter than the boiling point of the other, have demonstrated that some of the available heat energy can at times be converted into mechanical energy. When such interactions occur, there is generally a mechanism which produces intimate mixing of the two fluids. The literature on this subject has adequately been reviewed elsewhere. Of interest here is the production of fuel aerosol from an LMFBR molten fuel – coolant interaction, assuming that such an interaction can take place.

Several proposed experiments to determine aerosol production and size distribution from a fuel – coolant interaction are discussed in the following listing.

1) UO₂ Arc Melting in Tilt Pour Furnace – Any MFCI experiment requires a large supply of molten UO₂ to carry out the interaction on a sufficient scale.

A 70-kg capacity arc melting furnace (Figure 33), formerly used at AI for melting UC, has been acquired. A water-cooled copper hearth contains the molten mixture. After melting, the hearth can be tipped and the melt poured. About 10,000 amp of current is required during the melting process.

Plans are underway for converting a presently unused building, located at the AI Santa Susana Test Laboratory, to house the furnace. The most important modification required is to provide electrical power for the melting process.
2) Jet Dispersal — The production of an energetic MFCI using \( \text{UO}_2 \) and sodium has not yet been demonstrated, despite some effort, and perhaps it does not take place. Independent of this assumption, an experiment can be performed to directly interact molten \( \text{UO}_2 \) and sodium in a very turbulent mixing situation, and to measure the production of particulates. This possibility is suggested by the method of manufacturing fine metal powders for powder metallurgy. A molten stream of metal is allowed to fall freely from a crucible. High-velocity water jets are impinged on the falling metal to fragment it into fine powder.

A similar procedure could be used for MFCI simulation. As shown in Figure 34, molten \( \text{UO}_2 \) from a tilt pour crucible would have either water or sodium jets impinged on it. This provides a worst case simulation, since the \( \text{UO}_2 \) would be completely fragmented. The measurement of particle size produced by this apparatus would then set an upper limit to the magnitude of the fine size distribution of the MFCI aerosols.

There is reason to believe that extremely fine particulates may not be formed to any great extent by fuel-sodium interaction because of possible preferential chemical reaction of fine particulates to form plutonates and uranates. If such is the case, it would be demonstrated by comparison of the sizes of particulates produced by water jet and sodium jet interactions with molten \( \text{UO}_2 \).

3) Other Experiments — \( \text{UO}_2 \) can be directly poured into sodium or sodium - stainless steel once the tilt pour furnace is installed. \( \text{UO}_2 \) can also be poured onto grid plates or core catchers to investigate the melt-through process.
REFERENCES


AI-ERDA-13155
53