MASTER**ANALYSIS OF FLOW IMPEDANCE PHENOMENA**

Final Report
For Period June 1, 1978 to July 31, 1979

A. A. Bishop

University of Pittsburgh
Pittsburgh, Pennsylvania 15213

DISCLAIMER

This book was prepared to enhance the 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. References 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.

December 1979**Prepared for**

THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. ET-78-S-02-4932.M001

*REA***DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED**

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.

Abstract

Pressure drop data obtained during testing of the MARK I, II and IIA fuel assemblies in the Argonne National Laboratory liquid metal core component loop (CCTL) were analyzed. It is concluded that the previously unexplained pressure drop increase measured across the MARK II and MARK IIA assemblies was caused by metallic particulate fouling; the source was mechanical-chemical wear of the loops pump journal shaft. The implication to liquid metal breeder reactor (LMFBR) operation is that if a continuous source of metallic particles exists upstream of the core, a pressure drop increase can be expected. The size of the deposited particles should be larger than the thickness of laminar sublayer on a fuel rod. It is also concluded that the most probable source of metallic particulates will come from component failure and not from normal corrosion products. A small amount of deposited particulates can produce a relatively high pressure drop increase. Now that it has been concluded that the unexplained pressure drop increase which caused concern in the three sodium loops (FETR-Risley, CCTL-Argonne, and OARAI-PNC) was caused by particulate fouling, the term "Flow Impedance Phenomena" is unnecessary. Other types of fouling discussed are crystallization, oxidation-corrosion, and chemical decomposition. Particulate deposition and pressure drop increase models are compared.

TABLE OF CONTENTS

Abstract	i
Table of Contents	ii
List of Figures	iv
List of Tables	vi
Acknowledgements	vii
 A. Introduction	 1
B. Pressure Drop Fouling Data	3
1. Crystallization	3
2. Surface Oxidation and/or Corrosion	5
3. Particulate Deposition	9
4. Decomposition and Chemical Reaction	9
C. Discussion of Flow Impedance Phenomena Results From Support LMFBR Test Loops	 12
1. British Fuel Assembly Thermal Test Rig (FETR)	12
2. Japanese OARAI Test Loop	14
3. USA Fuel Component Test Loop (CCTL)	19
a. MARK I Testing	24
b. MARK II Fuel Assembly Testing	24
c. MARK IIA Fuel Assembly Testing	31
d. Cause of MARK II and MARK IIA Pressure Drop Increase	 43
4. Flow Impedance in Other Liquid Metal Test Loops and Reactors	 48
D. Experimental Investigation of Flow Impedance Phenomena	 49
1. ORNL Rod Bundle Tests	49
2. HEDL Flow Impedance Phenomena Program	49
3. WARD Single Heated Rod Test	51
4. Japanese Single Rod FIP Test Program	51

E.	Analysis of Pressure Drop Increase Caused by Particulate Fouling	53
1.	Pressure Drop, Friction Velocity and Laminar Sublayer Thickness	53
2.	Particulate Fouling Mechanisms	56
a.	Mass Flux Towards a Surface	58
(1)	Mass Flux from Aerosols	58
(2)	Mass Flux from Suspension	60
b.	Adhesion and Detachment Forces	62
c.	Determination of Whether Pressure Drop Increase is Caused by Particulate Deposition or Crystallization	64
3.	Models for Time Dependent Mass Deposition and Pressure Drop Increase	66
4.	Analysis of the MARK IIA Assembly Pressure Drop Data	74
F.	Implications of Particulate Fouling in Liquid Metal to Breeder Reactor Operation	81
G.	Conclusions	84
H.	Recommendations	86
I.	Nomenclature	88
J.	References	90

List of Figures

1. Effect of Calcium Sulfate Concentration on Friction Factor Increase
2. Corrosion-Oxidation Fouling: Deposit and Pressure Drop
3. Friction Factor Increase vs Time for Different Initial Surface Conditions (Surface Oxidation and Corrosion)
4. Magnetite Deposition vs Time: Particulate Fouling
5. Friction Factor Ratio Decreased vs Time: Particulate Deposition from Suspension
6. Effect of Heat Flux on Fouling Resistance and Pressure Drop Increase (Chemical Reaction of Flowing Oil at Surface)
7. Pressure Drop Increase vs Test Time for JOYO I
8. Pressure Drop Increase vs Time MONJU Fuel Assembly
9. CCTL MARK II and MARK IIA Fuel Assembly
10. MARK I, II and IIA Condensed Operating History
11. Simplified CCTL and MARK II Fuel Assembly Diagram
12. Pressure Drop Increase (Taps 1-2) vs Time CCTL MARK II
13. Pressure Drop Increase (Taps 2-3) vs Time CCTL MARK II
14. Pressure Drop Increase (Taps 3-4) vs Time CCTL MARK II
15. Pressure Drop Increase (Taps 4-5) vs Time CCTL MARK II
16. CCTL MARK II Flow Sweeps: Friction Factor vs Reynolds Number Taps 3-4 (Time Dependent Pressure Drop)
17. Pressure Drop Increase (Taps 1-2) vs Time CCTL MARK IIA
18. Pressure Drop Increase (Taps 2-3) vs Time CCTL MARK IIA

19. Pressure Drop Increase (Taps 3-4) vs Time CCTL MARK IIA
20. Pressure Drop Increase (TAPS 4-5) vs Time CCTL MARK IIA
21. CCTL MARK IIA Flow Sweeps: Friction Factor vs Reynolds Number; Taps 3-4 (Time Dependent Pressure Drop)
22. CCTL Pump Examination: Four Quadrants of Scarred Shaft Journal
23. Pressure Drop Increase in the Flow Sensor of the HEDL Test Loop
24. Resistance Coefficient Behavior for Sand Grain and Commercial Steel Pipe Type Roughness
25. Effective Equivalent Sand Roughness vs Spacing Ratio
26. Comparison of Crystallization and Particulate Deposition Pressure Drop Increase
27. Plot of Percent Increase in Pressure Drop vs Time
28. Particulate Deposition vs Friction Factor Ratio
29. Mass Deposit and Pressure Drop Increase Caused by Hot Water Oxidation
30. Pressure Drop Increase vs Time CCTL MARK IIA
31. Friction Factor Increase Caused by Particulate Deposition (Monolayer) on a Smooth Surface MARK IIA Conditions
32. Mechanism for Friction Factor Decrease Due to Particulate Deposition

LIST OF TABLES

1. Hydraulic Data for MARK II and MARK IIA
2. CCTL MARK II Pressure Drop History
3. CCTL MARK IIA Pressure Drop History
4. Comparison of MARK I, II and IIA Total Hydraulic Resistance Coefficient Increase
5. Hydraulic Calculations for MARK IIA Fuel Assembly (Rod Bundle Taps 3-4)
6. Particulate Mass Required to Produce a 30% Pressure Drop Increase Across MARK IIA Assembly
7. Dimensionless Stopping Distance and Velocity

Acknowledgements

To Fred Smith of the Argonne National Laboratory who supplied important MARK I, II and IIA fuel assembly experimental data and who provided valuable information during our discussions concerning operation of the CCTL.

To Earl Novendstern of the Westinghouse Advanced Reactors Division for use of the MARK II and IIA pressure drop data computer printouts he compiled.

To Dean Mundy, Marcia Huber, Stephen McCarthy, Stanley Pierchoski and Nicholas Pollack, senior undergraduate students in the Chemical Engineering Department for their help in data reduction.

A. Introduction

Several years ago data which showed that loop pressure drop increased as the operating time increased were obtained from facilities in the USA, Japan and the UK. (1) (2) (3) These unexplained pressure drop increases became known as Flow Impedance Phenomena or FIP. In all three cases the pressure drop increase occurred across a fuel assembly being tested in support of liquid metal fast breeder reactor (LMFBR) programs. The flow loops involved were the Fuel Element Thermal Test Rig (FETTR) at Risley, the Core Component Test Loop (CCTL) at Argonne National Laboratory and the O-arai Loop at the PNC Engineering Center. Because the hydraulic resistance coefficient increases were high (15% to 90%), attempts were made to determine the cause, to predict the effect on typical LMFBR operation, and to assess whether the pressure drop increase observed would occur during LMFBR operation. Subsequently it was discovered that the pressure drop increase across the fuel assembly in the FETTR Loop was caused by surface deposits of stainless steel particulates whose source was the break-up of a sprayed stainless steel surface in an auxiliary loop. (3) After examination, the pressure drop increase across the fuel assembly in the Japanese loop was also attributed to metallic particulate deposits; however, neither the source nor the concentration of the particles has been definitely identified. (4) The cause of the pressure drop increase across the fuel assembly in the CCTL has not been explained. The work summarized in this report was performed to analyze the cause of the CCTL pressure drop increase, to determine what characteristics are common to the three reported cases of FIP, to determine if other instances of

FIP have been reported from the German, French or other LMFBR test programs, to develop a physical model to explain time dependent pressure drop increase and to assess possible implications of FIP on LMFBR core operation.

Fouling, the deposit of undesired material onto a surface, is a common problem in heat exchanger operation. However, there are many aspects of fouling which are not understood, hence fouling has been described as a major unresolved problem in heat transfer.⁽⁵⁾ Several established causes of surface fouling are crystallization, particulates, oxidation-corrosion, and chemical decomposition. These mechanisms can also occur in combination. It is well known that fouling generally increases both thermal and hydraulic resistance. Although extensive experimental work has been conducted to investigate how fouling influences thermal resistance, only recently have detailed physical fouling models been proposed and compared with data.^{(6) (7) (8)} In contrast, virtually no physical models have been reported to explain or predict pressure drop caused by fouling. One reason for this deficiency is that most experiments are conducted to obtain thermal resistance data and systematically obtained pressure drop data are given secondary importance. A second reason is that pressure drop effects of fouling tend to be more complex than thermal resistance effects. Deposit spacing, size, amount, geometry and the roughness of the base surface are parameters which influence pressure drop caused by fouling. Moreover fouling can increase or decrease pressure drop.

Quantitative pressure drop fouling data found in the literature are discussed in the next section. Then attention is given to the FIP data, discussion of the data, and analysis of the CCTL MARK assembly data.

B. Pressure Drop Fouling Data

1. Crystallization

Whether crystallization occurs first in the hottest or coldest region of a system depends upon the solubility characteristics of the compound in solution. If the material has inverse solubility, crystals appear first when the solubility is exceeded at the hottest surface. Conversely, if the material in solution has normal solubility, crystals first appear when the solubility is exceeded at the coldest surface in the system. Surfaces have sites which promote nucleation and crystallization. When a solution of an inverse soluble salt such as CaSO_4 , CaCO_3 , or $\text{Ca}_3(\text{PO}_4)_2$ is being heated as it flows through heat exchanger tubes, fouling, also called scaling, often occurs because the solubility of these salts decrease as the temperature increases.

The pressure drop data in Figure 1 which were obtained by Smirnov and Michurov are for a solution of calcium sulfate following through a heated 0.32" ID smooth tube.⁽⁹⁾ The pressure drop increase is a strong function of the concentration of CaSO_4 . Because the solubility of CaSO_4 is low at high temperatures and the supersaturation of the salt was relatively high, Smirnov and Michurov suggested that crystallization occurred both at the heated surface and in the bulk solution. The solid particles of calcium sulfate in solution then deposited on the wall. In addition we suggest that at the two lower calcium sulfate concentrations where supersaturation was low precipitation of the salt from the bulk fluid phase was reduced significantly thereby changing the shape of the friction factor ratio versus time curves. For the two lower solution concentrations the friction factor ratio versus time appears to be more linear over a longer time period.

Figure 1

EFFECT OF CALCIUM SULFATE CONCENTRATION ON FRICTION FACTOR INCREASE

This behavior is in contrast to the greater non-linear shape of the two higher concentrations. Thus if the increase in the friction factor was caused entirely by crystallization at the tube wall and not by a combination of particulate deposition and crystallization at the wall, linearity would be observed at least up to approximately five hours. For all four solution concentrations, the pressure drop increased asymptotically. The asymptotic characteristic of pressure drop increase is not unique as will be shown in later data and discussions.

Crystallization is often preceded by an induction period during which crystal growth cannot be detected. It has not been established whether the induction period is caused by slow nucleation and slow crystal growth. After the induction period there is generally a linear relationship for inorganic compounds between crystal growth and time. The transition region between the induction period and the normal crystal growth period forms a "knee". The overall growth curve assumes an "S" or "sigmoidal" shape curve.(10) Close inspection of the 4.0 relative concentration pressure drop data curve of Smirnov and Michurov indicates a possible sigmoidal shape. Our reduction of the data produced a semi-log relationship between the pressure drop increase and time for the highest concentration shown.

2. Surface Oxidation and/or Corrosion

Another cause of fouling is oxidation and/or surface corrosion. Pressurized hot water flowing through a stainless steel tube oxidizes the surface and forms a magnetite film. Because the magnetite film is less dense and has a lower thermal conductivity than the parent base metal the thermal and hydraulic resistances are increased. Data from the

University of California boiling water heat transfer study, (11) and from the Babcock and Wilcox boiler tube study, (12) are given in Figure 2. It is fortunate that both the magnetite deposit thickness and pressure drop increase were measured in the German study. Again the asymptotic pressure drop increase is observed in both experiments. The data can be represented by a semi-log relationship between pressure drop and time. Although the formation of magnetite appears to be approaching a limit, magnetite is still being formed without there being a corresponding pressure drop increase. We also show in Section E-3 that the magnetite deposit and pressure drop have similar time dependent functional relationships.

The magnetite film on the Babcock and Wilcox boiler tube had a "ripple" roughness appearance. The friction factor of the "ripple" was 45% higher than that obtained from a Moody chart of the same roughness height (ripple height $\epsilon = 25 \mu$ and $\epsilon/D = 7 \times 10^{-4}$). The friction factor was independent of Reynolds number for $Re > 10^5$. Below this Reynolds number the sand grain features of Nikaradse's work were seen. Results of tests using three different tubes each having a different initial surface finish are shown in Figure 3. The asymptotic friction factor increase behavior is independent of the size of the initial roughness. Of greater importance, the magnitude of the asymptotic friction factor is identical for the two rougher tubes. Even the electrolytically polished tube has approximately the same final friction factor. These results suggest that the magnitude of the asymptotic friction factor is controlled by local parameters and can be calculated without knowledge of the initial surface roughness. Equal friction factors produce equal surface shear stresses for equal flow Reynolds numbers. Thus for a given

Figure 2

CORROSION - OXIDATION FOULING: DEPOSIT AND PRESSURE DROP

Figure 3
FRICTION FACTOR INCREASE VS TIME FOR DIFFERENT INITIAL SURFACE CONDITIONS
(SURFACE OXIDATION AND CORROSION)

system, local shear stress is the principal parameter which governs the magnitude of the asymptotic pressure drop increase.

3. Particulate Deposition

There have been numerous studies of particulate deposition from aerosols. (13) (14) (15) Although none of these studies concentrated on pressure drop behavior, they may be helpful in comparing particulate deposition rates in liquid and gas systems.

Thomas used a water-magnetite suspension to determine the effects of magnetite deposits on heat transfer and pressure drop in stainless steel tubes. (16) (17) (18) Magnetite concentrations were approximately 1.2 and 2.2 ppm. Major particle sizes ranged from 20 to 50 microns. Tubes were cleaned by pickling and re-used. Pickling increases the tube surface roughness.

Deposition of magnetite increased with time at a decreasing rate producing an asymptotic behavior. At times up to 40 hours the deposition rate approached zero as shown in Figure 4.

For all the data reported, the friction factor decreased with increasing times as shown in Figure 5. The friction factor decrease was asymptotic; the limit appeared to be that for a smooth tube at the same flow Reynolds number. The Thomas data show that when particulates deposit onto a surface the change in pressure drop is determined by the size of particles relative to the surface roughness. If the particulate size is comparative to the roughness size and both are larger than the laminar sublayer thickness, pressure drop can decrease. This effect is modelled in Section E-4.

4. Decomposition and Chemical Reaction

The last fouling mechanism to be considered is decomposition and/or chemical reaction. A typical example is the flow

Figure 4

MAGNETITE DEPOSITION vs TIME: PARTICULATE FOULING

Figure 5

FRICTION FACTOR RATIO DECREASE vs TIME PARTICULATE DEPOSITION FROM SUSPENSION

of a petroleum gas oil through a heated tube as discussed by Watkinson and Epstein. (19) After a 13 to 18 day run the deposits found in the tube were soft, powdery, black and soot-like material. The fouling rate was strongly temperature dependent and could be related to Arrhenius type $1/T$ expression for chemical reaction velocity constants. (We have expressed the pressure drop increase of $\Delta p / \Delta p_0$ instead of the original $\Delta p - \Delta p_c$.) Figure 6 shows that the pressure drop appears to increase before there is a significant thermal resistance increase. In addition the pressure drop reaches a limiting value although the thermal resistance is still increasing. Deposits could form in the valley of the roughness protrusion, within the laminar sublayer and not affect the pressure drop. The decomposition fouling mechanism is similar to the crystallization mechanism in that there is often an initial induction period which is followed by a linear growth rate of the deposit.

C. Discussion of Flow Impedance Phenomena Results From Support LMFBF Test Loops

1. British Fuel Assembly Thermal Test Rig (FETTR)

One of the early concerns regarding unexplained pressure drop increases was caused by the data obtained during tests of a Prototype Fast Reactor gridded subassembly in 650°C sodium at the UK Risley Engineering and Materials Laboratory.

(3) After a six months test period, the fuel assembly hydraulic resistance coefficient increased about 70%-90%. Almost a month of testing was completed before the hydraulic resistance coefficient started to increase. Actually the flow decreased 23%, the pressure drop only increased 12%, but the hydraulic resistance coefficient increased. The range of 70% to 90% is determined by whether a 1.8 or a 2.0 exponent

Figure 6

**EFFECT OF HEAT FLUX ON FOULING RESISTANCE
AND PRESSURE DROP INCREASE
(CHEMICAL REACTION OF FLOWING OIL AT SURFACE)**

on flow is used. A significant fraction of the reference pressure drop is caused by assembly support grids. The pressure drop increase was caused by deposition of stainless steel particles onto the surfaces of the fuel rods and fuel rod assembly grids. The particulate source was the break up of a sprayed stainless steel surface located in an auxiliary loop. It is estimated that 7 to 22 grams of sprayed surface escaped into the primary loop. Eleven grams of particulates covered the fuel assembly with most of the deposit in high turbulence and high velocity grid regions. The range of the particle size was 0.25 to 20 microns; the predominant particle size was 5μ . Maximum mean peak-to-valley height was approximately 0.0018"; axial peak-to-peak spacing was greater than 0.010". The maximum increase in the fuel rod diameter was approximately 0.0008".

An important feature of these data is that they clearly demonstrate that a relatively small amount of deposited material in the 5-8 μ range can cause a significant increase in the hydraulic resistance coefficient where velocities are high and flow passages are small. Assuming there were 1000 gallons of sodium in the loop, the concentration of particulates was only approximately 5 to 7 ppm.

2. Japanese OARAI Test Loop

Initial component sodium flow testing in the isothermally operated O-ARAI loop continued for approximately 5000 hours at 842°F (450°C). In 1971 the loop was modified and a JOYO fuel assembly was flow tested at 1112°F (600°C). (2) Sodium flow velocity through the assembly was 17.5 ft/sec. After 1000 hours the pressure drop began to increase. The increase as shown in Figure 7 reached approximately 8% after 2400

Figure 7

PRESSURE DROP INCREASE vs TEST TIME FOR JOYO I

hours and the test was stopped. (The increase appears to be approaching an asymptote.) The loop was drained and refilled. When testing was resumed the pressure drop increased in a short time to 20%. It is not clear whether the increase continued from the original 8% increase reference level; however we suggest that this was the case. The pressure drop increase remained at the 20% level for 1000 hours; the test was then terminated.

Four other JOYO type fuel assemblies were tested and the pressure drop increased in each test. Although the pressure drop increase (7 to 24%) generally reached a maximum constant value, the magnitude of the maximum value and the rate at which the maximum value was reached were different. There was considerable pressure drop increase difference between two identical assemblies tested with and without a magnetic filter in the loop. After being tested in sodium several assemblies were tested in water. For two assemblies the pressure drops were comparable to those obtained in sodium.

Four MONJU fuel assemblies were flow tested at 1112°F (600°C); each showed an increased pressure drop in sodium and when tested later in water. Figure 8 shows the pressure drop increase across a MONJU assembly.⁽⁴⁾ Placing filters in the loop appeared to reduce the pressure drop increase. Pressure drop increases for the MONJU assemblies were generally less than for the JOYO assemblies. Differences in equivalent diameters and flow velocities in the different type assemblies should be considered. The reference Reynolds numbers were approximately 50×10^4 for the JOYO fuel assemblies and 75×10^4 for the MONJU fuel assemblies. Equivalent diameters ranged between 0.186" to 0.096" for JOYO assemblies and was approximately 0.125" for the different MONJU fuel assemblies.

Figure 8

PRESSURE DROP INCREASE vs TIME (MONJU FUEL ASSEMBLY)

The size and distribution of particles collected on a magnetic filter ranged from 0.5 to 30 microns and approximately 65 weight percentage of the particle was greater than 2 microns. The mean diameter was 2 to 3 microns. Eighty weight percent of the particles was chromium, iron and manganese. Filtration through 1 μ filter paper of the washings from a MONJU assembly secured after sodium testing was estimated to be greater than 130 ppm by weight.

Although the cause of the pressure drop increase has been determined to be metallic particulates which adhered to the surfaces of the fuel rods, neither the source of the particles nor the concentration has been clearly identified, the fact that over 50% by weight of the particles had diameters larger than 2 μ and that the particles are principally metallic tends to indicate that the source might be other than just normal corrosion products. The question concerning the particle source arises in another context. Five JOYO type assemblies having 19 to 127 fuel rods 4.7 to 6.2' long and four MONJU type fuel assemblies each having 169 fuel rods 9' long were tested and a pressure drop increase was observed in each case. The mass of a single layer of small diameter particles spaced at an arbitrary distance along each fuel rod is small but not insignificant and account must be made for this mass. Moreover if there are sizeable low velocity regions in the loop some of the particles will drop out of suspension. The results indicate either a high concentration of particles in the loop or a continuous source of particles upstream of the test sections.

Not enough consideration is given to the fact that the pressure drop increase did not occur in the first JOYO assembly tested until after 1000 hours of testing at 1112°F (600°C). In subsequent tests, including retesting of the first JOYO

fuel assembly, the pressure drop increase occurred when tests were initiated. One explanation is that 1000 hours operation at 1112°F was required to accumulate sufficient corrosion products with large enough diameters to act as a source. However we tend to think that another metallic particulate source became available during the 1000 hour period and probably still exists. This point should be resolved. When the loop was drained and refilled, particulates which had dropped out of suspension were picked up causing an effective high concentration resulting in a higher rate of deposition and increased pressure drop. Moreover it has been established that the particulate concentration in the drain tank is higher than that in the test loop sodium.

3. USA Fuel Component Test Loop (CCTL)

Flow impedance phenomena in liquid metal systems first came to the general attention of the American breeder reactor community during testing of the MARK IIA fuel assembly in the Core Component Isothermal Test Loop (CCTL) at Argonne National Laboratory. (1)(20)(21) Although there were several geometrical differences between the MARK I, II and IIA assemblies, the fuel pin bundle region was essentially the same. Dimensions of the MARK II and MARK IIA are given in Figure 9; the condensed operating history is given in Figure 10, hydraulic data are shown in Table 1, and a loop diagram is shown in Figure 11.

Between taps 3-4 the energy loss is predominately frictional. This section is used as a reference for the subsequent discussion. Measurements between taps 1-2, taps 2-3, and taps 4-5 include enlargement and/or contraction pressure drop losses. There are no valves in the CCTL; therefore, flow changes were achieved by varying the pump shaft speed through its Dynamatic Coupling.

Figure 9
CCTL MARK II AND MARK II-A FUEL ASSEMBLY

Figure 10
**MARK I, II AND II-A CONDENSED
 OPERATING HISTORY**

HYDRAULIC DATA FOR MARK II AND MARK IIA

TABLE 1

	MARK II	MARK IIA	MARK I
Reference Temperature (°F)	1100	1100	-
Volumetric Flow Rate (gpm)	522	525	400
Reference Reynolds Number	9.6×10^4	9.7×10^4	-
Equivalent Diameter (in)	0.131	0.131	-
Sodium Velocity (ft/sec)	24.3	24.5	-
Reference Pressure Drop (psi) ⁽¹⁾			
Taps 1-2	6.4	27.3	-
Taps 2-3	13.0	11.0	-
Taps 3-4	21.5	22.4	-
Taps 4-5	8.5	8.0	-
Total Pressure Drop (psi)	49.4	68.7	47.4

(1) Best estimate from the experimental data.

Figure 11
SIMPLIFIED CCTL AND MARK II
FUEL ASSEMBLY DIAGRAM

a. MARK I Testing

MARK I fuel assembly was flow tested for 3687 hours at 1060°F; the flow rate was 400 gpm (~ 18.6 ft/sec). In July 1968 at the beginning of the test period the pressure drop was 47.3 psi; at the conclusion of the test period the pressure drop was 44.6 psi. No pressure drop increase was measured during MARK I fuel assembly flow testing.⁽²²⁾ The pressure drop decrease is not considered to be important. Both the loop and fuel assembly were modified and MARK II flow testing began in May 1970.

b. MARK II Fuel Assembly Testing

During May and early June 1970 when the CCTL was being brought up to reference flow rate and temperature conditions for the MARK II, the pressure drop across the assembly fluctuated especially at the lower flow rates and 400°F temperature. Wetting of stainless steel by sodium is a function, among other things, of the system temperature and sodium flow Reynolds number.

Table 2 shows that on June 16, 1970 the first time MARK II reference flow rate was reached, the pressure drop across taps 3-4 was 21.5 psi. This value of pressure drop was also obtained from our analysis of the flow sweep data. Therefore 21.5 psi was used as the reference pressure drop across tape 3-4 for MARK II.

During the five day period from June 16, 1970 to June 21, 1970 the flow rate was constant at 522 gpm and the pressure drop remained constant at ~ 21.5 psi. On June 22, 1970 the flow rate suddenly dropped 4.2%. There was virtually no change in the pressure drop, the sodium temperature remained constant at 1050°F, the pump speed remained constant; however, the

TABLE 2: CCTL MARK II PRESSURE DROP HISTORY (6)

Date	Pressure Drop(6) (psi)	Flow Rate E.M. Pump (GPM)	Friction Factor (λ)	Temp (°F)	Pump Speed (RPM)	Voltage (MV)
(1) 6/16/70	21.9	522	0.0180	1050	1075	8.3
6/17/70	21.5	522	0.0176	1050	1075	8.3
6/18/70	21.5	522	0.0176	1050	1075	8.3
6/19/70	21.7	522	0.0178	1050	1075	8.3
6/20/70	21.7	522	0.0178	1050	1075	8.3
6/21/70	21.7	522	0.0178	1050	1075	8.3
(2) (5) 6/22/70	21.8	500	0.0195	1050	1075	8.0
6/23/70	21.8	500	0.0195	1070	1075	8.0
6/24/70	21.5	492	0.0200	1085	1075	7.8
6/25/70	21.2	492	0.0196	1100	1065	7.8
(3) 9/14/70	23.6	513	0.0201	1100	1130	8.2
(4) 3/14/71	23.7	507	0.0206	1100	1145	8.1

- (1) First time at rated conditions; Reference Pressure Drop
- (2) 4.2% drop in flow; no Δp change, pump speed constant, 3.6% drop in voltage
- (3) Date of last Mark II flow sweep, pump speed increases but voltage decreased
- (4) Last day at rated flow conditions pump speed increased, flow rate down, voltage down
- (5) Venturi meter was put on line - This is the only apparent difference between the 6/21/70 operation and 6/22/70 operation.
- (6) Taps 3-4

voltage dropped 4%. This unusual combination of a constant pressure drop coupled with the 4.2% flow reduction produced a 10% increase in the hydraulic resistance coefficient across section 3-4 which is shown in Table 2 and illustrated in Figure 14.

The only other change made on June 22, 1970 was placing the venturi flow meter in service. The venturi flow meter remained on line from June 22, 1970 to July 7, 1970. During that period the venturi meter reading increased unexpectedly almost 37% although the EM flow reading decreased only approximately 2.5%. After July 7, 1970 the venturi meter was isolated and all flow measurements for MARK II were recorded by the EM flow meter.

On July 2, 1970 the loop was shut down for six hours. On start-up there was a perturbation in the hydraulic resistance coefficient as seen in Figure 14. The measured hydraulic resistance coefficient increased to a maximum of 15% (across section 3-4) in mid-January 1971 and remained at that value until testing was stopped in March 1971. There was a hydraulic resistance coefficient increase across all sections of the MARK II assembly, refer to Figures 12, 13 and 15. In contrast to MARK IIA where the initial pressure drop increase was uniform and could be represented by a curve, a curve was not drawn through the MARK II data because of the scatter.

The pressure drop increase across the MARK II assembly was detected during an earlier review of the MARK IIA pressure drop data. Observe that pump speed increased simultaneously with flow decrease over the entire hydraulic resistance coefficient increase period. Such behavior is unexpected.

During the MARK II flow test period, four flow sweeps were made over the 10^4 to 10^5 Reynolds number range. Flow

**Figure 12 PRESSURE DROP INCREASE (Taps 1-2) vs TIME
CCTL MARK II**

Figure 13 PRESSURE DROP INCREASE (Taps 2-3) vs TIME
CCTL MARK II

Figure 14 **PRESSURE DROP INCREASE (Taps 3-4) vs TIME**
CCTL MARK II

Figure 15 **PRESSURE DROP INCREASE (Taps 4-5) vs TIME**
CCTL MARK II

sweep data are graphed in Figure 16. At 400°F sodium does not completely wet stainless steel.(23) Incomplete wetting is probably the cause of the friction factors at 400°F being lower than friction factors for smooth surfaces. Even at higher temperatures a time lag exists before a surface is completely wetted. The friction factor data in the figures were reduced using the pressure drop data computer printout generated by E. Novendstern. (24) The last flow sweep indicated an approximate 15% increase above the reference for Sections 3-4.

After testing, the MARK II was removed from the CCTL, cleaned (with a series of Dowanol alcohol, alcohol-water and water rinses) and shipped to the Hanford Engineering Development Laboratory. (25) The assembly was inspected visually at 3X magnification; there was no evidence of wear, corrosion or vibration damage. A gray surface film which could be wiped off easily and which was analyzed to be composed principally of 45% chromium, 40% sodium, 9% iron, 5% aluminum and 1% nickel was found on the bottom third of the assembly. Examination of MARK I revealed a similar film. A total of 30 particles were removed from the assembly for examination, twenty-five of these particles were metallic, magnetic and had a stainless steel composition. The particles had irregular shapes and the sizes ranged up to 1/8 inch.

c. MARK IIA Fuel Assembly Testing.

The major modifications to the MARK II assembly was inclusion of a shield/orifice and flow distribution block assembly, removal of the top grid plate and inclusion of additional mountings for accelerometers. The modified assembly was designated MARK IIA.(25)

In October 1971 MARK IIA flow testing was initiated at 67% rated flow and approximately 600°F. Pressure drop

Figure 16

CCTL MARK II FLOW SWEEPS
FRICTION FACTOR vs REYNOLDS NUMBER
 (Time Dependent Pressure Drop)
 Taps 3-4

measurements during the early test period were considerably more repeatable and consistent than for the initial MARK II test period. This behavior was probably caused by the higher initial MARK IIA flow rate and temperature. As discussed in Reference 47 the time required for sodium to wet stainless steel completely depends on both temperature and Reynolds number. Our analysis of the data indicates that there was no pressure drop increase across either of the four assembly sections over the test period October 1971 to February 11, 1972.

On February 11, 1972 the flow rate and temperature were increased to the rated 525 gpm (24.5 ft/sec) and 1100°F. The previous conditions were 19.9 ft/sec and 1000°F. Table 3 and Figure 19 shows that the friction factor increased almost 10% in one day. (Although not strictly true, the terms friction factor and hydraulic resistance coefficient are used interchangeably.) The pressure drop continued to increase until February 17, 1972, when it remained approximately constant for several days. Following February 21, 1970 the pressure drop started to increase again and continued to increase at a reduced rate until the test was terminated on May 31, 1972. Between taps 3-4 the maximum pressure drop increase was approximately 30%, as shown in Figure 19 and Table 3. The absolute value of the pressure drop increase is relative and depends solely on the selected value of the reference pressure value. Selection of a lower or higher reference pressure drop changes the 30% value but does not affect the overall behavior. Pressure drop showed a consistent increase over the other sections of the fuel assembly as shown in Figure 17, 18, and 20. However, across section 1-2, where the orifice produced the major pressure drop, the pressure drop reached a local maximum value and remained at that value for a longer period

TABLE 3
CCTL MARK II-A PRESSURE DROP HISTORY

Date	Pressure Drop(6) (psi)	Flow Rate E.M. Pump (GPM)	Friction Factor (λ)	Temp (°F)	Pump Speed (RPM)	Voltage (MV)
(1) (7)						
2/11/72	23.8	528	0.0191	1100	1275	8.5
2/12/72	24.3	525	0.0197	1100	1278	8.3
2/13/72	24.6	518	0.0205	1100	1282	8.3
2/14/72	26.4	526	0.0213	1100	1310	8.3
2 15 72	26.3	523	0.0215	1100	1315	8.3
2/16/72	26.1	520	0.0216	1100	1305	8.2
(2)						
2/17/72	27.0	526	0.0218	1100	1317	8.4
2/18/72	27.0	526	0.0218	1100	1320	8.4
2/19/72	27.0	526	0.0218	1100	1325	8.4
2/20/72	27.2	526	0.0218	1100	1325	8.4
2/21/72	27.0	526	0.0218	1100	1325	8.4
(3)						
3/29/72	28.3	527	0.0228	1100	1370	8.4
(4)						
4/ 7 /72	28.4	526	0.0230	1100	1372	8.4
(5)						
5/31/72	28.9	526	0.0234	1100	1375	8.4

- (1) First day at rated conditions. First day pressure drop increased above reference, $\lambda = 0.0180$.
- (2) Conditions constant for several days
- (3) Pressure drop increases again in this period.
- (4) Date of last flow sweep
- (5) Last day of operation
- (6) Taps 3-4
- (7) From 1/27/72 to 2/11/72 flow rate ~400 gpm, temperature was 900°F

Figure 17

**PRESSURE DROP INCREASE (Taps 1-2) vs TIME
CCTL MARK IIA**

Figure 18

**PRESSURE DROP INCREASE (Taps 2-3) vs TIME
CCTL MARK IIA**

Figure 19
PRESSURE DROP INCREASE (Taps 3-4) vs TIME
CCTL MARK IIA

Figure 20

**PRESSURE DROP INCREASE (Taps 4-5) vs TIME
CCTL MARK IIA**

of time before continuing to increase than did the pressure drop over the other three sections. For all sections the pressure drop increase was asymptotic. Observe that there is less scatter in the MARK IIA initial pressure drop increase compared with MARK II.

The venturi flow meter was placed in operation on January 19, 1972 and remained in operation until the end of the test period. Before February 10, 1972 there was a 5% difference between the venturi and EM flow meters. After February 10, 1972 the venturi flow reading increased until the two flow meters agreed.

Five flow sweeps were made during MARK IIA testing and the reduced data from these tests are graphed in Figure 21. Early in the test period the friction factor behavior parallels the traditional friction factor versus Reynolds number relationship for a typical smooth stainless steel surface. Flow sweep #9 on April 7, 1972 late in the test period shows that the friction factor had become independent of the Reynolds number, which is a characteristic of a completely rough surface. The last flow sweep friction factor data shows a slight sand grain type roughness effect. In contrast to the friction factor versus Reynolds number behavior for commercial stainless steel tubes, friction factors for sand grains go through a local minimum value before leveling off in the complete rough surface region. This point is discussed in greater detail later in Section E-1.

Seizure in the CCTL centrifugal pump terminated the MARK IIA test. The test assembly was removed, with sodium intact, and shipped to HEDL where it was examined. (26) Radiographs showed a sodium void starting just below the hexagonal duct-to-nosepiece transition and extended to

Figure 21

CCTL MARK II-A FLOW SWEEPS
FRICTION FACTOR vs REYNOLDS NUMBER
 (Time Dependent Pressure Drop)
 Taps 3-4

the shield located below the rod bundle. The nosepiece was cut off. The assembly was wrapped with heating tape and heated to about 270°F to melt the sodium which drained through two 60-micron filters. An attempt to obtain several sodium samples failed when the crimps on the sample lines were not successful. A sample was obtained from the sodium remaining in the nosepiece. The assembly was in good condition; there were no loose wires, no evidence of gross vibration or damage, and no gross corrosion. The foreign particles adhering to the pin bundle were similar in size and quantity to those found during examination of the MARK II. The rod bundle, shield and nosepiece were cleaned by an ethanol bath and a rinse in de-ionized water. Each cleaning solution was filtered through 60 μ filters. A total of 425 mg of material was recovered from all filters. Twenty-two percent of the particles was a water insoluble silicon compound. Reference 26 states that the metallic composition of the particles was similar to that found during the MARK II examination.

During MARK IIA testing, two filtrations were made using a 10-micron filter. One was made on February 14, 1972 and the second on March 24, 1972. A Cr-Ni-Fe phase, which had not been detected during earlier CCTL sodium filtration, was found during the first filtration. Boron and an almost pure nickel particulate phase were found for the first time during the second filtration. In both filtrations the measured concentrations were considerably smaller than 1 ppm.

Extensive examination of the pump revealed that the shaft journal was visibly scarred and metal was missing, as illustrated in Figure 22. (22)

TABLE 4 COMPARISON OF MARK I, II AND IIA. TOTAL HYDRAULIC RESISTANCE
COEFFICIENT INCREASE

Assembly	Flow Rate		Pressure Drop		Hydraulic Resistance Coefficient Increase
	gpm		psi		%
	Initial	Final	Initial	Final	
MARK I	400	400	47.3	44.6	-7
MARK II	522	507	49.4	56	14
MARK IIA	525	526	68.7	86.3	26

Figure 22. CCTL PUMP EXAMINATION AFTER OPERATION
FOUR QUADRANTS OF SCARRED JOURNAL SHAFT

d. Cause of MARK II and MARK IIA Pressure
Drop Increase

Particulate fouling caused the pressure drop increase in both MARK II and MARK IIA. The source of the particles was mechanical and chemical wear of the pump's shaft journal. Pump malfunction occurred several days after the MARK II flow rate was increased to the reference flow rate and coincided with initiation of the pressure drop increase. Our conclusion is based on the fitting together results of the operational data and is supplemented by the following discussion and Section E-4, Analysis of MARK IIA Assembly Pressure Drop Data.

(1) The first significant fact is that although MARK I operated continuously at 1050°F for over five months there was no pressure drop increase. Thus temperature and time is not responsible. MARK I is quite similar to MARK II and MARK IIA. The major difference is the lower sodium velocity of 400 gpm (~18.6 ft/sec) for MARK I versus the 525 gpm (24.5 ft/sec) for MARK II and MARK IIA. (It might be speculated that if MARK I had been operated at the higher MARK II reference flow rate and slightly higher temperature pump malfunction might have happened earlier.)

(2) Scatter in the MARK II pressure drop increase data is caused by initiation of pump malfunction and to the shut down-startup on July 2. The fluctuation and the lower pressure drop encountered during early MARK II operation and during the first three flow sweeps was caused by incomplete wetting of stainless steel by sodium at lower flow rates and temperatures.

(3) Satisfactory operation of MARK II at rated flow and at 1050°F continued over a five day period (June 16, 1970 to

June 21, 1970) without a pressure drop increase. The sudden 4.2% flow reduction on June 22, 1970 occurred at constant pressure drop, and constant pump speed but a reduction in supplied pump voltage. This hydraulic anomaly indicates pump malfunction and the result was equivalent to a 10% hydraulic resistance coefficient increase in a single day.

(4) Once the pump started to deteriorate, the source of particulates was continuous and the particulate concentration increased upstream of the MARK II and MARK IIA assemblies. The magnitude of the pressure drop increase in MARK II was limited only by the availability of particules.

(5) Relatively large metal particles (up to 1/8 inch diameter) were found impacted on the MARK II fuel rod surfaces. Smaller particles which possessed less momentum did not adhere as strongly to the stainless steel surface and were lost during the assembly cleaning and sodium filtration process.

(6) It is only coincidental that the venturi flow meter was placed in operation simultaneously with the first pressure drop increase in MARK II. In fact we now see that the initial 20% higher venturi flow measurement was the result of and not the cause of the pressure drop increase. The difference between the venturi and the EM flow meters increased to 37% on July 17, 1970 when the venturi meter was isolated. As seen on the simplified CCTL diagram, the venturi meter is one of the first components downstream from the pump. One side of the venturi flow meter might have become partially plugged with particles from the pump.

(7) The flow sensitivity of the pressure drop increase is illustrated by MARK IIA operation. From November 1971 to

February 10, 1972 there was no pressure drop increase even though the velocity through the assembly was 19.9 ft/sec and the sodium temperature was 1000°F. On the first day at rated flow and temperature, February 11, 1972, a ~10% pressure drop increase occurred. Of the various types of fouling which cause a pressure drop increase, particulate fouling is most sensitive to velocity and Reynolds number because fluid dynamics governs transport of the particles to a surface. Another reason for the flow sensitivity, which is consistent with our thesis, is that somehow pump malfunction was aggravated by higher speeds and flow rates thereby producing more particles. Higher fluid velocities also produced higher particle momentum.

(8) Although the MARK II was operated at rated flow and temperature almost three times as long as MARK IIA, the total pressure drop increase was half that across the MARK IIA. We attribute this difference to there being a higher concentration of particles during MARK IIA initial operation at rated flow. The difference is not simply an accumulation of particles. Observe also that for both assemblies over 90% of the total pressure drop occurred during the first month of operation at rated flow. As stated above, a higher production of particles could be associated with the higher MARK IIA pump speed.

(9) Two sodium filtrations were made during the period when pressure drop was increasing across MARK IIA. During the first filtration a Cr-Ni-Fe phase, which had not been detected before, might have come from the pump. The boron-high nickel phase detected during the second filtration had to come from the pump. The pump journal shaft is coated with Colmonoy alloy which contains 77.2% Ni and 2.5% B.

(10) A simple calculation shows that as much as 0.9 lbs of metal could have been removed from the scarred journal shaft shown in Figure 22. If all this material were released at once the particulate concentration would be 120 ppm assuming the CCTL capacity is 1000 gallons. The actual concentration would be considerably lower than 120 ppm because some particles were deposited on the assemblies and the release occurred over a period of time. The only place for the missing metal to go was into the loop sodium. Moreover it was established that the scarred shaft did not happen during pump disassembly.

(11) Particles collected during two on line filtrations were equivalent to less than 1 ppm and 99% of the filtered particles was less than 2μ diameter. This measured concentration is not necessarily inconsistent with that calculated based on the missing pump material for two reasons:

- (a) A 10μ filter was used which decreases the ability to capture particles in the 4 to 8μ range.
- (b) It is difficult to select a location to sample where the particle concentration is representative of the average. For example the CCTL diagram shows that the sodium empties into the large pressure vessel before it is drawn into the pump section. The lower sodium velocity in the vessel would allow some particles to escape and settle at the bottom of the vessel. Thus there could be a significant difference in particulate concentration upstream and downstream of the pump. If the filtrations were made upstream of the pump particle concentration measurements would be low.

(12) During the final inspection of MARK IIA, sodium which had solidified in the assembly was melted and filtered producing only 450 mg of particulates. However, 60 μ filters were used and few if any particles in the important 5 to 10 μ range would be reclaimed. In addition success was achieved in sampling only the sodium in the assembly nosepiece. The particulate concentration of the sodium in the nosepiece and in the rod bundle portion of the assembly would not be expected to be the same.

(13) Because of the possibility that particles settled out in the pressure vessel, which acted as a low velocity plenum, a continuous particle source upstream of the assembly was necessary to sustain the pressure drop increase. The pump served as the continuous source when the sodium velocity was increased to the reference value.

(14) Pressure drop increase versus time for the MARK IIA assembly can be matched by a semi-logarithmic curve which is characteristic of fouling pressure drop behavior especially fouling caused by particulates or oxidation-corrosion. Refer to Figures 27, 28, 29, and 30.

(15) Of the various types of fouling which cause pressure drop changes, oxidation-corrosion, chemical decomposition, and crystallization are strongly temperature dependent. Moreover crystallization would not be expected during isothermal operation of a system.

(16) The analysis of filtered particles captured during examination of the MARK IIA was similar to that of particles found during examination of the MARK II fuel assembly and indicated that the main source of particles was a failed pump bearing. (26)

4. Flow Impedance in Other Liquid Metal Test Loops and Reactors

Fraas and Ozisik reported that an unexplained pressure drop occurred on the NaK side of a liquid metal to water heat exchanger. (27) Initially the NaK side pressure drop was approximately double the calculated value. Furthermore the pressure drop increased with time and doubled after several months of operation. They stated that the pressure drop increase was caused by a mass transfer phenomenon whereby structural metal went into solution in the hot zone and deposited in the form of tiny needle-like crystals on the tube walls of the cold zone in the NaK system. Microscopic examination disclosed that these crystals were spaced at relatively wide intervals, but apparently the crystals had a pronounced roughening effect on the walls and caused a much larger pressure drop even though there was no change in the flow passage area.

Endurance tests for 7500 hours at 1292°F and for 300 hours at 1382°F using prototypical fuel assemblies for the German SNR sodium cooled breeder reactor produced no pressure drop change. No pressure drop increase has been reported for any operating LMFBR or other liquid metal component test loops other than for the UK-Risley FETTR loop, the ANL-CCTL facility and the OARAI-PNC Japanese loop. There was one report that a pressure drop increase might have occurred across one fuel assembly tested in the EBR II; however to our knowledge it was never confirmed whether it was a true pressure drop increase or variation in instrument measurement.

In both the UK-Risley loop and the ANL-CCTL the pressure drop increase was caused by a common feature, particulate fouling resulting from component failure.

D. Experimental Investigation of Flow Impedance Phenomena

After the pressure drop increase was observed in the CCTL and OARAI facilities, experimental programs were started in attempts to duplicate and understand the results. Pressure drop data were obtained at HEDL, WARD, ORNL in the United States and at PNC in Japan.

1. ORNL Rod Bundle Tests

Four rod bundles were tested at 25 ft/sec and 1100°F isothermal conditions for 72 to 168 hours at the Oak Ridge National Laboratory. In three tests there was no pressure drop increase. During the fourth rod bundle test there was only a 2.5% pressure drop increase. These data show that Flow Impedance Phenomenon in the CCTL and OARAI facility is influenced by parameters other than high coolant temperature, flow velocity and operating time.

2. HEDL Flow Impedance Phenomena Program

The Hanford Engineering Development Laboratory has used a Flow Impedance Analysis System (FIAS), prototype Applications Loop (PAL) and a Sodium Characterization System (SCS) to investigate the occurrence of FIP.⁽²⁸⁾ By adjusting the sodium temperature in the loop, pressure drop increase was induced in the test section (flow sensor) when the temperature in the test section was reduced below the sodium temperature in the rest of the loop. The pressure drop vs time data in Figure 23 show that in one test the pressure drop increased 150%.⁽²⁹⁾ The tests have been repeated under different Reynolds numbers, system temperatures, and temperature differences. The cause of the pressure drop increase is crystallization of a silicon compound onto the surface of the test section. It has been observed that when new stainless steel is first heated above 1000°F in sodium silicon is released. ⁽³⁰⁾

Figure 23

**PRESSURE DROP INCREASE IN THE FLOW SENSOR
OF THE MEDL TEST LOOP**

The amount of silicon compound and its concentration in the HEDL test loop should be compared with that expected in LMFBR primary loops.

Crystallization as discussed earlier is a common cause of fouling. In Figure 23 a possible induction period, knee in the curve, and the linear relationship between pressure drop increase and time are seen. These are often characteristics of crystallization or chemical decomposition fouling.

3. WARD Single Heated Rod Test

Westinghouse Advanced Reactors Division (WARD) pressure drop data for sodium flowing past a single electrically heated rod test section, taken between 5/17/75 to 2/9/76, were analyzed for evidence of FIP. Sodium velocities ranged from 3 to 11 ft/sec and reference sodium test temperature was 1000°F. During test periods when flow and temperature were constant pressure drop measurements ranged from +11% to -18% around the reference pressure drop. Earlier we suggested that the increase might have been caused by FIP.(31) Following a second analysis we now conclude that the behavior to be too oscillatory to be classified as a true pressure drop increase. Post-examination of the heater rod showed no unusual surface conditions. Moreover the pressure drop vs flow relationship at the beginning of the test period was the same as that at the conclusion of the tests

4. Japanese Single Rod FIP Test Program

To obtain more detailed data concerning FIP simpler geometries such as a single cylindrical tube, a rod in a tube and a single electrically heated rod in a tube were tested in a loop especially designed for the tests.(32) Data were obtained simultaneously from two test sections which were connected in series. The test sections could be operated at

different temperatures. We don't know if the sodium and drain tank in the OARAI loop are used in the single pin test loop; this is an important factor regarding the source and concentration of particulates.

Isothermal tests were conducted first. Asymptotic pressure drop increases of various magnitudes were observed in all tests. During some of the tests mechanical filters were inserted at the inlet of each test section. The percentage pressure drop increases were generally smaller than increases seen in tests of JOYO and MONJU assemblies. Pressure drop increases were also observed during the heated rod test program; these tests are still in progress.

As with the JOYO and MONJU assembly pressure drop increases, the cause of the pressure drop in the single rod tests is concluded to be particulate fouling.

It is important that the particulate concentration and source be firmly established.

E. Analysis of Flow Impedance Phenomena Caused by Particulate Fouling

It has been shown that time dependent pressure drop increases can be caused by a variety of fouling mechanisms such as crystallization, particulate deposition, corrosion and material decomposition. There is no longer need to use the term "Flow Impedance Phenomena" (FIP); the simpler and less mysterious term "fouling" is more direct, better understood, and is consistent with the literature. Only particulate fouling will be discussed further because we have identified this mechanism to be the cause of the pressure drop increase in both MARK II and MARK IIA. In addition particulate deposition caused the pressure drop increase across the British fuel assembly in the Thermal Test Rig and the Japanese fuel assemblies in the O-ARAI Test Loop. Parameters which enter into particulate deposition rates and associated pressure drop increase are discussed in this section.

1. Pressure Drop, Friction Velocity and Laminar Sublayer Thickness

A commonly used simple model for turbulent flow through pipes assumes zero flow velocity at the wall and a laminar sublayer adjacent to the wall. The thickness of the laminar sublayer δ , which is governed by the Reynolds number and shear stress can be approximated by

$$\frac{\delta}{D} = \frac{5}{Re} \sqrt{\frac{2}{f}} \quad (1)$$

Another hydraulic parameter used to analyze particulate deposition is the friction velocity U^* which is related to

the shape of the velocity profile.

The total hydraulic resistance coefficient is composed of the friction component and a drag component. It is generally assumed that these components are additive.

$$\lambda_T = \lambda_F + \lambda_D \quad (2)$$

On a smooth surface only the λ_F component exists which decreases with increasing Reynolds number. On a completely rough surface only the λ_D component exists. In a given Reynolds number range the combined effect of decreasing λ_F and increasing λ_D produces a local minimum as shown in Figure 23. At higher Reynolds numbers the drag component becomes dominant and independent of Reynolds number. The independence occurs when the protrusions project completely out of the laminar sub layer. This behavior is illustrated by the classic sand grain experiments of Nikuradse. Commercial pipe-walls do not exhibit the local minimum in the value of the friction factor. In commercial steel pipes the protrusions are less pronounced and a small number of them are distributed over a large area.

There will be no increase in the total hydraulic resistance coefficient if the surface roughness height is less than the laminar sub layer thickness, therefore, particles which deposit from a suspension onto a surface must be larger than the sub layer thickness if the particles are to cause an effect on the friction factor. Particles can decrease the resistance coefficient if they are deposited onto a rough surface when the size of particles and roughness are comparable. In that case the particles produce a "smoothing" effect. This effect was observed by Thomas. (16) (17) (18)

Figure 24

**RESISTANCE COEFFICIENT BEHAVIOR FOR
SANDGRAIN and COMMERCIAL STEEL PIPE
TYPE ROUGHNESS**

The arrangement of the deposited particles is a significant parameter in determining the drag component of the resistance coefficient. A maximum drag coefficient exists at a specific spacing arrangement for a single layer of sand grain type particulates deposited on a surface. The relative effectiveness of a sand grain in causing resistance can be measured by the ratio of the actual height, k , to the equivalent sand roughness k_s . Figure 25 is generated from the data given by Schlichting.(33)

In analyzing pressure drop increase caused by particulate deposits we assume that only the particulates actually deposited on the surface are effective. Neither the concentration nor the concentration gradient of the particles near the surface is considered to be a factor in increasing the pressure drop. This is tantamount to assuming Newtonian flow and should be valid for the low concentration suspensions encountered (i.e. in the order of ppm). Moreover, it is assumed that only a monolayer of particles enters the pressure drop increase analysis and that given the relative roughness and particle spacing the usual friction factor vs. Reynolds number relationships or charts can be used.

2. Particulate Fouling Mechanisms

Particles in a turbulently flowing aerosol or suspension must first penetrate the laminar sub layer adjacent to a surface before they are deposited onto the surface. Even if particles have sufficient momentum to reach a surface not all of them will stick; some may bounce and not be recaptured. Particles can be captured by three principal mechanisms, diffusion, inertia impaction, and interception. If the particle size is larger than one micron capture by diffusion is often neglected. Basically, particle deposition can not

Figure 25

EFFECTIVE EQUIVALENT SAND ROUGHNESS vs SPACING RATIO

be independent of time because characteristics of the deposit-suspension system affects subsequent deposit rates.

a. Mass Flux Towards a Surface

(1) Mass Flux in Aerosols

There have been numerous studies conducted to determine the rate at which particles are deposited from aerosols onto a surface. (14) (15) (34) Although different materials and conditions were used, results are similar. Generally it is assumed that particles which reach the outer edge of the laminar sub layer have a velocity which is proportional to the friction velocity. The distance, normal to the surface, that the decelerating particle could travel before its velocity is reduced to zero in the relatively stagnant laminar sub layer is called the stopping distance, X_s .

Most of the experimental aerosol data for particle deposition rates onto smooth tubes have been correlated using two dimensionless groups, a dimensionless particle velocity v^+ , a Stanton number, and a dimensionless stopping distance X_s^+ . Over a wide range of conditions the form of the correlation is

$$v^+ = \phi (X_s^+, Re) \quad (3)$$

where

$$v^+ \equiv v/U^*$$

$$X_s^+ \equiv X_s U^* / \nu$$

$$Re \equiv DU / \nu$$

$$\nu \equiv \dot{M}/c$$

One difference in the various deposition models is the value of the particle velocity as it enters the laminar sublayer. If the initial entrance velocity is assumed to be $0.9 U^*$ and if the particle Reynolds number is in the Stokes regime, the dimensionless stopping distance and the stopping distance are

$$X_s^+ = 0.05 (U^* d_p / \nu)^2 (\rho_p / \rho_f) \quad (4)$$

$$X_s = \frac{U^* d_p^2 \rho_p}{18 \mu} \quad (5)$$

Other assumptions concerning the initial magnitude of particle velocity will change the numerical results but not the basic form of the equation for the dimensionless particle flux to a surface. Other general assumptions are that (1) particle motion obeys Stokes law, (2) the surface is smooth, (3) the deposition rate is independent of whether the particles adhere to the surface, (4) the deposition equation is for a fixed particle size, (5) the particle deposition rate is time independent. It should be noted that Equation 3 provides no insight into how particles are arranged on the surface or how the pressure drop is affected.

The data of Friedlander, who performed some of the first deposition studies from aerosols, can be expressed as:

$$v^+ = (X_s^+)^2 / 2140 \quad (6)$$

$$0.1 < X_s^+ < 10$$

$$0.8 \mu < d_p < 0.3 \mu$$

More recently Forney and Spielman investigated deposition rates for larger particle sizes and obtained three different correlations which covered the range $S_p^+ < 5$ to $S_p^+ > 30$. (34)

(2) Mass Flux from Suspensions

We found only three sources which describe particle ($>1\mu$) deposition from suspensions.* One source was the work of Thomas and Grigull which contributed substantially to our understanding of particle deposition from suspension. Their data and correlations were obtained using a magnetite-water suspension which flowed through a vertical stainless steel tube. The magnetite was made radioactive by doping with chromium-51. As discussed earlier, one importance of the Thomas and Grigull work is that they measured both the time dependent particle deposition rate and pressure drop. The particle concentration range was narrow, 1.17 and 2.08 ppm; the tube surface was rough and the mean particle size was large (20-50 μ).

The empirical equations obtained from their data for the particle deposition mass flux were:

$$\dot{N} = \dot{N}_0 \exp(-bN)$$

$$N = \frac{1}{b} \ln(\dot{N}_0 b t + 1)$$

$$\dot{N} = \frac{\dot{N}_0}{\dot{N}_0 b t + 1}$$

where

$$\dot{N}_0 = 0.6395 \cdot 10^{-8} \text{ Re}^{1.073}$$

$$b = 76.47 \cdot 10^6 \text{ Re}^{-1.361}$$

No deposition occurred when the flow Reynolds number was less than 10^4 . The asymptotic nature of the time vs. deposition rate is evident in the equation.

* Several studies have been reported which describe the transfer and deposit of crud in water reactors. However crud size is less than 1μ .

The second source of particulate deposition from suspension data found was that of Burrill. Burrill measured particle deposition rates for a water-magnetite solution which flowed through nickel or zircalloy tubes.(35) No empirical correlation of the data was presented. Burrill concluded and his data show that for the lower concentration runs the deposition rate varied directly with the particle concentration. There was a strong logarithmic relationship between suspension Reynolds number and the deposition rate. He interpreted his data as consisting of two deposition ranges. At relatively low turbulent Reynolds numbers ($<10^4$) a particle inertial coasting mechanism controlled particle deposition; at Reynolds numbers greater than 10^5 particle mass transfer controlled the particle deposition rate.

The third source of data was found in Reference 43.

It is obvious that a greater quantity of suspension data coupled with indepth theoretical analysis is required before our understanding of and our ability to predict particulate deposition from suspension are comparable to that for aerosols. Knowledge of deposition behavior is required to be able to predict pressure drop increase.

Calculated values of v^+ and X_s^+ for the CCTL MARK IIA data are compared with calculated values from the Thomas, Burrill and UK data in the section on Analysis of MARK assembly pressure drop data.

b. Adhesive and Detachment Forces

Once a particle reaches a surface adhesion must develop in order for the particle to remain fixed. Limited experimental data show that the forces of adhesion between particles and a surface are several orders of magnitude greater in aerosols than in suspensions.⁽³⁶⁾ However, to our knowledge there have been no experimental studies to determine the magnitude of particulate adhesive forces in sodium stainless steel systems. The UK data from the thermal test rig indicated that there was strong adhesion between stainless steel particles and the stainless steel fuel rod surface in sodium. In contrast washing the MARK IIA stainless steel surface with alcohol or water-alcohol mixture appears to have loosened any attached particles. There were a number of larger particles which remained impacted on the MARK IIA fuel rod surfaces. Capillary or electrical forces which exist in gaseous media are generally small in liquids. The principal contribution to the adhesive force between two surfaces in liquids comes from molecular interaction or van der Waal forces. Particular liquid properties might also generate repulsive forces. For several systems it has been shown that the adhesive force F_{ad} is directly proportional to the particle diameter d_p .

At low impact velocities, particles which strike a surface tend to adhere but as the impact velocity increases rebound may occur. Bounce can occur when the kinetic energy of the rebounding particle is great enough to escape the attractive forces at a surface.⁽³⁷⁾ However, Lifshitz⁽³⁸⁾ has suggested that adhesive forces increase as the impact velocity increases. Calculating adhesive forces is complicated because material,

shape, finish, age, temperature, prior history, and fluid media properties need to be considered.

As is well known the detachment of a particle from a surface is governed by a force balance.

Detachment of a particle from a horizontal surface occurs if

$$F_f \geq \mu (F_{ad} + W - F_l) \quad (11)$$

also

$$F_{ad} = C_1 dp \quad (12)$$

$$F_f = C_x dp^2 \frac{U_{det}^2}{2} \quad (13)$$

$$F_l = C_y dp^2 \frac{U_{det}^2}{2} \quad (14)$$

where

C_x, C_y drag and lift coefficients

U_{det} determine velocity

Putting equations 12, 13 and 14 in equation 11 gives:

$$U_{det}^2 \left(\frac{C_x + C_y}{2 \mu} \right) = \frac{C_1}{d_p} + \frac{W}{d_p^2} \quad (15)$$

The adhesive forces of small particles are much larger than their weight.

$$U_{\text{det}}^2 \left(\frac{C_x + C_y}{2\mu} \right) = \frac{C_1}{d_p}$$

or $U_{\text{det}}^2/A = C_1/d_p$

$$U_{\text{det}} = \frac{AC_1}{dp} \quad (16)$$

As seen by equations (12) and (16) large particles generally have greater adhesion but are detached more easily. The magnitude of the detachment velocity increases with decreasing particle size for a fixed duct diameter and increases with duct diameter for a fixed particle size.

A high priority need are data which describe the adhesion forces between two stainless steel surfaces in sodium.

c. Graphical Comparison of Particulate and Crystallization Pressure Drop Increase

If there is interest in determining whether the pressure drop increase is caused by particulate deposition or crystallization the following discriminators might be used:

1. The particulate deposition rate is strongly influenced by the suspension velocity or Reynolds number over a wide velocity range. All data reviewed indicate that the deposition rate increases continuously as the velocity increases. Of course if the velocity increases above a critical value the increased shear stress can start to remove some of the deposited material.

It is well known that crystal growth rates can often be correlated satisfactorily by an equation of the form

$$R = K (C - C_s)^n = K (\Delta C)^n \quad (1)$$

where R is crystal growth rate, K is the surface reaction parameter, ΔC is the local supersaturation, and n is related to the overall growth order. If mass transfer controls growth n is often unity; if kinetics controls $n > 1$. Thus if molecules arrive at a crystal surface faster than they can be incorporated, the solution velocity will not significantly increase crystal growth. Therefore pressure drop increase by crystallization should be less sensitive to the magnitude of the velocity over a wide velocity range.

2. Fouling by crystallization is often preceded by an induction period during which time there is no or little evidence of crystal growth. There is limited evidence of an induction period in Runs 3 and 4 on Figure 1. The induction period is caused by slow crystallization or slow nucleation. There is still discussion concerning the exact mechanism. Regardless of which mechanism is responsible, the length of the induction period increases as the supersaturation decreases. An induction period is also seen in the crystallization pressure drop increase data of HEDL shown in Figure 23. In contrast, pressure drop increase caused by particulate deposition is not characterized by an induction period for all the data we found.

3. Fouling on a vertical surface by particulate deposition will not occur unless the velocity is high enough at a given concentration and particle size. Crystallization depends primarily on concentration supersaturation. Crystallization fouling depends on the surface temperature-solubility relationship.

4. Fouling vs time for particulate deposition pressure drop increase produces a typical curve which is concave downward (or upward if the pressure drop decreases); crystallization would tend to produce a sigmoidal shape curve. Deposition by decomposition exhibits some of the characteristics of crystallization fouling; conversely oxidation-corrosion deposition exhibits similar particulate deposition behavior.

A suggested graphical comparison of pressure drop caused by drystallization and particulate deposition is illustrated in Figure 26.

3. Models for Time Dependent Mass Deposition and Pressure Drop Increase

Asymptotic behavior which is a common feature of both the accumulative particulate deposition and the pressure drop increase should be explained by any model which is representative. In heat exchanger design and operation the amount of deposit is expressed in terms of thermal resistance; as stated earlier, little attention has been devoted to generating pressure drop increase models.

Although particle spacing would be expected to complicate the representation of pressure drop increase models, the available data do not support this trend. Figures 27, 28, and 29 show that the pressure drop increase versus time behavior can be adequately represented by an exponential function. A similar behavior, shown in Figure 32, is true for the CCTL MARK IIA data. However during the initial pressure drop increase period the exponential relation is much steeper. It is very significant that in those tests where measurements were obtained of the mass deposit and pressure drop increase, the slopes are similar but are shifted. This simple dependence between mass deposition and pressure drop increase is unexpected. Moreover if this

CRYSTALLIZATION

PARTICULATE DEPOSITION

Figure 26 COMPARISON OF CRYSTALLIZATION AND PARTICULATE DEPOSITION PRESSURE DROP INCREASE

Figure 27 **PLOT OF PERCENT INCREASE IN
PRESSURE DROP vs TIME**

Figure 28

PARTICULATE DEPOSITION vs FRICTION FACTOR RATIO

Figure 29 **MAGNETITE DEPOSIT (g/m^2)**

Figure 30
PRESSURE DROP INCREASE vs TIME
CCTL MARK II-A

relationship is generally valid, models for deposition and pressure drop can be developed in parallel. Epstein recently published an excellent review of fouling in heat exchangers and tabulated various deposition models.⁽⁴¹⁾

The simplest asymptotic deposition model is that suggested by Kern and Seaton.^{(42) (6)} In this model, the net fouling rate, $\dot{N}$, is expressed by the difference between the deposition rate $\dot{N}_d$ and the mass removal rate $\dot{N}_r$.

$$dN/dt = \dot{N} = \dot{N}_d - \dot{N}_r \quad (17)$$

If $\dot{N}_d$ is assumed to be time independent and $\dot{N}_r$ is taken to be directly proportional to N , then $\dot{N}_r$ increases with time and approaches $\dot{N}_d$ asymptotically. Integration of Equation 17 gives

$$\begin{aligned} N &= \frac{\dot{N}_d}{b} [1 - \exp(-bt)] \\ &= N^* [1 - \exp(-t/t_c)] \end{aligned} \quad (18)$$

where N^* is the asymptotic value of m and the time constant t_c equals $1/b$ or $N^* = \dot{N}_d t_c$. The assumption that the deposition rate $\dot{N}_d$ towards the surface is independent of time simplifies the integration but is probably not correct for particulate fouling. If the deposition rate depends on the thickness of the laminar sublayer and the stopping distance then the deposition rate towards the surface could actually increase because consideration of the pressure drop increase shows that the laminar sublayer thickness decreases.

The apparent contradiction that deposition and removal (or entrainment) occurs simultaneously is resolved for a horizontal surface by Cleaver and Yates by postulating

localized turbulent bursts.⁽⁴⁴⁾ Deposition is caused by fluid back sweeps which cover larger areas and there is particle entrainment caused by the turbulent bursts. Whether the turbulent burst hypothesis is required to account for coupled deposition to and removal from a vertical surface has not been investigated.

The functional relationship for $\dot{N}_d$ is:

$$\dot{N}_d = \phi_3 [\bar{C}, (\epsilon/D), Re, U, \psi, X_s] \quad (19)$$

where (ϵ/D) is the surface relative roughness and ψ is an adhesion factor.

The particle entrainment rate, $\dot{N}_r$, relation also can be expressed by:

$$\dot{N}_r = \phi_4 [\tau, X, \psi] \quad (20)$$

where X is the thickness of the deposit. A closer look at Equations 19 and 20 shows that they are not completely independent because;

$$\tau = \phi_5 (Re, \epsilon/D) \quad (21)$$

In addition ϵ/D , ψ and S are time dependent. Thus equation 17 is in reality non-linear.

Another simple form of Equation 17 is:

$$\dot{X} = A - BX \tau / \psi \quad (22)$$

where again it is assumed that neither τ or A is time dependent. The pressure drop increase equation is of the same asymptotic form

$$\dot{\tau} = D - E \tau X / \psi \quad (23)$$

However X can not be assumed time independent. Because of the difficulty in measuring the adhesive factor, ψ , it would be expected that empirical expressions will be developed for τ or $\tau(t)$ when more data becomes available for pressure drop increases caused by particulate deposition.

4. Analysis of the MARK IIA Pressure Drop Data

Neither the MARK II nor MARK IIA assemblies were operated initially at rated flow and temperature. The flow sweep data were used to establish a reference friction factor vs Reynolds number relationship for the assembly. The reference pressure drop curve could be used to bracket the time when the pressure drop increase began. However, flow sweeps were taken at intervals of 2 months and it was necessary to place the daily pressure drop data which contained variations in temperature and flow velocity on the same basis. A common basis was required to establish more accurately the time when pressure drop increase was first observed.

The pressure drop across the assembly between taps 3 and 4 is predominately friction and is initially almost smooth. Therefore

$$\Delta p = \frac{\lambda U^2 \rho}{2D} \quad (24)$$

$$\lambda = C_1 / \text{Re}^m$$

$$\text{giving } \Delta p = C_2 \rho^{1-m} \mu^m U^{2-m} \quad (25)$$

From the flow sweep data:

$$\Delta p = C_3 U^n \quad (26)$$

Combining Equations 25 and 26 gives $n = 2-m$ and

$$\frac{\Delta P_2}{\Delta P_1} = \left[\frac{\rho_2}{\rho_1} \right]^{n-1} \left[\frac{\mu_2}{\mu_1} \right]^{2-n} \left[\frac{U_2}{U_1} \right]^n \quad (27)$$

Use of Equation 27 permits day-to-day variations in parameters to be corrected to the reference basis 525 gpm and 1100°F. The various Figures were generated using the flow sweep data, the daily pressure drop data, and Equation 27.

On April 7, 1972, the date of the last flow sweep, the friction factor had increased to 0.023 as seen in Figure 21 and Table 3. Because particulate deposits are assumed to exhibit a sand grain type roughness, $k_s/D = 0.00331$ at $Re = 97,000$, the reference Reynolds number. (Note that the relative roughness assuming commercial stainless steel tubing is only ~ 0.0015 at the same Reynolds number.)

Using Figure 25 and the assumption that the particulate deposit on the MARK II and MARK IIA assemblies was a monolayer thick, calculations were made to assess the particle diameter and spacing required to produce the approximate 30% pressure drop increase across the MARK IIA between taps 3-4.

As the particle spacing-to-diameter ratio s/d_p increases from unity the drag component increases to a maximum value and then decreases. Nikuradse used sand grains spaced at $s/d_p = 1$ and the corresponding value of k_s/D gives an 11μ diameter particle. Calculations of various hydraulic parameters for MARK IIA assembly are summarized in Table 5.

HYDRAULIC
CALCULATIONS FOR MARK IIA FUEL ASSEMBLY
(Rod Bundle Taps 3 - 4)

TABLE 5

Parameter	Initial	Final
Velocity (ft/sec)	24.5	24.5
Reynolds Number	97,000	97,000
Rod Length (in.)	48	48
Roughness (μ)	0.77	-
Equivalent Diameter (in.)	0.131	0.131
Equivalent Roughness (ϵ/D)	0.000229	0.0015
Sand Grain Equivalent Roughness (k_s/D)	-	0.00331
Laminar Sublayer Thickness (μ)	3.6	1.3
Nikuradse Sand Grain Roughness, k_s (μ) ($S/d_p = 1$)	-	11
Nikuradse Sand Grain Roughness, k_s (μ) ($S/d_p = 2$)	-	3
Nikuradse Sand Grain Roughness, k_s (μ) ($S/d_p = 3.3$)	-	6
Friction Factor (λ)	0.0180	0.0234
Friction Factor (f)	0.00448	0.00598
Wall Shear Stress (lb_f/in^2)	0.0146	0.0195
Friction Velocity (ft/sec)	1.16	1.34
Rod Surface Area (ft^2)	52	52
Total Surface Area (ft^2)	68	68

Table 6 PARTICULATE MASS REQUIRED TO PRODUCE A 30%
PRESSURE DROP INCREASE ACROSS MARK IIA ASSEMBLY

dp	s/dp	Mass Deposited	λ_f	$(k_s/D)_f$
μ	-	lb	-	-
11	1.0	1.25	0.0234	0.00331
6	3.3	0.044	0.0234	0.00331
6	1.4	0.245	0.0234	0.00331

The monolayer arrangement is illustrated in Figure 31. For 6μ diameter spherical stainless steel particles having a 3.3 space-to-diameter ratio as little as 0.044 pounds (~20 grams) on the entire assembly including wire-wrap and enclosure is calculated to be sufficient to produce the observed pressure drop.

Examination of the scarred shaft journal of the pump showed that as much as 0.9 lbs of metal could have been removed by mechanical and chemical effects. Thus the calculated amount of material is well within the amount which had been eroded from the pump shaft even if the amount was somewhat less than 0.9 lbs. Twenty grams is in good agreement with the 11 grams which caused the 90% increase in the hydraulic loss coefficient across the UK-Risley fuel assembly. In the UK-Risley assembly grids rather than wire-wrap were used and enlargement contraction losses were a significant fraction of the total pressure drop. Particles which were deposited in narrow grid flow passages would cause a proportional higher pressure drop. The MARK IIA calculations and the UK-Risley assembly data highlight the important fact that a relatively small amount of deposited material can cause

Figure 31

**FRICTION FACTOR INCREASE CAUSED BY
PARTICULATE DEPOSITION (MONOLAYER) ON A
SMOOTH SURFACE MARK-II A CONDITIONS**

$$\lambda_0 = 0.0189$$

$$\delta_0 \approx 3.6 \mu$$

$$\delta_f \approx 1.0 \mu$$

$$\lambda_f = 0.0234$$

$$k/k_s \approx 0.5$$

$$s/d_p = 3.3$$

$$k = 6 \mu$$

$$d_p/k = 1$$

a high pressure drop increase in high velocity regions where equivalent diameters are small.

Pressure drop decreased in the Thomas experiments because the particle size range was comparable to the roughness of the tubes used. This smoothing effect is modeled in Figure 32. The pressure drop change, whether it decreases or increases, appears to be proportional to the amount of particulate deposited.

Earlier we showed that the time dependence of the particulate deposit and pressure drop increase is similar. Thus if the particulate mass can be calculated pressure drop increase might also be calculated. In order to assess whether particulate deposition rates from aerosols can be used for suspensions, values of the dimensionless particle velocity v^+ and the dimensionless stopping distance X_s^+ were calculated for the UK-Risley, Thomas, Burrill and MARK IIA data and tabulated below.

TABLE 7 DIMENSIONLESS STOPPING DISTANCE AND VELOCITY

Source	$\bar{C}$	dp	X_s^+	v^+
	ppm	μ	-	-
MARK IIA	12	6.0	140	4.3×10^{-7}
UK-Risley (3)	7	5.0	82	6.4×10^{-8}
Thomas (18)	2.1	35.0	915	2.3×10^{-4}
Burrill (35)	80	0.5	0.24	4.1×10^{-5}

The range of X_s^+ for particulate deposition from aerosols is approximately 0.1 to 30 and the corresponding range of v^+ is 10^{-6} to 10^{-1} . (14) (15) A comparison with the tabulated results shows that with the exception of the Burrill data which were for small diameter particles, values of X_s^+ for the other

Figure 32

MECHANISM FOR FRICTION FACTOR DECREASE DUE TO PARTICULATE DEPOSITION

$$\begin{aligned}
 \lambda_0 &= 0.0285 \\
 D &= 0.22'' \\
 Re &= 182000 \\
 \delta &\approx 8\mu \\
 d_p &= 20 \text{ to } 50\mu \\
 \lambda_f &= 0.0171 \\
 \epsilon_0 &= 50\mu
 \end{aligned}$$

suspensions exceeded 30. However the values of V^+ were orders of magnitude lower than 10^{-1} the aerosol value corresponding to the maximum value of X_s^+ . A number of assumptions were used in the calculation of X_s^+ and V^+ in the table; nevertheless, it appears that aerosol correlations can not be used to calculate particulate deposition rates from suspensions. More suspension data are required before a definitive comparison can be made. One reason for the difference is that Reynolds number for the suspensions we investigated are higher than for aerosols and the stainless steel or magnetite density are higher than a typical aerosol particle density.

F. Implications of Particulate Fouling in Liquid Metal Breeder Reactor Operation

Assessing the consequences of particulate fouling on LMFBR operation requires answers to the following questions.

- a. Will there be fouling during typical LMFBR operation and if fouling does occur will a pressure drop increase or a cladding temperature decrease ensue?
- b. What are the differences between a LMFBR primary loop geometry and the geometries of the test loops in which pressure drop increases were observed?

There are at least two potential sources of particulates in a LMFBR primary loop. The first major source of interest is corrosion products generated by dissolution of metal in the hot leg and subsequent crystallization in the cold leg. The second source of interest is metallic or non-metallic particles which come from an extraneous source such as the failed stainless steel sprayed surface in the UK-Risley loop or the worn pump journal shaft in the Argonne CCTL. The particle size density and material are important parameters which determine whether deposition occurs in the core.

Thorley reported that the size and shape of corrosion particles in sodium-stainless steel systems are essentially independent of time and that a large part of the cold zone corrosion deposit is composed of 2μ size metallic particles. (45) Ray et al. reported that over a period of time metallic corrosion products will in many cases be converted to carbides, oxygen-sodium compounds or nitrides etc. and that the apparent density of these cold leg deposits is about 10% the density of stainless steel. (46)

Under typical LMFBR operating conditions the laminar sublayer on a fuel rod is calculated to be $\sim 3\mu$ thick. The stopping distance, X_s , for a 2μ size corrosion particle which is 1/10 as dense as stainless steel is $\sim 0.5\mu$. If the concept of stopping distance is valid for deposition from suspensions deposition rates for low particulate concentrations would be small. Even if non-metallic particles reach the cladding surface it is uncertain whether they would adhere. It is probable that non-metallic particles do not adhere to stainless steel in sodium as well as metallic particles; this important feature should be investigated experimentally. Moreover 2μ size particles are smaller than the laminar sublayer and monolayer deposition should not increase the pressure drop. Moreover corrosion products or particles generated by a dissolution-crystallization mechanism will be formed and trapped essentially in large volume, low velocity, cold regions of the primary loop such as the IHX. In summary, small size corrosion products are not of major concern in producing pressure drop increase in LMFBR cores.

The second and less probable source of metal particles could result from the failure of a component upstream of the core. Although less probable than corrosion products, pressure drop increases in the UK-Risley and Argonne CCTL are evidence

that component failure can occur. If a continuous source of metallic particles greater than $\sim 4\mu$ size were generated upstream of the reactor core a pressure drop increase across the core should be expected. It is necessary that the source be continuous over a period of at least several days. A particle burst would probable get trapped in the IHX and not recirculate. The CCTL and UK-Risley operation produced two such sources. It is possible that when the OARAI loop particulate concentration is analyzed in depth a third source will be uncovered. To us it appears that such a source can arise only by unique component failure. This is the reason pressure drop increases have not been reported from other loops and/or operating LMFBRs. If most of the particles are metallic and deposited a monolayer thick, heat transfer should not be affected adversely.

The three loops in which particulate fouling and pressure drop increases occurred were operated isothermally. In contrast in a LMBR reactor there is high heat flux and well defined hot and cold legs. The fact that the reactor is non-isothermal would affect the transport and location where corrosion products would be formed. However there would be no intrinsic influence on the generation of extraneous metallic particles. The effect of heat flux or radial temperature gradient on metallic deposition rates and adhesion in sodium-stainless steel systems requires experimental confirmation.

If selective fouling of certain fuel assemblies occurred and the hydraulic resistance coefficient increased, flow rates in the affected assemblies would be decreased. Such a decrease could be measured by assembly outlet coolant thermocouples. Use of magnetic filter might also detect metallic particle concentrations.

Experimental data coupled with more extensive analysis are necessary in order to predict accurately the magnitude of pressure drop increases which could occur in IMFBR systems. Parameters which are important and can be measured are particle size, density, material, concentration, velocity and system temperature.

G. Conclusions

1. The condition called Flow Impedance Phenomenon (FIP) is fouling, a common problem in heat exchangers. Fouling is caused by any one of several mechanisms including particulate deposition, crystallization, surface oxidation-corrosion, or chemical reaction at a surface.

2. The cause of the pressure drop increase in the MARK II and MARK IIA fuel assemblies was deposition of metallic particulates. A continuous source of metallic particles was generated by chemical and mechanical shearing at the surface of the CCTL pump journal and bearing shaft.

3. A monolayer deposit of 6-to-8 μ diameter particles spaced 2 to 3 diameters apart is sufficient to account for a 30% pressure drop increase in MARK IIA. The total mass of deposit could be less than 0.1 lbs (45 grams). Post operational inspection of the pump showed that almost 1 lb of material might be missing from the scarred journal shaft and bearing. A relatively small amount of deposited material can produce a significant pressure drop increase. This important conclusion is collaborated by the UK-FETL experience where 10 grams of deposited material produce a 70% to 90% increase in the hydraulic resistance coefficient.

Particles generated by dissolution-crystallization processes or particles which go through the core on a "once

thru" basis will deposit in a large volume, low velocity region of the loop such as the IHX.

4. Pump malfunction, which subsequently lead to pump seizure, began several days after rated flow and temperature conditions were first obtained during MARK II fuel assembly operation. This conclusion is reinforced by the fact that MARK I fuel assembly was tested for over 6000 hours without any pressure drop increase; however, MARK I operated at a 20% lower flow rate than either MARK II or IIA.

5. If a continuous source of metallic particles larger than 4 to 8 μ diameter exists upstream of the core a pressure drop increase can be expected.

6. The reason pressure drop increases have not been observed generally in LMFBR reactors or support test loops is that the most probable cause is component failure as evidenced by the failure of the sprayed stainless steel surface in the UK-FETL and pump failure in the ANL-CCTL.

7. A weak link in our ability to analyze deposition rates from suspensions is lack of accurate particle adhesion and concentration data. There is an urgent need for additional data.

8. Although the cause of the pressure drop increase in the Japanese O-arai Loop has been found to be caused by metallic particulate deposition, the source has not been clearly determined. We suggest another particulate source is present other than normal corrosion products.

9. Given the particle diameter, the particle concentration, and the hydraulic characteristics of the assembly, the maximum pressure drop can be calculated assuming an equivalent monolayer thickness.

10. A monolayer deposit of particles whose diameter is comparable to that of the laminar boundary layer thickness will not cause an increase in pressure drop. A typical corrosion product particle diameter is 2μ and the laminar sublayer thickness for a typical LMFBR fuel assembly is $\sim 4\mu$.

11. For given values of the dimensionless stopping distance X_s^+ particle deposition rates characterized by V^+ are less from solid-liquid suspensions than from aerosols. More analysis and data are required to formulate and check physical models to describe pressure drop increase caused by particulate deposition. It appears that the same models used to analyze particle deposition and removal can be used to analyze pressure drop increase. Aerosol deposition correlations grossly overestimate metallic deposition rates from suspensions where concentrations are low, particle velocity is high, and particles are somewhat larger than submicron size.

H. Recommendations

1. The term Flow Impedance Phenomena (FIP) should no longer be used because particulate fouling, a common problem in heat exchanger operation, can explain the pressure drop increase in all three situations for which the term FIP was coined.

2. All known possible continuous sources of metallic particles such as stainless steel sprayed surfaces should be removed from locations upstream of reactor cores. Although the large inlet reactor vessel plenum might isolate the core from the particle source, the designer cannot assume isolation to be effective.

3. Experimental data are required to determine the conditions which control the adhesion and detachment of metallic particles at stainless surfaces in sodium under typical LMFBR conditions. Effects of non-isothermal systems, particle size, flow velocity and particle concentration also must be determined.

4. The analytic program to develop models to explain and predict the rate and maximum pressure drop increase caused by particulate deposition should be continued. Both the experimental and analytical program should be given priority.

5. Accurate on-line methods to determine particulate concentrations should be developed, and a study should be made to determine a location where representative particulate samples can be obtained. Use of magnetic filters to measure metallic particles concentrations should be investigated.

6. If the hydraulic resistance increases $\geq 10\%$ or the flow rate decreases $\geq 4\%$ across a LMFBR fuel assembly, component failure is likely the cause and the reactor should be shut down; these preliminary criteria should be investigated.

Nomenclature

A, B, D, E	parameters
b	parameter
C	concentration
$\bar{C}$	average particle concentration
C	constant
D	equivalent diameter
d_p	particle diameter
F_f	frontal force
F_{ad}	adhesive force
f	Fanning friction factor
K	surface reaction parameter
k	actual sand grain height
k_s	equivalent sand grain height
n, m	pressure drop exponential functions
$\dot{N}$	particle flux
ΔP	pressure drop
Q/A	heat flux
R	crystal growth rate
Re	Reynolds number
s	particle spacing
T	temperature
t	time
t_c	time constant
U	velocity
U^*	friction velocity
U_{det}	detachment velocity
V	particle velocity parameter
V^+	dimensionless deposition velocity
X	deposit thickness
R_f	fouling thermal resistance

x_x^+	dimensionless stopping distance
x_s	stopping distance

Subscripts

d	deposition
F	friction
f	fluid, final condition
p	particle
r	removal
T	total
o	initial condition
1,2,...	constants or functions

Greek Letters

δ	laminar sublayer thickness
ϵ	pipe roughness
λ	Moody friction factor
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	shear stress
Φ	functional relationship
ψ	adhesion parameter

References

1. "Reactor Program Development Progress Report," ANL-RPD-5, Argonne National Laboratory, May 1972.
2. "Sodium Flow Test Results for a Simulated Core Fuel Subassembly of the Experimental Fast Breeder Reactor JOYO," Power Reactor and Nuclear Fuel Development Corporation Report JAPFNR-40, April 1972.
3. F. I. Buckley and G. K. Greenslade, "Endurance Test on a 163 Pin PFR Type Sub Assembly in Sodium at 650°C," TRG Report 2026 (R).
4. Communications Y. Himeno to A. A. Bishop.
5. J. Taborek et al., "Fouling - The Major Unresolved Problem in Heat Transfer, Parts I and II," 12th National AIChE-ASME Heat Transfer Conference, Tulsa, Oklahoma, August 1971.
6. D. Q. Kern and R. E. Seaton, "A Theoretical Analysis of Thermal Surface Fouling," British Chemical Engineering, 4, p258, May 1959.
7. A. P. Watkinson and O. Martinez, "Scaling of Heat Exchanger Tubes by Calcium Carbonate," ASME paper 76-HT-H.
8. J. W. Suitor et al., "The History and Status of Research in Fouling of Heat Exchangers in Cooling Water Service," 16th National Heat Transfer Conference, 76-CSME/CSCHE-19.
9. O. K. Smirnov and Yu P. Michurov, "Investigating the Thermohydraulic Characteristics of Steam Generating Tubes Under Conditions of Formation of the Solid Phase of Impurities in the Medium at Supercritical Parameters," Teploenergetika 22 (7) pp 83-85, 1975.
10. P. W. M. Jacobs, "Kinetics of Thermal Decomposition of Solids," Kinetics of Reactions in Ionic Systems, Plenum Press, pp. 37-52, 1969.
11. H. Buchberg et al., "Final Report on Studies in Boiling Heat Transfer," COO-24-UCLA March 1951.
12. R. Richter et al., "Magnetite Formation and Pressure-Loss Increase in a Benson Boiler," ASME-71-WA/HT-44.
13. S. K. Friedlander and H. F. Johnstone, "Deposition of Suspended Particles from Turbulent Gas Streams," Ind. Engng. Chem. 49, pp 1151, 1957.

14. T. Kneen and W. Strauss, "Deposition of Dust from Turbulent Gas Streams," *Atmospheric Environment* 3, pp 55-67, 1969.
15. B. Y. H. Liu and T. A. Ilori, "Aerosol Deposition in Turbulent Pipe Flow," *Environmental Science and Technology* 8, 4, pp 351-355, April 1974.
16. G. Blank and D. Thomas, "The Benson Experimental Assembly and the Steam Laboratory of Siemens Zeitschrift No. 3, pp 139-151, 1968.
17. D. Thomas and U. Grigull, "Experimental Investigation of the Deposition of Suspended Magnetite from the Fluid Flow in Steam Generating Boiler Tubes," *Brennst-Wärme-Kraft* 26, 3, pp 119-115, 1974.
18. Communication D. Thomas to A. A. Bishop.
19. A. P. Watkinson and N. Epstein, "Gas Oil Fouling in a Sensible Heat Exchanger," *Chem. Eng. Progr. Sym. Ser.* 65, 92, pp 84-90, 1969.
20. Reactor Program Development Progress Report, ANL-RPD(6) Argonne National Laboratory, June 1972.
21. Reactor Program Development Progress Report, ANL-RPD(7) Argonne National Laboratory, July 1972.
22. Communication F. Smith to A. A. Bishop.
23. E. N. Hodkin et al., BNES London, p167, April 1973.
24. Communication E. Novendstern to A. A. Bishop.
25. R. L. Myers, "CCTL MARK II Fuel Assembly Interim Examination and Modification," HEDL-TME-72-39, May 1972.
26. R. L. Myers, "CCTL MARK II and IIA Final Examination," HEDL-TME 74-8, February 1974.
27. A. P. Fraas and M. N. Ozisik, "Heat Exchanger Design," John Wiley and Sons, 1965.
28. W. Yunker, "Formation and Hydraulic Effects of Deposits in High Temperature Sodium Sodium Coolant System," *Proceedings of the International Conference on Liquid Metal Technology in Energy Production*, pp 698-701, 1976.
29. J. M. Atwood, "Sodium Engineering and Technology Technical Progress Report," HEDL-TME 76-26, pp 76-84, April-June 1976.

30. J. M. Atwood, "Sodium Engineering and Technology Technical Progress Report," HEDL-TME 78-21, April-June 1978.
31. A. A. Bishop et al., "Mass Transfer Related Pressure Drop Fluctuations in Flowing Sodium Systems," Proceedings of the International Conference on Liquid Metal Technology in Energy Production, pp 702-708, 1976.
32. Communication Y. Himeno to A. A. Bishop.
33. H. Schlichting, Boundary-Layer Theory, McGraw-Hill, p 587, 1968.
34. L. J. Forney and L. A. Spielman, "Deposition of Coarse Aerosols from Turbulent Flow," Aerosol Science 5, pp 257-271, 1974.
35. K. A. Burrill, "The Deposition of Magnetite Particles from High Velocity Water Onto Isothermal Tubes," AECL-5308, February 1977.
36. A. D. Simon (Translated by M. Corn), "Adhesion of Dust and Powder," Plenum Press, 1969.
37. N. A. Esmen et al., "The Adhesion of Particles Upon Impact," J. Aerosol Science 9, pp 547-556, 1978.
38. H. Krupp, Particle Adhesion Theory and Experiment, Advances Colloid Interface Sci. Bd 1, 1967.
39. J. C. Brice, "The Kinetics of Growth from Solution," J. of Crystal Growth 1, pp 218-224, 1967.
40. A. R. Konak, "A New Model for Surface Reaction-Controlled Growth of Crystals from Solution," Chem. Eng. Science 29, pp 1537-1543, 1974.
41. N. Epstein, "Fouling in Heat Exchangers," Sixth International Heat Transfer Conference 5, pp 235-253, August 1978.
42. D. Q. Kern, Chemical Engineering Progress 62, 7, p 51, 1966.
43. R. M. Hopkins and N. Epstein, "Fouling of Heated Stainless Steel Tubes by a Flowing Suspension of Ferric Oxide in Water," Proceedings of the International Heat Transfer Conference, paper HE 1.6.

44. J. W. Cleaver and B. J. Yates, J. Colloid and Interfacial Science 44, p. 464, 1973.
45. A. W. Thorley et al., "Fission and Corrosion Product Behavior in Primary Circuits of LMFBRs: A Status Review of Work Being Done in the UK TRG-Report 2856(R).
46. W. E. Ray et al., "The Structure of Sodium Corrosion Deposits and Their Effect on Heat Transfer Coefficients," Nuclear Technology, 16, October 1972.
47. A. A. Bishop et al., "Heat Transfer Effect of Entrained Gas in Liquid Sodium Systems," Nuclear Engineering and Design 52, pp 1-13, 1979.