

QUARTERLY TECHNICAL PROGRESS REPORT ON AEC-SPONSORED ACTIVITIES

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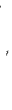
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ABSTRACT

This report is a summary of the technical progress made by Atomic Power Development Associates, Inc., in the period October through December 1969 under AEC Contract No. AT (11-1)-865. The individual projects are covered under the following headings:

Sodium-Water Reaction Test Program
Project Agreement No. 10

Sodium Technology Project
Project Agreement No. 11

Comparison of Methods for Heterogeneity Analysis
Project Agreement No. 19



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The results of four additional wastage tests are summarized and problems arising during the tests are related. Detailed analysis of all Rig-10 wastage data is continuing, and preparations are under-way for testing in Rig 43 with steam injections.

Other effort reported is acoustic leak detection and hot erosion studies.

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Performance evaluation of the APDA hydrogen detector is reported. Documentation of the work on impurity monitoring devices and sodium purification processes is also covered.

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Analysis was completed of ZPR-III Assembly 48 comparing results obtained with volume-weighted and flux-weighted cross sections to obtain the effects of plate heterogeneity on assembly reactivity and sodium voiding. A review was initiated of bilinear averaging techniques used to obtain spatially averaged cross sections.

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SODIUM-WATER REACTION TEST PROGRAM

PROJECT AGREEMENT NO. 10

PROJECT ENGINEER:

H. V. CHAMBERLAIN

I. PREFACE

A. Background Information

Achievement of the LMFBR program objectives is highly dependent on the development of reliable system components. With regard to the current status of development, the steam generator is recognized to be the weakest link in the heat transport system. The question of what occurs in a steam generator during a sodium-water reaction and how to accommodate such a reaction in the design has been a problem since the inception of sodium- and NaK-cooled reactors. The damage resulting from a reaction may be caused by water leaks of two general categories: large leaks and small leaks. Until recently designers have been concerned with large leaks such as those resulting from the complete circumferential rupture of a water tube. However, in late 1962 a steam generator in the Enrico Fermi Atomic Power Plant (EFAPP) experienced a sodium-water reaction due to a tube failure produced by vibration. Subsequent examination of the unit indicated that a general corrosion had occurred in the area of the sodium-water reaction, producing wastage and failure of some of the adjacent tubes. It is not known at what stage in the propagation of the leaks the wastage occurred; that is, did the wastage occur as a result of the initiating leak, or did it occur as a result of the subsequent leaks? The questions raised by this experience clearly indicate that a sodium-water reaction program should consider both small and large leaks. Subsequent to the EFAPP experience, the British conducted some tests in which they found that significant tube wastage rates can be incurred with small leaks.

B. Scope

As part of the AEC program of steam generator development, a project was initiated at APDA for the purpose of investigating both small and large leaks. A series of tests is being run to

- Establish a means of estimating the extent of tube wastage during a small leak of water into sodium in a sodium-heated steam generator.

- Determine the dominant parameters of tube wastage during a small water leak so that these parameters may be taken into account in the design of a unit.

C. Relationship to Other Projects

This program is applicable to the development of sodium-heated steam generators and to the technology of sodium-water reactions in the LMFBR program. Data generated in the program will be used to prepare design criteria and design analysis procedures for steam generators from the standpoint of sodium-water reactions. All of the activities of this program are within the scope of the Components Element (Vol. 3) of the LMFBR Program Plan (Wash 1103). However, some of the activities interface with the Instruments and Control Element (Vol. 4) of the Program Plan. With regard to sodium-water reactions in steam generators, the emphasis in Program Element 3 is on developing information related to mechanisms producing wastage and to the effect of various system parameters and jet characteristics on material wastage. In Program Element 4, the emphasis is on evaluating and on demonstrating leak detection systems which would minimize damage to the steam generator and secondary heat transport system.

Information on the test program and the results to date are available in the proceedings of the Sodium Components Development Program Information Meetings held on April 14, 1964, in Hollywood, California, and on June 17, 1965 in Chicago, Illinois; APDA quarterly technical progress reports on AEC-sponsored activities; in the following papers: "An Investigation of Tube Wastage Caused by Small Leaks of Water in Sodium-Heated Steam Generators," presented at the IAEA Symposium on Alkali Metals - Corrosion Studies and Systems Operating Experience, held at Vienna, Austria, November 28 to December 2, 1966; "Tube Wastage in Sodium-Water Reactions" and "Surface Temperature Measurements in Sodium-Water Reactions," presented at the American Nuclear Society Winter Meeting in Chicago, Illinois, in November, 1967; "Sodium-Heated Steam Generators," presented at the American Nuclear Society National Topical Meeting on Fast Reactor Systems, Materials, and Components, held in Cincinnati, Ohio, in April, 1968; and "Wastage of Steam Generator Materials by Sodium-Water Reactions," presented at International Conference on Sodium Technology and Large Fast Reactor Design, held at Argonne National Laboratory, Argonne, Illinois in November 1968; and a report, "Evaluation of Materials Wastage Due to Reactions of Water in Sodium," APDA-227, June, 1969.

II. TECHNICAL PROGRESS

A. Rig-10 Tube Wastage (Task 20)

J. A. Ford
G. H. Reicks
T. Iguchi

The objective of this task is to establish a means of estimating the extent of tube wastage during a small leak of water into sodium in a sodium-heated steam generator.

1. Job 02 - Test Planning

The scope of the FY-70 program is to conduct 12 material wastage tests by the end of June 1970. The tests will be made using 2-1/2 Cr-1 Mo steel as the target material with nozzle-to-target spacings of 1/4 inch, 1 inch, and 2 inches. The water injection rate will range from approximately 0.005 to 1.5 lb/sec; the bulk sodium temperature will be approximately 600 F. The objectives of the tests are to (1) clearly confirm the phenomenon of a decreasing wastage rate that was observed at leak rates beyond approximately 0.01 lb/sec, (2) determine the effect of nozzle L/D on the wastage pattern, and (3) obtain preliminary wastage data for a two-inch leak-to-target spacing.

2. Testing (Job 03)

a. Wastage Results

Four additional wastage tests (Tests No. 46, 47, 48b and 51) were completed during this report period. A summary of the test data is given in Table 10.1 and the wastage results for the target tubes are shown in Figure 10.1.

As indicated in the previous progress report,¹ plugging problems in the injection nozzle were encountered in Tests No. 48 and 48a, which used nominal 8-mil-diameter capillary. Because of this problem, preparation for Test No. 48b included flow-testing of the 8-mil capillary material before fabricating it into nozzles and then flow-checking 5 test nozzles before actually conducting the test. Initial flow-testing of the test nozzles was successfully conducted; however, during a second flow test of each nozzle one of the nozzles plugged. Following removal of the plug by inserting a small-diameter wire into the capillary, this nozzle was again successfully flow-tested. Also, the other test nozzles were successfully flow-tested a third time. Based on these tests, it was concluded that the procedure for preparation of the capillary material and the nozzle was satisfactory and that this procedure could be used successfully to conduct Test No. 48b.

TABLE 10.1
SUMMARY OF PRELIMINARY DATA
FROM RIG-10 TESTS

	TEST NO.			
	48b	46	47	51
SODIUM SYSTEM				
Flowrate, gpm	400	400	400	400
Velocity past target tube, ft/sec ~	2	2	2	2
Bulk temperature, F	603	600	610	606
Sodium level above injection, point, ft	8.3	8.6	8.3	8.3
Plugging temperature, F				
Before injection	395	400	390	398
After injection	460	← Saturated →		
INJECTION WATER SYSTEM				
Water added, lb	0.24	10	20	20
Temperature, F	603	600	610	606
Pressure, psig	2650	2650	2650	2650
Orifice size, in.	0.0084	0.043	0.062	0.059
Orifice length, in.	0.31	0.285	0.22	-
Injection point-to-target spacing, in.	← 1/4 →			1
Injection duration, sec	54.9	50.4	62.5	59.5
Injection rate, lb/sec	0.0044	0.20	0.32	0.34
RECIRCULATION WATER SYSTEM				
Pressure, psig	← 100 →			
Coolant	← N ₂ →			
WASTAGE - TARGET TUBE				
Tube material	← 2-1/4 Cr-1 Mo →			
Wastage pattern	← Toroidal →			
Depth penetration, mils	20	15	4	12
Wastage rate, mils/sec	0.37	0.30	0.064	0.20
Wastage rate, mils/lb H ₂ O	83.3	1.5	0.2	0.6
Maximum measured tube temperature, F	1444	1870	1817	1821
Time of maximum temperature, sec	39.9&45.9	48.7	5.8	60.5*
COVER GAS				
Pressure, psig				
Before injection	5	5	5	5.2
During injection, peak	11.5	15.0	19	26.9**
Hydrogen concentration				
Before injection, ppm	7,400	8,400	9,000	16,000
Peak during test, ppm	41,500	300,000 (est)	540,000	572,000
Change in concentration, ppm	34,100	291,600 (est)	531,000	556,000
Rate of change, ppm/sec	292	3,823	7,920	7,996
Elapsed time between leak initiation and initial H ₂ change, sec	59	54	60	45
Elapsed time between leak initiation and peak concentration, sec	244	228(est)	158	142

* One second after end of injection

** Four minutes after injection.

Test No. 48b was conducted with a leak-to-target spacing of 1/4 inch and a leak of approximately 0.0044 lb/sec; all measurements indicated that the test was successful and no plugging of the nozzle had occurred. This test ran for 54.9 seconds, which is somewhat longer than the predicted duration of 48 seconds.

The preliminary results of Test No. 48b are given in Table 10.1. The examination of the temperature chart showed that a notable rise in temperature occurred when the test was triggered and no thermocouples decreased below the initial temperature of 603 F. The maximum temperature of 1444 F was measured on thermocouple No. 2 after 39.9 seconds and again after 45.9 seconds of the test run. The temperatures of the thermocouples in the target area during the injection period were in the range of 900 to 1400 F. Four of the six target area thermocouples indicated cyclic behavior with an average frequency of approximately 8 cps. The maximum temperature was recorded on thermocouple No. 2, which was in the 2:00 o'clock position on the target tubes; however, thermocouple No. 4, in the 6:00 o'clock position, registered high temperatures consistently throughout the test. This may have been caused by a slight change in the direction of the jet, which could have resulted from a reaction product build-up in the target area.

A significant build-up of reaction products was noted in the target area, and a uniform coating of products was contained on the rest of the bundle. The wastage consisted of a shallow pit approximately 1/4 inch in diameter with a very small plateau in the center approximately 1/16 inch in diameter. This small plateau underwent slightly less wastage than the rest of the material in the pit. The maximum depth of wastage was 20 mils, yielding a wastage rate of 0.3 mil/sec. This rate is considerably below that which would be predicted based on the results of all previous tests at 1/4-inch spacing.

The results of this test appear to correlate better with the results for the tests having a 1-inch spacing rather than with the tests having 1/4-inch spacing. A significant difference between this test and the others of 1/4-inch spacing at leak rates in the range of 10^{-3} to 10^{-2} lb/sec was the type of wastage pattern observed. Most of the tests in this leak rate range for 1/4-inch spacing indicated well-defined pits of very small diameter. In Test No. 48b damage was relatively large in diameter and the edges of the pit were not well defined as in previous tests. The results of this test, therefore, tend to indicate that there is some variable that affects the wastage pattern which was not maintained constant between the previous 1/4-inch-spacing tests and Test No. 48b.

Test No. 46 was conducted with a leak-to-target spacing of 1/4 inch and a leak rate of approximately 0.20 lb/sec to determine the effect of increased leak rate on wastage. This test ran for a duration of 50.4 seconds, which compared favorably with the predicted duration of 54 seconds.

The preliminary test results from Test No. 46 are given in Table 10.1. Inspection of the high-speed oscillograph temperature chart indicated that all six target thermocouples dropped below 300 F immediately after the injection started and were very erratic thereafter. At the end of the injection period, thermocouples indicating high temperatures dropped off rapidly while thermocouples indicating temperatures below the bulk sodium temperature suddenly increased to indicate high temperatures. Inspection of the temperature charts from those tests with large injection rates shows that a significant temperature change occurs in the reaction zone when, it is assumed, essentially all of the water has been injected. The observance of continued high temperatures beyond this point is assumed to be produced by a splitting action of a gas-liquid mixture as the reservoir becomes completely empty; this time period usually ranges from 5 to 10 seconds. The acoustic results appear to substantiate this assumption because they show a significant reduction in amplitude of signal where the temperature changes. The maximum measured reaction temperature of 1870 F occurred 48.7 seconds after triggering on thermocouple No. 6 in the target area. The cover gas pressure increased from 5 psig to 15 psig during the injection period.

Inspection of the tube bundle after the test revealed a large deposit of reaction products in the lower third of the tube bundle. The target area was relatively clean, while the flow paths below the target area were almost completely plugged with deposits of reaction products. A preliminary inspection of the tube bundle assembly indicated very little wastage on the target tube, but damage had occurred as far away as the inner cylinder, which was at least 5 inches from the injection point. Wastage on the adjacent tubes was as high as 45 mils penetration (0.89 mil/sec). In total, 9 adjacent tubes in rows A, B, and C had some wastage. Table 10.2 summarizes this data and also includes data from other tests where wastage occurred on adjacent tubes. The inner cylinder also had wastage; the depth is estimated to be approximately 15 mils for a distance of about 5 inches. The wasted area was directly behind the gap between tubes A-5 and A-6. Wastage also occurred on some thermocouple clips and the tube support brackets.

Test No. 47 was conducted with a leak-to-target spacing of 1/4 inch and a leak rate of approximately 0.32 lb/sec to determine the effect of a further increase in leak rate on wastage. This test ran for a duration of 62.5 seconds, which compared well with the predicted duration of 64 seconds. All measurements indicated that the test was successful and no plugging of the nozzle occurred.

The preliminary test results for Test No. 47 are given in Table 10.1. Analysis of the high-speed oscillograph temperature chart indicated the six target thermocouples dropped to 240 to 340 F from approximately 600 F immediately after triggering. For the remainder of the injection period the thermocouple temperatures behaved in a very

TABLE 10.2 - SUMMARY OF WASTAGE DATA ON
TUBES ADJACENT TO TARGET TUBE

MATERIAL - 2-1/4 Cr-1 Mo

Test No.	Leak Rate, lb/sec	Tube Location*		Penetration, mils	Wastage Rate, mils/sec
		Row	No.		
41	0.071	B	3	10	0.36
		B	5	15	0.54
44	0.077	B	5	7	0.48
46	0.20	C	2	13	0.26
		B	2	28	0.56
		B	3	45	0.89
		B	4	19	0.38
		B	5	18	0.36
		B	6	26	0.52
		A	2	10	0.20
		A	3	21	0.42
47	0.32	A	6	15	0.30
		C	5	45	0.72
		B	3	27	0.43
		B	5	17	0.27
		A	2	~65**	>1
A	3	~65**	>1		
51	0.34	C	1	10	0.17
		C	2	~2	0.03
		C	3	~2	0.03
		C	5	7	0.12
		C	6	10	0.17

* The target tube is C-4

** Completely penetrated

erratic manner. Some temperatures remained submerged throughout most of the injection period, while other temperatures were cycling to very high temperatures. An unusual temperature indication during this test was that the highest recorded temperature of 2002 F did not occur on the target tube but was measured on thermocouple No. 11, which is located on a B row tube (B-5) directly behind the target tube; this maximum temperature was measured 48.2 seconds after the injection was initiated. The maximum temperature measured on the target tube (1817 F on thermocouple No. 2) occurred 5.8 seconds after the test was initiated.

Inspection of the tube bundle after the test indicated a large build-up of reaction products with an approximate 1-1/2-inch-thick layer on top of the outer skirt assembly, and with large reddish brown deposits both above and below the target area. The target area itself was relatively clear of deposit. An extended period of 2-1/2 hours of steam-cleaning was required to complete the removal of deposits from the tube bundle. First inspection of the cleaned tube bundle assembly showed a very nominal amount of wastage on the target tube, which was confirmed later by preliminary measurements to be approximately 4 mils in maximum depth, yielding a wastage of 0.064 mil/sec. Disassembly and further inspection of the tube bundle revealed some very startling results: First, the tube directly below the target tube showed a very deep penetration of 56 mils and 1-7/8 inches in length (Figure 10.2a). Tube B-5, behind the target tube and one row down, was wasted to a depth of 17 mils; the pattern of wastage showed an imprint of a thermocouple on the surface. The thermocouple that was attached to this tube was wasted to a small diameter for a distance of 1-1/2 inches from the hot junction. Tube B-3 had wastage 27 mils deep. The support strap on this tube was completely wasted through at this point (the support bracket is fabricated of 40-mil-thick carbon steel). The wasted area on tube B-3 was measured to be 2-3/4 inches distant from the injection point. Inspection of the A row of tubes, which is two rows in from the target tube, showed that tube A-3 was completely penetrated for a longitudinal distance of 2-1/4 inches and a width of 11/32 inch, and the total wasted length covered a distance of 3-1/4 inches (see Figure 10.2b). The wasted area was in the shape of a tadpole. Also, the exposed edges of the wasted areas were wasted to a very sharp, knifelike edge. The penetration in this tube was 3-1/4 inches distant from the injection point. Tube A-2, directly above tube A-3, was completely penetrated for a distance of 1-9/16 inches and a width of 3/16 inch (see Figure 10.2c). The wastage pattern was similar to that of tube A-3, except that the tadpole was swimming in a reverse direction. The wasted area on tube A-2 was a distance of 4 inches from the injection point. Between tubes A-2 and A-3 and directly behind on the carbon steel inner cylinder there was a wasted area over 5 inches long with a maximum depth of 56 mils. This wasted area was 5 inches from the injection point. The tube support bracket to the left of the wasted area on both tubes A-2 to A-3 was completely penetrated (both places).

Test No. 51 was conducted with a leak-to-target spacing of 1 inch and a leak rate of approximately 0.34 lb/sec to determine the effect of increased spacing on wastage at higher leak rates. This test ran for a duration of 59.5 seconds, which compared well with the predicted duration of 64 seconds. All measurements indicated that the test was successful and no plugging of the nozzle occurred. The preliminary results of Test No. 51 are given in Table 10.1.

Immediately after triggering, the temperature in the reaction zone increased and further analysis of the high-speed oscillograph temperature chart after the test indicated that the maximum temperature of 1821 F occurring on thermocouple No. 6 occurred 60.5 seconds after triggering, or approximately 1 second after the normal injection was completed. Again it was noted that at the end of the injection period some temperatures decreased while others increased. The maximum temperature during the main injection period (1585 F occurring on thermocouple No. 3) occurred 37.3 seconds after triggering. The period of the temperature cycles on all target thermocouples averaged 0.2 second and was consistent throughout the test period. This short, steady cycle is very unusual when compared with previous tests, in that the periods of temperature cycle in previous tests were usually longer and varied more from thermocouple to thermocouple and throughout the test period.

Inspection of the tube bundle after the test but prior to steam cleaning revealed no large build-up of reaction products. The build-up was only 3/4 inch deep on top of the outer skirt assembly compared to 1-1/2 inch deep observed in Test No. 47. A reddish brown deposit surrounded the inspection plate on the outer skirt assembly except for several polished areas surrounding the inspection plate. The tube bundle was free of large deposits and the target area was clean. There appeared to be a sharp boundary between the clean and coated areas.

After steam cleaning, an inspection of the target area revealed that the guillotine and nozzle were askew of the target and that there was considerable wastage on the guillotine. The inside surface of the inspection plate was wasted for a length of 9-1/4 inches and a width of 10-1/2 inches. The pattern of wastage suggested that the material producing the wastage had flowed upward and fanned out. Also, apparently some water or steam flowed between the inspection plate and outer skirt assembly, as indicated by the wastage areas on the outside surface of the skirt assembly above the inspection plate. The outside surface of the skirt assembly where the inspection plate overlapped had a warped appearance. The lower cutter bar of the guillotine was severely wasted along with the inner surface adjacent to the upper cutter bar. All of this wastage occurred behind the nozzle in reverse of the normal injection direction. Somehow injection water must have been deflected backwards, possibly by the upper cutter bar or by some other obstacle such as flashback from the C row of tubes. Examination of the tube bundle and trigger mechanism is continuing in an effort to determine what caused this unusual wastage behavior.

The wastage observed on the tube bundle itself was quite small and was insignificant when compared to that observed in Test No. 47, which was conducted under almost identical conditions except that the leak-to-target spacing was 1/4 inch instead of 1 inch. The target tube (C-4) had approximately 12 mils wastage and also showed a very slight

impression of thermocouple clips for thermocouples 3 and 4. Tube C-1 had an estimated wastage for a distance of 1-1/2 inch with a depth of 5 mils. Tube C-3 had the impression of a thermocouple clip and was wasted for a depth of 10 mils. Tube C-5 had an impression of thermocouple 8 and its stainless steel clip. Other tubes that had polished surfaces were C-7 and B-5. These wastage data are presented in Figure 10.3.

Of particular interest is the wastage obtained on tubes adjacent to the target tubes. One important observation is that the wastage rates on these tubes are for the most part significantly less than the highest wastage rate obtained to date (3.4 mils/sec on the target tube from Test No. 37). Since tubes A-2 and A-3 were completely penetrated over a wide area in Test No. 47, their wastage rates may be greater than 3.4 mils/sec; however, determining the actual wastage rate is not possible. In Figure 10.3, the wastage rates on the adjacent tubes are compared to a curve based on maximum wastage rates for tests conducted in systems both with and without flowing sodium.² As can be seen, the wastage rates on adjacent tubes are 1/10 to 1/40 of the maximum wastage rates seen. Thus, although under some conditions the wastage rates on adjacent tubes can be considerably higher than that on the target tube, they are significantly lower than the maximum rates obtained in various test apparatus.

In both Tests No. 46 and 47 wastage of the wall of the inner cylinder strongly suggests that more extensive wastage would probably have occurred if, instead of the cylinder, there were additional rows of tubes. The occurrence of this extensive wastage points out the need for inspection of a wide area of the steam generator if a leak of that magnitude (~0.3 lb/sec) occurs.

3. Test Analysis (Job 04)

M. K. Deora

The scope of this job is to perform additional detailed analysis of all Project-10 wastage data to (1) provide a better understanding of the material wastage phenomena, (2) determine the most meaningful correlation of the data, and (3) provide guidance for the experimental program to be conducted in FY-70.

Review of the symposium³ on deformation of solids by impact with liquid was completed. The main objective of the review was to gain an understanding of the wastage process that occurs on materials from liquid jet impacts, and further to compare these results with the existing Rig-10 wastage rates and patterns to determine the possible similarity between the two types of experiments. A draft memorandum summarizing the information gathered from this survey has been completed and is ready for internal review. The results of this review will be presented in the next progress report.

The remeasurement of the diameter and length of the capillaries used in all Rig-10 wastage tests has been completed and are shown in Table 10.3. It should be noted that the values reported are somewhat higher than those reported in earlier progress reports. In the previous progress report a discussion was presented comparing the results of Tests No. 37 and 45 to determine the effect of capillary L/D on the type of wastage pattern produced. Because of an apparent anomaly between the measured capillary diameters, which were significantly different, and the flow rates, which were essentially the same, the effect of capillary L/D on wastage pattern could not be established. Although the remeasured diameter for the capillary from Test No. 37 is now much larger than previously (9.7 versus 7.9 mils) the remeasured diameter for Test No. 45 is also somewhat larger (11.6 versus 10.0 mils). Therefore, a conclusion on the effect of capillary L/D on type of wastage pattern is still not possible.

B. Rig-43 Tube Wastage (Task 21)

J. A. Ford
G. H. Reicks

The objective of this task is to perform scoping wastage tests to establish the significance of various system parameters on material wastage during small sodium-water reactions. The three series of tests to be conducted in FY-70 are (1) tests to extend the range of leak rates for which correspondence checks are made between Rig 10 and Rig 43 and to determine the effects of injection water pressure on material wastage rates, (2) tests to determine the effect of steam injection on material wastage rates, and (3) tests to determine the effect of water leaks in the gas space on material wastage rates. The first series of tests has been completed¹ and modifications to Rig 43 are currently being made in order to accomplish the remaining two series of tests.

1. Design, Procurement, and Fabrication
of Steam Injection System (Job 06)

Fabrication and installation of the steam injection system was completed by the outside contractor. The system is now ready for APDA to install heater instrumentation and thermal insulation.

2. Water Injection into Gas Space Design (Job 11)

a. Justification

Leakage of water into sodium may occur at any location along the barrier separating the two fluids in a sodium-heated generator. Past experience with sodium-heated steam generators indicates that if leakage occurs in a unit, there is a high probability that its location will be at the attachment between the water tube and the tube sheet. Most current designs for sodium-heated steam generators have a cover gas space in the unit and

TABLE 10.3 - PHYSICAL MEASUREMENTS OF RIG 10 CAPILLARY MATERIAL--CARBURIZED TYPE 316 STAINLESS STEEL

Test No.	Diam, * in.	Length, ** in.	L/D	Test No.	Diam, in.	Length, in.	L/D
3	0.0074	0.19	25.7	27	0.0191	0.27	14.1
4	0.0088	0.19	21.6	28	***	0.27	-
5	0.0080	0.19	23.8	29	0.0186	0.31	16.7
6	0.0088	0.19	21.6	29a	0.0186	0.31	16.7
7	0.0071	0.19	26.8	30	0.0360	0.27	7.5
8	0.0085	0.19	22.4	31	0.0176	0.27	15.3
9	0.0090	0.19	21.1	32	0.0072	0.27	37.5
10	0.0055	0.27	49.1	33	0.0195	0.27	13.8
11b	0.0054	0.27	50.0	35	0.0400	0.27	6.75
12	0.0053	0.27	50.9	36	0.0192	0.31	16.1
13	0.0054	0.27	50.0	37	0.0097	0.31	32.0
14	0.0071	0.27	38.0	38	0.0106	0.27	25.5
15	-	0.27	-	39	0.0147	0.31	21.1
16	0.0072	0.27	37.5	40	0.0117	0.31	26.5
17	0.0061	0.27	44.3	41	0.0390	0.31	7.95
18	0.0072	0.27	37.5	42	0.0820	0.31	3.78
19	-	0.27	-	43	0.1300	0.31	2.38
19a	0.0059	0.31	52.5	44	***	0.31	-
21	0.0076	0.19	25.0	45	0.0116	0.19	16.4
21a	0.0081	0.27	33.3	46	0.0430	0.285	-
22	0.0076	0.27	35.5	47	0.0600	0.22	3.67
22a	0.0071	0.31	43.7	48	0.0092	0.31	34.4
23	0.0065	0.31	47.7	48a	***	-	-
24	0.0118	0.27	22.9	48b	0.0087	0.31	35.6
25	-	0.27	-	50	0.0193	0.31	16.1
26	0.0068	0.27	39.7	51	0.0630	-	-

* Accuracy is ± 0.2 mil

** Accuracy is $\pm 1/16$ inch

*** Hole plugged

at least one, and often both, of the tube sheets is located in the gas space so that leaks which occur in this area will not be below the surface of the sodium. Examination of sodium-water reaction studies in the United States and abroad indicates that very little information is available on the effect of leaks of water above the surface of the sodium.

Although many variables should be studied in order to develop a clear picture of the effect of gas space leaks on material wastage rate and pattern, only four scoping tests are proposed at this time.

b. Scope

The scope of this job is to provide the necessary modifications to Rig 43 to enable the conduct of scoping material wastage tests in the gas space between the surface of the sodium and bottom of the cover of the reaction vessel. These tests will consist of the injection of water at an array of tubes simulating a steam generator tube bundle in the gas space. The test will contain the necessary equipment and instrumentation to measure the reaction area temperature and to record the event by high-speed movies. If possible, the modifications to the rig for gas space testing will provide the flexibility for testing over the full range of interest for all variables expected to have an effect on wastage in the gas space. Modifications to the rig should be kept relatively simple, with as few deviations as possible from the existing design.

c. Design Requirements

The design requirements for these modifications are:

- A new flange with the necessary attachments will be fabricated with the penetrations at

Injection water tube and guide tube
Six thermocouples
Sodium inlet pipe
Liquid level probe
Viewing and lighting port as required.

- The target assembly will consist of a minimum of six open, 1-inch-diameter, straight tubes on the same tube pitch as currently being used in Rig 10.
- The initial spacing between the injection nozzle and the target tube in the tube array will be 1/4 inch; however, provisions should be made for adjustment of the spacing over the range from 1/4 to 1-1/2 inches.
- The tube array will be long enough that the lower end is always submerged in sodium for a distance of at least 3 inches and its upper end is high enough to always project at least 2 inches above the elevation of the injection nozzle orifice.
- The method of initiating the leak will be the same as that currently used in Rigs 10 and 43.

- The injection nozzle, tube array, sodium level, or a combination of these will be adjustable to give a range in injection elevation from 1 inch below the sodium surface to 12 inches above, consistent with the other requirements listed.
- The modifications will be designed for temperatures of 350 to 900 F except the provision for viewing and photographing, which may be limited to a system temperature of 600 F if required.
- Sodium flow should be directed through the target tubes during the test if feasible.
- No internal baffling is required for maintaining a specific sodium velocity past the target tube at the sodium surface; however, the design should consider the possibility of the future addition of baffling to provide a predictable velocity of sodium across the part of the tube bundle which is submerged.
- The tube assembly can be supported from either the guide tube or be suspended from the top flange.
- The injection rate will be determined in the same manner as is currently being done on Rig 10 - by accurately measuring the volume of water added to the system and the injection duration as indicated by both the temperature trace from thermocouples at the tube surface and the acoustic noise measurement.
- Carbon steel will be used for the new flange and penetrations consistent with the temperature limitations above.

d. Testing Requirements:

The testing requirements are as follows:

- (1) Due to the size limitation of the rig, the maximum amount of water injected per test will be 1 lb and the maximum rate of water injection will be 0.01 lb/sec.
- (2) During the test, sodium will be flowing at a rate of 20 gpm through the system.
- (3) Four tests will be conducted in Rig 43 in the gas space; the conditions for these tests are given in Table 10.4.

TABLE 10.4 - TEST CONDITIONS FOR RIG 43 GAS SPACE LEAKS

Target Material - 2-1/4 Croloy

Test No.	Leak-to-Target Spacing, in.	Orifice Size, in.	Leak Rate, lb/sec	Water Injected, lb	Water Pressure, psig	Sodium Temp, F	Leak Elevation Above Na Surface, in.
1c	1/4	0.006	0.0026	1.0	2650	600	2
2c	1/4	0.006	0.0026	1.0	2650	600	8
3c	1/4	0.010	0.008	1.0	2650	600	2
4c	1/4	0.010	0.008	1.0	2650	600	0

e. Design

Conceptual drawings of the modifications based on the above requirements and preliminary cost estimates to make the modifications were completed, reviewed, and approved.

Work was initiated on doing the detailed design of the modifications.

C. Leak Detection (Task 22)

1. Leak Detection Criteria (Job 20)

J. H. Coleman
J. A. Ford
P. S. Lindsey

The scope of this job is to establish a basis for evaluating methods of detecting sodium-water reactions in sodium-heated steam generators. The need is for early detection of leaks to prevent damage to the unit. Included in this effort are (1) definition of leak detection criteria for the LMFBR program, (2) description of a reference LMFBR secondary sodium coolant system, (3) determination of the behavior of the reaction products throughout the coolant system, (4) assessment of candidate detection systems, and (5) recommendations for a leak detection system for an LMFBR plant.

Work was initiated in FY-68 on establishing the criteria, describing a reference secondary system, and making a preliminary evaluation of the candidate leak detection systems. In FY-69, the first draft of the report was written and, after review, revised to incorporate more up-to-date information. In FY-70, the scope is to incorporate additional comments in the revised report before publication.

Incorporation of the comments was completed, the report edited, and then issued as APDA Technical Memorandum No. 52. This completes work on this task.

D. Hot Erosion Studies (Task 60)

The scope of this task is to establish the relative contribution of erosion and corrosion to the wastage process by injecting water, sodium, and sodium hydroxide against targets made of the materials of interest to the LMFBR program. Construction of test equipment and initial operation was completed in FY-68. Several operating problems including failure of the injection tube were encountered during the initial operation period.

In FY-69 the scope of the work was (1) to make an evaluation of the design and performance of the hot erosion test equipment, including analysis of the failed injection tube, and (2) to make recommendations for corrective action. The design report was essentially completed and ready for internal review by the end of FY-69. In FY-70 the final report is to be issued.

1. Design Evaluation of Hot Erosion Test Equipment (Job 12)

Incorporation of comments in the draft of the design evaluation report was completed and editing of the report is in progress. No further work on this task is planned after the report is completed and transmitted to the AEC.

E. Material Wastage Topical Report (Task 70)

The objective of this task is to prepare a report covering the material wastage studies conducted by APDA. Included will be the Rig-10 and Rig-43 material wastage tests, caustic corrosion studies, hot erosion studies, and jet characteristics.

1. Research and Planning (Job 01)

Preparation of the detailed outline of the report was essentially completed and ready for internal review.

F. Leak Detection Topical Report (Task 71)

The objective of this task is to prepare a report covering the leak detection studies conducted by APDA. Included will be the leak detection criteria, preliminary evaluation of leak detection systems, acoustic detection studies, and Rig-10 experience with a cover gas hydrogen analysis.

1. Research and Planning (Job 01)

The outline of that portion of the report covering the acoustic detection work was approved. Work was initiated on preparing the detailed outline of the whole report.

2. Preliminary Design (Job 02)

The preliminary draft of the section covering the acoustic leak detection studies was completed and issued internally for review and comment.

III. NEXT REPORT PERIOD ACTIVITIES

A. Rig-10 Tube Wastage (Task 20)

Four Rig-10 tests (Job 03) will be made, thereby completing the scheduled FY-70 Rig-10 test program, and preliminary test results will be published. Detailed analysis of existing wastage data (Job 04) will continue.

B. Rig 43 Tube Wastage (Task 21)

Installation of the steam injection system for Rig 43 (Job 06) will be completed. Preparation of the test specification for the steam injection tests and conducting the scoping tests (Job 03) will be continued and preliminary results published.

Detailed design of the modifications to Rig 43 (Job 11) required to conduct gas space leaks will be completed; the procurement, fabrication, and installation of needed items will be completed; testing (Job 03) will be initiated.

C. Material Wastage Topical Report (Task 70)

A draft of the report will be completed and submitted to the AEC-RDT for review and comment.

D. Leak Detection Topical Report (Task 71)

A draft of the report will be completed and submitted to the AEC-RDT for review and comment.

E. Final Project Summary Report (Task 72)

Work will be initiated on preparing a report summarizing the major activities of this project.

REFERENCES

1. Quarterly Technical Progress Report on AEC-Sponsored Activities, July through September, 1969, APDA-248.
2. Chamberlain, H. V., Kanamori, A. J., and Lindsey, P. S., "Evaluation of Materials Wastage Due to Reactions of Water in Sodium," APDA-227, June 1969.
3. Bowden, F. R. S., "A Discussion of Deformation of Solids by the Impact of Liquids and its Relation to Rain Damage in Aircraft Missiles, to Blade Erosion in Steam Turbines and Cavitation Erosion," Philosophical Transactions of the Royal Society, Vol. 260, No. 1110, pp 73-315, July 28, 1966.

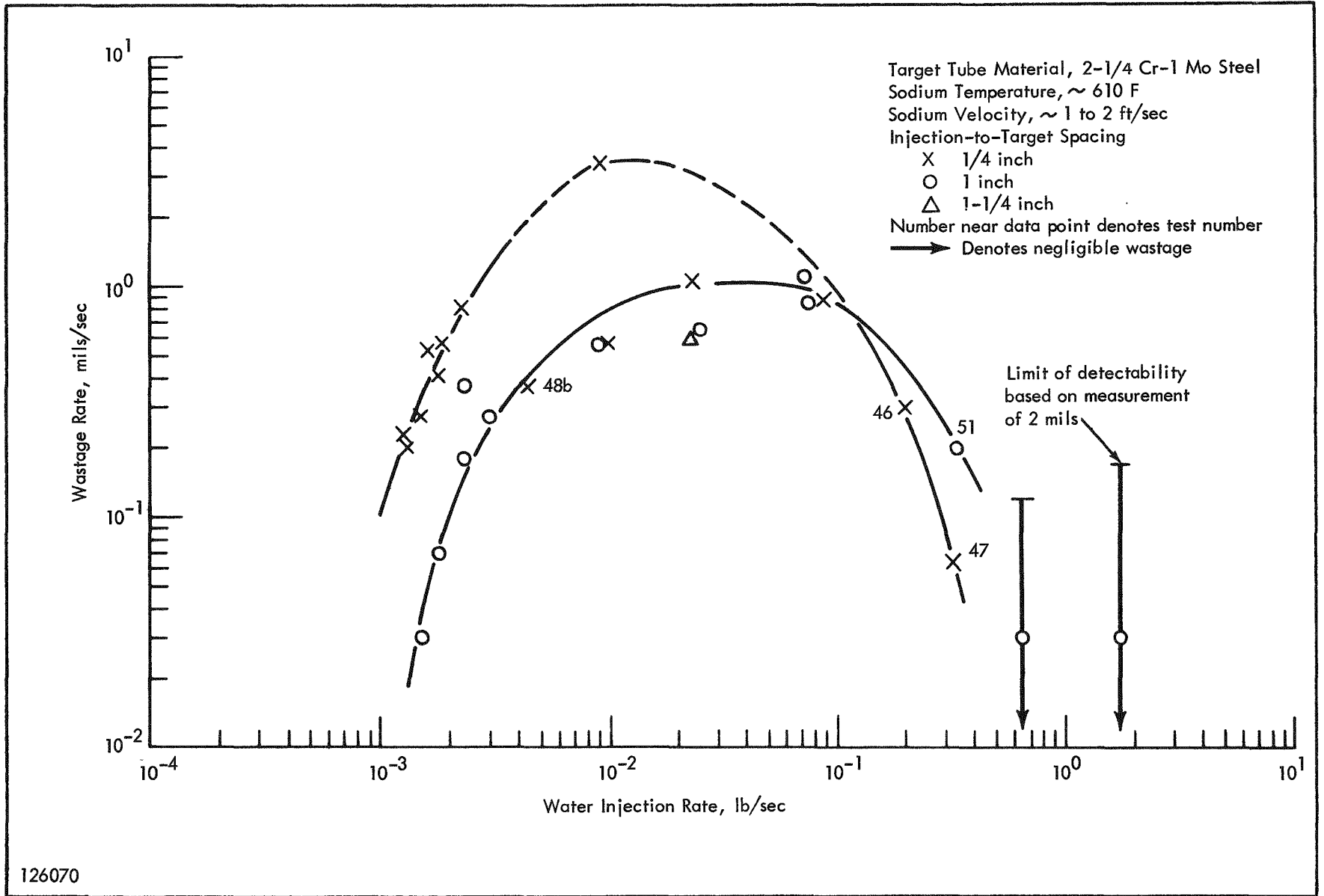
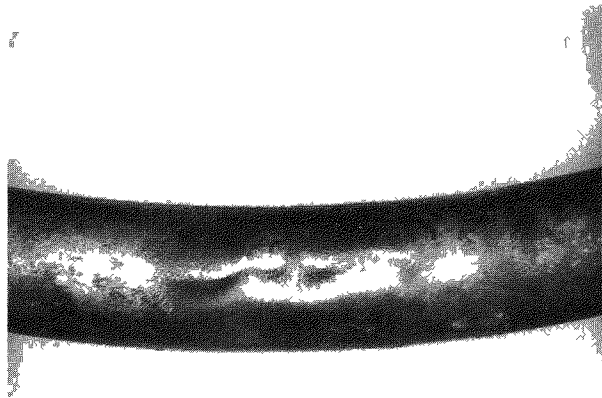
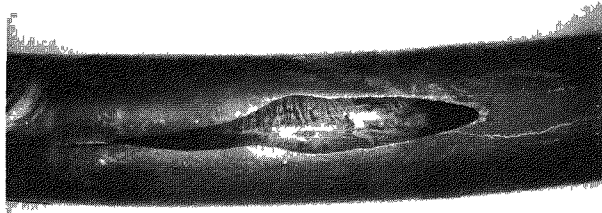


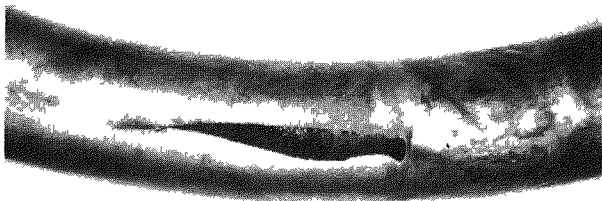
FIG. 10.1 COMPARISON OF TARGET TUBE MATERIAL WASTAGE RATES IN RIG-10 TESTS



(a) Tube C-5



(b) Tube A-3



(c) Tube A-2

125870

FIG. 10.2 TUBE WASTAGE PATTERN FROM RIG-10 TEST NO. 47

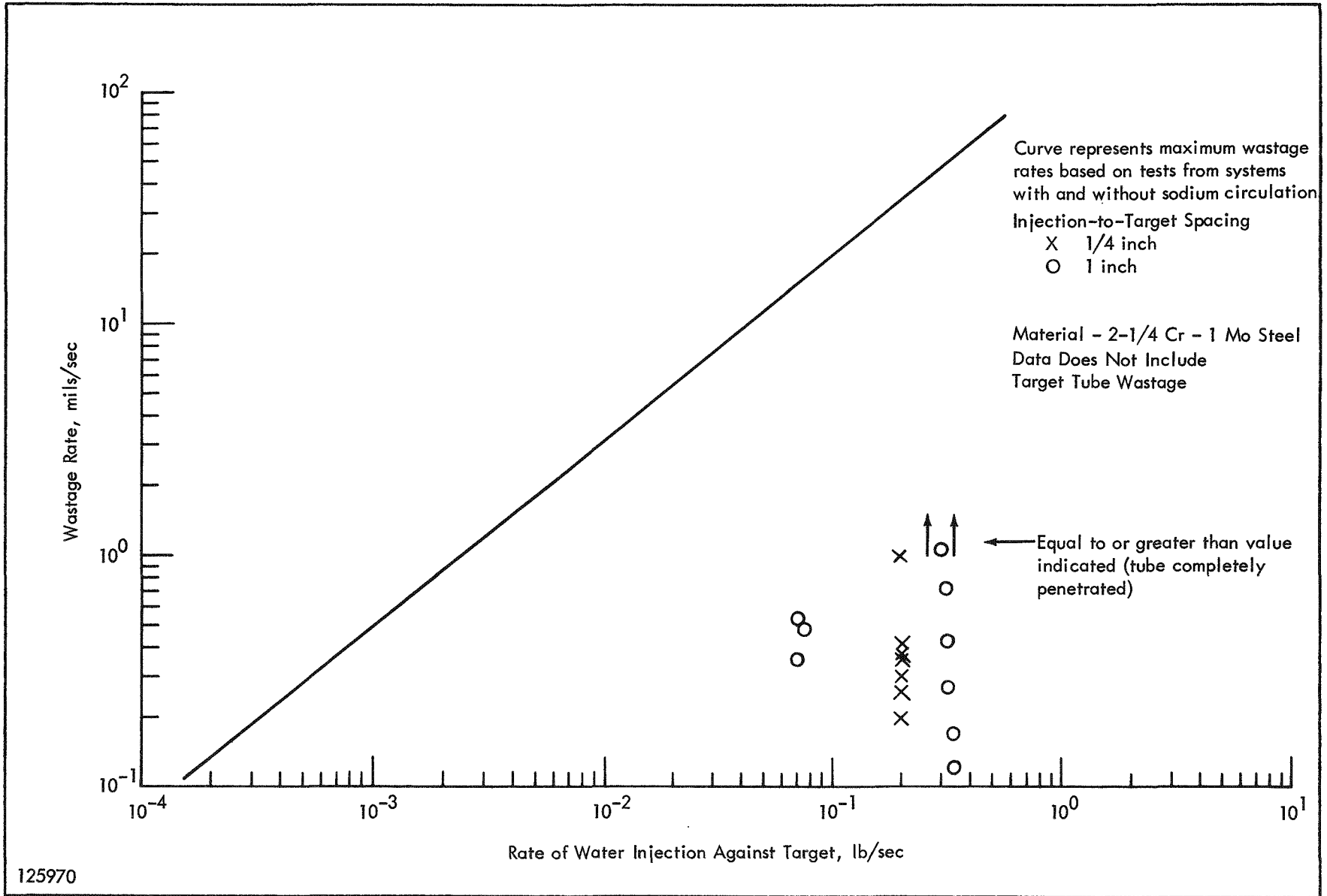


FIG. 10.3 MATERIAL WASTAGE ON TUBES ADJACENT TO TARGET TUBE

SODIUM TECHNOLOGY PROJECT

PROJECT AGREEMENT NO. 11

PROJECT ENGINEER: J. E. MEYERS

I. PREFACE

A. Scope

The present scope of the sodium technology project encompasses the following elements:

1. Impurity monitoring devices, including the development and evaluation of the Rhometer, oxygen meter, hydrogen meter, and plugging meter.
2. Sodium purification processes, including the evaluation and/or development of cold trapping, hot trapping, centrifuging, movable bed gettering, and thermal decomposition.
3. Sodium sampling and analysis, including the reliability of through-flow samplers, oxygen analysis, and hydrogen analysis.
4. Physical and chemical behavior of sodium and impurities, including the investigation of the solubility of hydrogen and sodium carbonate in sodium, the equilibrium distribution of hydrogen between sodium and the cover gas, and interaction of hydrogen and oxygen in sodium.

B. Relationship to Other Projects

This project is oriented entirely to the Commission's research and development program on the LMFBR.

II. TECHNICAL PROGRESS

A. Impurity Monitoring Instruments

1. Rhometer (Task 20)

W. D. Huston
C. C. Scott

The objective of this program is to develop and test an automatic temperature compensator and resistivity meter system capable of operating

in the range of 400 F to 1000 F with sufficient sensitivity and stability to detect a change in sodium resistivity equivalent to 1 ppm of oxygen.

a. Loop Evaluation, Prototypes (Job 06)

Because of budget limitations recently imposed on Project Agreement 11, this job has been terminated. However, since the sodium technology loop is being operated to evaluate the APDA hydrogen detector, Rhometer performance data are being accumulated and will be reported in the topical report (see Job 07).

b. Topical Report (Job 07)

The objective of this job is the publication of a topical report of the development and testing of the Rhometer resistivity meter with automatic temperature compensation through FY-1970.

The first draft of the report has been reviewed internally and comments are being incorporated prior to submittal to the AEC for review and comment.

2. Oxygen Meter (Task 27)

J. E. Meyers
M. K. Deora

a. Topical Report (Job 06)

The objective of this job is the publication of a topical report on the oxygen meter evaluation program performed at APDA incorporating all of the results obtained through FY-70.

A draft of this report was submitted this quarter to the AEC for review and comment.

3. Hydrogen Detector (Task 21)

J. H. Coleman
J. A. Ford

a. Data Evaluation (Job 09)

The scope of this job is to prepare computer programs for the IBM 1130 which will (1) model the hydrogen detector installation on the sodium technology loop and (2) reduce the raw data from the test to aid in data evaluation. Complete data evaluation will be performed under this job.

Preliminary calibration of the hydrogen detector in APDA's sodium technology loop has been completed. The data are being analyzed and will be reported in the topical report to be issued during the final quarter of this fiscal year.

b. Topical Report (Job 10)

The objective of this job is the publication of a topical report covering the installation of the APDA hydrogen detector and its operation through FY-70.

A detailed outline of the report was initiated during this quarter.

B. Sodium Purification Processes

1. Centrifuging (Task 12)

J. Matte

a. Topical Report (Job 15)

Comments from the AEC were incorporated and the report is now being printed in finalized form.

C. Physical and Chemical Behavior of Sodium Impurities

1. Hydrogen Solubility (Task 31)

A. A. Gordus*
E. F. Hill
S. A. Meacham

a. Topical Report (Job 06)

The first draft of this report has been reviewed internally and comments are being incorporated prior to submittal to the AEC for review and comment.

D. Sodium Sampling and Analysis

M. K. Deora
A. J. Friedland

1. Sampling Reliability (Task 70)

a. Topical Report - Oxygen (Job 03)

A draft of this report has been submitted to the AEC for review and comment.

2. ASTM Round Robin on Oxygen
in Sodium (Task 73)

E. F. Hill
S. A. Meacham

a. Reduction of Data and Report (Job 05)

All of the AEC comments have been incorporated and the report is in the final stages of editing required for publication.

* University of Michigan

III. NEXT REPORT PERIOD ACTIVITIES

Effort will continue on performance evaluation of the APDA hydrogen detector and the automatically temperature-compensated Rhometer in the sodium technology loop.

Effort will continue on the preparation of the Rhometer, hydrogen detector, and hydrogen solubility reports.

The topical reports on the ASTM round robin on oxygen in sodium, the centrifuge, and the oxygen meter will be published in final form.

The project summary report will be initiated.

COMPARISON OF METHODS FOR HETEROGENEITY ANALYSIS

PROJECT AGREEMENT NO. 19

SENIOR PROJECT ENGINEER: J. B. Nims

PROJECT ENGINEER: E. M. Page

I. PREFACE

A. Scope

The objective of this program is to provide a consistent comparison and evaluation among various methods of computing heterogeneity effects in fast reactor critical assemblies and power reactors, particularly with regard to its effect on sodium void analysis. In the case of plate-type criticals, specific voiding and heterogeneity experiments will be analyzed by various methods. In the case of the power reactor, a conceptual design will be chosen for analysis.

Four methods are to be applied in the heterogeneity analysis, as follows:

1. One-dimensional transport theory calculations by DTF-IV of the flux distribution for the plate or pin arrangement forming a symmetric cell followed by flux-weighting the cross sections in each region of the cell to define cell-homogenized cross sections. The homogenized cross sections are then used in diffusion theory calculations to incorporate the heterogeneity effects directly in the calculations.¹
2. The same as Method 1 above, but using the cell-homogenized cross sections in perturbation theory to calculate heterogeneity corrections to a homogeneous calculation.²
3. The same as Methods 1 and 2 above, but using bilinear averaging to define the homogenized cross sections.³
4. Use of collision probability-perturbation methods to obtain correction terms to homogeneous diffusion theory calculations.^{4, 5}

In addition, attempts will be made to furnish Oak Ridge National Laboratory with consistent data to allow Monte Carlo calculations of selected cases, thus furnishing a more nearly exact approach that can serve as a reference calculation.

B. Relationship to Other Projects

A consistent analysis of heterogeneity effects in fast critical assemblies and power reactors is of general interest to the LMFBR industry and complements the current ANL efforts in this area.

II. TECHNICAL PROGRESS

A. Real Flux-Weighting

An analysis of ZPR-III Assembly 48 that compares results obtained with volume-weighted and flux-weighted cross sections to obtain the effects of plate heterogeneity on assembly reactivity and sodium voiding has been essentially completed. The work is divided into two major portions: (1) the effect of heterogeneity as present in the standard drawer⁶ was studied to provide continuity with earlier work done on this configuration; and (2) calculations of specific heterogeneity experiments were performed that involved three different arrangements of a given set of material plates in the central portion of the assembly. The reference arrangement is designated "normal" with the other two designated as "bunched" and "unbunched," referring principally to the relative positioning of the plutonium-loaded plates.⁷

The normal drawer loading differs from the standard only in that the 1/4-inch-thick plutonium alloy plate of the standard drawer was replaced by two 1/8-inch plutonium alloy plates in the normal drawer, a substitution that does change the average drawer composition. This revision was required to obtain a reference loading (normal drawer) that could be more effectively bunched and unbunched while its average composition remained fixed. The sodium voiding and heterogeneity experiments treated here are confined to the front 4 inches of the central 21 drawers in each half of the assembly, designated A and B in Figure 19.1.

1. Reference Calculations

It is convenient to define a calculational approach that does not include the effects of heterogeneity to provide a reference against which the various analytical techniques that do account for heterogeneity may be compared. The most obvious reference case would be a completely homogeneous treatment of the system in question; however, due to the nature of the calculational techniques employed, it becomes convenient to define as a reference case a volume-weighting approach such as used in Reference 1. This approach performs a homogeneous calculation of the assembly with multigroup diffusion theory using group cross sections obtained in the following manner: first, all cross sections with the exception of those in the resonance regions of the heavy elements are obtained through spectrum-weighting techniques as provided by a homogeneous spectrum consistent with a homogenous composition such as that which would result from an MC² run for the cell made using the P1

mode and homogeneous self-shielding.* Heavy element capture and fission resonance-shielded cross reaction calculations are then performed with the IDIOT Code^{9, 10} in the resolved and unresolved resonance regions for each heavy-element plate in the drawer, utilizing an equivalence principle based on explicitly formulated Dancoff factors for asymmetrical plate arrays. The resulting plate-dependent group cross sections are finally volume- and number-density-weighted to produce heavy-element capture and fission cross sections for the cell for the resonance region portion of the reference multi-group library. This volume-weighted library is available for both sodium-in and sodium-out conditions. Eigenvalue and first-order perturbation theory calculations performed using these cross sections will be referred to as the reference solution.

While this reference approach does account for the effect of the absorber plate array on the resonance escape probability in the standard fashion, it does not account for the depression in group flux through an absorber plate and the spatial flux-peaking in fuel plates at the higher energies.

Reference calculations will be performed at a later time using a completely homogeneous approach, i. e. , as above but with homogeneous treatment of heavy-element self-shielding, to obtain a base for measuring the heterogeneity effect of the plate array on energy self-shielding and to afford a basis for a consistent comparison with others essentially starting with a pure homogeneous model. For the most part, however, the volume-weighted approach will be used as the reference.

2. Analytical Approach

Accounting for heterogeneity effects through the use of flux-weighted cross sections actually encompasses Methods 1 and 2 listed in Section I. A. A brief outline of the two approaches is given below.

Method 1

- a. A cell calculation in one-dimensional slab geometry using multigroup transport theory (DTF-IV) is performed to obtain average group fluxes in each plate of the cell.
 - (1) The cell includes the width of one ZPR-III drawer and associated matrix.
 - (2) Separate calculations are performed for sodium-in and sodium-out conditions.

* The cross sections being used in this study, essentially an updated version of the MENDF/B data, are described in Reference 8.

- (3) The cross section set described above, before volume-weighting, is used for each plate in the cell, i. e., heavy-element capture and fission energy self-shielded cross sections for each plate are used which reflect the effects of isotopic density, plate geometry, and surrounding moderator material appropriate for that plate.
- b. The resulting average plate fluxes, plate volumes, and isotopic number densities are used to weight the individual plate cross sections to obtain a set of spatially averaged multigroup microscopic cross sections for each isotope of interest, as well as a single set of macroscopic cross sections representing the average composition of the cell. Such sets are obtained for both sodium-in and sodium-out conditions.
- c. To obtain multigroup homogeneous assembly fluxes and an eigenvalue that reflects the effects of plate heterogeneity, a multigroup diffusion theory calculation is run (SCRAMBLE)¹¹ using the sodium-in cell macroscopic cross sections obtained as described above from DTF-IV. The corresponding calculation of a sodium-voided region uses the macroscopic cross sections from the sodium-out DTF-IV case in the appropriate region of the SCRAMBLE problem.
- d. Calculation of the reactivity effect of sodium voiding by perturbation theory utilizes the homogeneous SCRAMBLE fluxes computed as described above for the sodium-in condition and a perturbation cross section $\Delta\Sigma$ defined as,

$$\Delta\Sigma = \Sigma_{(\text{Na-out})}^{\text{fw}} - \Sigma_{(\text{Na-in})}^{\text{fw}}$$

where the macroscopic cross sections for the sodium-out and sodium-in conditions are the flux-weighted values obtained from the DTF-IV calculation described in Step b above.

- e. Isotopic contributions to the perturbation analysis are obtained through use of isotopic perturbation cross sections for isotope i defined as,

$$\Delta\Sigma_i = N_i \left[\sigma_{i(\text{Na-out})}^{\text{fw}} - \sigma_{i(\text{Na-in})}^{\text{fw}} \right]$$

where the microscopic cross sections are those obtained from the DTF-IV calculation described in Step b above and N_i is the homogeneous number density of isotope i .^{*} It should be noted that,

* In the case of sodium, $N_i (\text{Na-out}) = 0$

$$\Sigma_{(Na-out)}^{fw} = \sum_i N_i \sigma_i^{fw}(Na-out)$$

$$\Sigma_{(Na-in)}^{fw} = \sum_i N_i \sigma_i^{fw}(Na-in)$$

- f. The effects of heterogeneity on system reactivity and sodium-void worth are obtained by comparing the Method 1 results to those obtained for the reference case employing volume-average cross sections (See II. A. 1).

Method 2

- a. Spatially averaged flux-weighted cell cross sections for the sodium-in and sodium-out conditions are obtained in a fashion identical to Method 1, Steps a and b.
- b. The effects of heterogeneity are directly calculated (SCRAMBLE) as a perturbation to the homogeneous reference calculation employing volume-averaged cross sections (Sec. II. A. 1). The heterogeneity effect on system reactivity is found using the real and adjoint fluxes of the reference sodium-in calculation in a perturbation calculation over the entire core employing a perturbation cross section defined as

$$\Delta\Sigma = \Sigma_{(Na-in)}^{fw} - \Sigma_{(Na-in)}^{vw}$$

where,

$\Sigma_{(Na-in)}^{fw}$ = flux weighted sodium-in macroscopic cell cross section from DTF-IV as used in Method 1 above

$\Sigma_{(Na-in)}^{vw}$ = volume weighted sodium-in macroscopic cell cross section as used in the reference case (Section II. A. 1)

- c. The heterogeneity effect on the reactivity change due to sodium voiding is also found using the fluxes of the homogenous reference sodium-in calculation in a perturbation calculation, the calculation being made over the voided region with a perturbation cross section defined as

$$\Delta\Sigma = \left[\Sigma_{(Na-out)}^{fw} - \Sigma_{(Na-out)}^{vw} \right] - \left[\Sigma_{(Na-in)}^{fw} - \Sigma_{(Na-in)}^{vw} \right]$$

where,

$\Sigma_{(Na-in)}^{fw}$, $\Sigma_{(Na-out)}^{fw}$ = flux-weighted sodium-in and sodium-out macroscopic cell cross sections from DTF-IV as used in Method 1 above

$\Sigma^{vw}(\text{Na-in})$, $\Sigma^{vw}(\text{Na-out})$ = volume-weighted sodium-in and -out macroscopic cell cross sections as used in the reference case

3. Standard Drawer Calculations

The original loading of Assembly 48 utilized standard drawers for all core lattice positions (except for the control rods). A previous study treated this configuration with emphasis placed on investigating various techniques for the analysis of sodium-voiding experiments.¹ The current study restricts treatment of this configuration to investigating only the effects of heterogeneity on system criticality and on sodium voiding from the central region designated A and B. This will provide continuity and serve as a comparative analysis to the earlier calculations, the comparison having the value of pointing out differences resulting from the cross section re-evaluations⁸ that were performed subsequent to the earlier work.

a. Criticality

Table 19.1 lists the system criticality results obtained for the sodium-in standard drawer loading using the homogeneous reference model, Method 1, and Method 2. Also included are the comparable results of the earlier work obtained with MENDF/B cross section data as reported in Reference 1.

TABLE 19.1 - HETEROGENEITY EFFECTS ON CRITICALITY OF ASSEMBLY 48 STANDARD DRAWER (Na-IN)

Cross Section Set Used	Reference k_{eff}	Heterogeneity Effect, Δk		Heterogeneity k_{eff}	
		Method 1	Method 2	Method 1	Method 2
Current Data (Ref. 8)	0.9762	0.0137	0.0148	0.9899	0.9910
MENDF/B Data (Ref. 1)	0.9840	0.0139	0.0148	0.9979	0.9988

It should be noted that while the difference in k_{eff} due to differences in basic data is almost 1% Δk , the computed heterogeneity effects with the different data are almost the same. Furthermore, treatment of the heterogeneity as a perturbation to the reference case (Method 2) is seen to give similar results to the more explicit method (Method 1).

b. Sodium Voiding

The reactivity effects of voiding the 3.08 kg of sodium from the central region A plus B (Figure 19.1) were computed by perturbation theory

for the reference case as well as by Methods 1 and 2. Table 19.2 lists the results of the present study, of the earlier work using the MENDF/B library, and the experimental value.

TABLE 19.2 - HETEROGENEITY EFFECT OF CENTRAL SODIUM VOIDING IN THE STANDARD DRAWERS OF ASSEMBLY 48 (REGION A + B, 3.08 KG OF SODIUM)

Cross Section Set Used	Ref. Case	Sodium Void Coefficient, ih/kg *			
		Heterogeneity Effect		Voiding with Heterogeneity Effect	
		Method 1	Method 2	Method 1	Method 2
Current Data (Reference 8)	2.55	-0.82	-4.01	-1.73	-1.46
MENDF/B (Ref. 1)	3.76	-1.91	**	1.85	**

* Experimental = 5.6 ih/kg

** Not Calculated

A comparison of the current results with those using the earlier (only slightly different) MENDF/B data points out the extreme sensitivity of the calculated central sodium void coefficient for Assembly 48. This sensitivity is evidenced mathematically by the nature of the group-dependent contribution to the sodium worth shown in Table 19.3, where it can be seen that the total is made up of the sum of negative and positive group components, many of which are comparable in magnitude to the total. This is evidenced physically by the fact that the maximum positive reactivity effect due to sodium voiding measured in Assembly 48 is extremely small ($\sim 0.0002 \Delta k$) due to a combination of physical effects involving both positive and negative reactivity changes. The results of Table 19.2 also indicate the rather pronounced effect that heterogeneity can have on sodium worth calculations and shows the rather large differences between Methods 1 and 2 used in the heterogeneity treatment. As indicated in Reference 1, these differences are due to the effect of heterogeneity on the calculated real and adjoint flux spectra, an effect not accounted for in the perturbation approach of Method 2.

The heterogeneity effect on sodium void reactivity arises chiefly from the peaking of the high-energy flux in the fissile plates with sodium in the assembly, and the partial flattening of these fluxes upon sodium removal. This causes a decrease in the effective fission cross section for the sodium-out condition and produces a corresponding negative contribution to the sodium void effect. However, a compensating effect is also produced by this fast flux peaking, since it causes the slope of the high-energy sodium-in adjoint flux

to increase. Such an increase results in a corresponding increase in the positive sodium void contribution from spectral hardening that accompanies sodium removal. Changes also occur in the low-energy effective capture and fission cross sections upon sodium voiding due to the reduced low-energy spatial flux depression in the plates that accompanies sodium removal. This occurs principally in the resonance energy region of the heavy elements; however, the net effect of this is minimized due to partial cancellation of the capture and fission contributions which are affected in the same direction.

The energy dependence of the heterogeneity effect on sodium void reactivity is given in Table 19.3 as computed by Method 1. The importance of the change in high-energy flux-peaking upon sodium removal is evident in groups 1 through 4. Method 2 would show an even greater negative effect for these groups, since the compensating positive spectral effect mentioned above is neglected in the Method 2 treatment.

4. Analysis of Heterogeneity Experiments

Analysis of the Assembly 48 heterogeneity experiments described below have been performed.

In the first experiment, the experimental region A plus B of the standard drawer configuration (Fig. 19.1) was reloaded with the slightly modified plate arrangement described in Sec. II. A designated as the "normal" drawer loading. This served as a reference loading. Sodium void coefficient measurements were performed in region A plus B for this "normal" loading. The plates of this loading were then rearranged to form two other configurations in region A plus B, designated as bunched and unbunched loadings, and referring principally to the proximity of the several plutonium plates to each other. Two types of measurements were performed for both the bunched and unbunched drawer configurations. First, the reactivity change relative to the normal configuration was determined and second, sodium void coefficients in region A plus B were measured.

It should be noted that our analysis of these heterogeneity configurations utilized slightly modified plate dimensions and number densities recently obtained from Argonne National Laboratory that were not available during either the previously reported work or for the standard drawer calculations of the current effort. However, the modifications are small and form little basis for inconsistency with the earlier work, since comparisons between the standard and normal drawer loadings are not particularly meaningful due to the differences in plutonium and stainless steel content.

a. Reactivity Effects

Table 19.4 gives the reactivity effects resulting from the bunching and unbunching of the normal drawer as determined by experiment, by

TABLE 19.3 - GROUP DEPENDENCE OF HETEROGENEITY EFFECT ON SODIUM VOID WORTH IN THE STANDARD DRAWERS OF ASSEMBLY 48 - REGION A + B, 3.08 KG OF NA

Group	Sodium Void Coefficient, ih/kg		Heterogeneity Effect (Method 1 - Reference) ih/kg
	Reference	Method 1	
1	2.20	1.88	-0.32
2	1.68	1.15	-0.53
3	3.69	3.08	-0.61
4	5.27	4.82	-0.45
5	- .26	- .29	-0.03
6	.05	.16	0.11
7	.36	.60	0.24
8	.66	.85	0.19
9	1.18	1.30	0.12
10	.88	.93	0.05
11	.22	.26	0.04
12	- .36	- .34	0.02
13	-1.11	-1.03	0.08
14	-1.74	-1.71	0.03
15	-1.54	-1.52	0.02
16	-3.08	-3.03	0.05
17	- .72	- .83	-0.11
18	-2.27	-2.16	0.11
19	-1.21	-1.07	0.14
20	- .67	- .65	0.02
21	- .55	- .56	-0.01
22	- .22	- .23	-0.01
23	.07	.09	0.02
24	.02	.03	0.01
25	0	0	0
	2.55	1.73	-0.82

TABLE 19.4 - PLATE CONFIGURATION EFFECT ON
 CRITICALITY OF ASSEMBLY 48
 (REGION A + B, Na-IN)

	<u>Assembly Reactivity Change, ρ</u>	
	<u>Normal to Bunched</u>	<u>Normal to Unbunched</u>
Reference	13.3	9.4
Method 1	85.4	-24.5
Method 2	*	*
Experimental	75.2	-20.0

* Not yet calculated

the reference method and by Method 1.* The observed experimental results are as expected, since bunching of the fissile plates enhances the high-energy flux peaking and causes an increase in reactivity; unbunching has the opposite effect. Note that Method 1 predicts the reactivity effects of bunching and unbunching rather well. The poor agreement of the reference calculation is to be expected, since this calculation cannot account for the differences in flux distribution through the plates among the three configurations; only the effects on heavy-element energy self-shielding are accounted for through use of the equivalent principle with Dancoff factors.

b. Sodium Void Effects

As evidenced by the results for the standard drawer (Table 19.2) as well as previous studies,¹ little can be derived from a direct comparison of calculated sodium void reactivity with experiment for a given Assembly 48 configuration due to the extreme sensitivity of the results to both data and methods. More meaning can be derived from a comparison of the measured and calculated differences in the sodium void coefficient among the three drawer arrangements used in the heterogeneity experiments. Table 19.5 shows these differences as computed by Methods 1 and 2 together with the reference method and experimental results.

The inconsistent results of the reference calculation are to be expected, as explained above. For the experiments involving a major configuration change in the plutonium plates (normal to bunched or bunched to unbunched), Method 2 overpredicts the effect. This is to be expected, since

* Method 2 has yet to be calculated.

Method 2 overpredicts the effects of high-energy flux peaking on the sodium void reactivity (See II. A. 3. b). The best agreement is afforded by Method 1 which predicts fairly well the negative effect of going from normal to bunched, the positive effect in going from bunched to unbunched, and the very small effect between normal and unbunched.

TABLE 19.5 - PLATE CONFIGURATION EFFECT ON SODIUM VOID COEFFICIENT FOR ASSEMBLY 48 REGION A + B, 3.08 KG SODIUM)

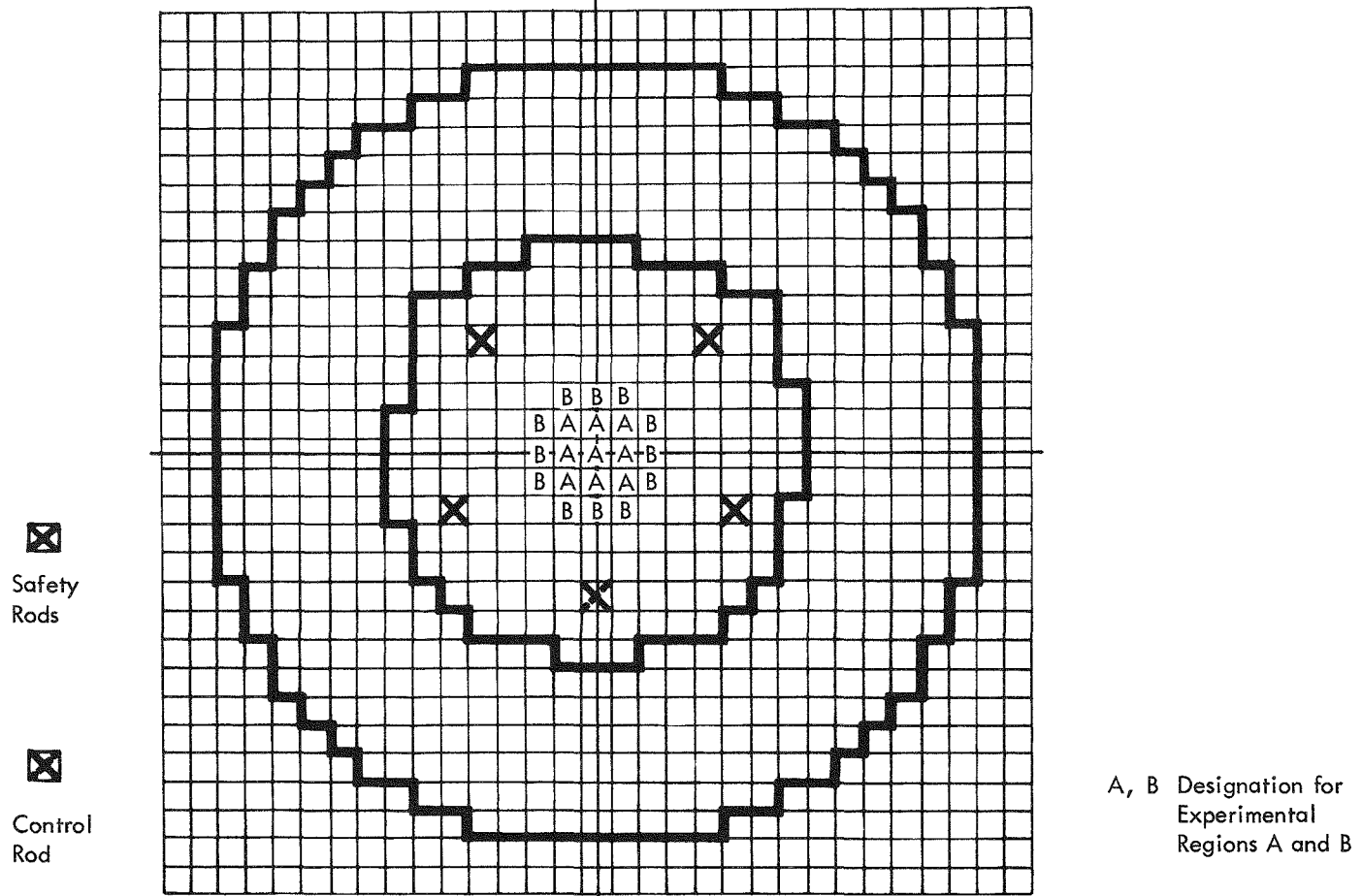
	Change in Sodium Void Coefficient, ih/kg		
	<u>Normal to Bunched</u>	<u>Normal to Unbunched</u>	<u>Bunched to Unbunched</u>
Reference	-1.3	-1.7	-0.4
Method 1	-3.0	-0.2	2.8
Method 2	-3.8	0.1	3.9
Experimental	-2.1	0.5	2.6

B. Bilinear Averaging

A review has been initiated of bilinear averaging techniques used to obtain spatially averaged cross sections. Emphasis will be placed on the techniques proposed by Nicholson.¹²

III. NEXT REPORT PERIOD ACTIVITIES

During the third quarter of FY-1970 models for the analysis of ZPR-III Assembly 51 and ZPR-VI Assembly 6 will be constructed. Deficiencies in the homogeneous self-shielding techniques in the very low energy groups, as calculated by the IDIOT code, will be examined to allow consistent and truly homogeneous reference cases to be computed. Liason will be established with Oak Ridge National Laboratory to define and initiate the Monte Carlo reference calculations. Investigation of the relative merits of using the CELPERT and CALHET codes for the collision probability-perturbation method of calculating heterogeneity (Method 4) will be undertaken. Review of the various bilinear averaging techniques will continue, and definition of the approach to be finally taken should be completed (Method 3).



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FIG. 19.1 ASSEMBLY 48 DRAWER ARRANGEMENT FOR HETEROGENEITY AND SODIUM-VOIDING EXPERIMENTS

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