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**THE DENSITY-FLOW REGIME
OF FRANKLIN D. ROOSEVELT LAKE**

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THE DENSITY-FLOW REGIME
OF FRANKLIN D. ROOSEVELT LAKE*

By

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Technical Planning Section
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March 15, 1965

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ABSTRACT

A correlation of 2 yr data describing the thermal regime of Lake Roosevelt and comparisons with Yih's theoretical work and Debler's laboratory studies shows excellent agreement regarding the position of the interfacial layer between the upper relatively stagnant zone and the region of the primary flow transport. This agreement, however, could easily lead the investigator to conclusions regarding the entire flow regime that cannot be supported.

Further study of the temperature data and confirmation by velometer shows the location of a second, lower interface that roughly conforms to the one above but showing "waves" of instability. It is apparent that more complex theory will have to account for the variance between dynamic and static equilibrium.

The study indicates that information on refined mass transport relations is necessary for heat budget studies. The study also indicates that projects or operational concepts involving storage or release of cool water are made difficult because density currents tend to bypass cooler masses. The dynamic equilibrium prevents the formation of "normal" density currents and, as a result, Lake Roosevelt fills with cool water by displacement from the North without any significant horizontal distribution.

THE DENSITY-FLOW REGIME OF FRANKLIN D. ROOSEVELT LAKE

INTRODUCTION

During 1964, a detailed study of the temperature and density of Lake Roosevelt was undertaken. This study was performed at the request of several agencies; there had long been a need for a better understanding of the Lake's thermal movements. Recently, there had been problems in accounting for cool water masses experienced during Hanford's annual river cooling program.

Considerable emphasis has been placed on the thermal regime of Lake Roosevelt as it contributes to the overall picture expected after completion of the U. S. -Canadian Treaty Projects. Reservoirs are known to distort both the extent and timing of the natural, annual thermal cycle. Recognizing that such structures were planned and constructed before serious study of thermal effects was integrated with project planning, some agencies now seek not only to improve the understanding of these effects but to capitalize on the advantages where practicable. In regard to this report, the programs of the Bureau of Commercial Fisheries and the U. S. Atomic Energy Commission fall in this category.

EXPERIMENTAL PROCEDURE

Because of the distances involved, and the desire to minimize data bias because of time, aircraft was chosen for all data surveys. The lake was divided into ten segments of 10 miles in length, which appeared to give appropriate coverage on the basis of previous experience. Consideration was then given to the thermal measurements.

In previous years, thermocouples read with a standard decade box and ice bath were used. This cumbersome array was supplanted in 1963 by a Wallac Resistance Temperature Detector having case compensation and a 110 meter probe. Data obtained with this instrument were precise to ± 0.1 C. Previous experience had shown the necessity to read data this

closely to find thermal evidence of shear gradients with some confidence. Despite its accuracy, the Wallac instrument proved difficult to use because of cord weight and the length of time required to achieve equilibrium at each depth. A review of available equipment produced the following apparatus tailored for accuracy and aircraft transport.

These were the components:

- Power converter

A standard A. T. R. dc-ac inverter (Type 12T, Model RME, 12VDC input, 110VAC output, 60 cycle, 90 watt continuous power) that used the Cessna 180 power supply to run the chart recorder.

- Temperature measurement system

The temperature measurement system was a portable, battery regulated, three resistance bridge unit (Rosemount Eng. Model 410B). A switch provided a selection of three temperature ranges (0 to 10 C, 10 to 20 C, 20 to 30 C). All resistance bridges were factory calibrated for the sensor and cable and were factory installed. The bridge residual effect ranges from 0.002 to 0.05% of full scale output voltage (output voltage range is 0.00000 to 0.010000).

- Thermister and cable

Included in the water temperature measuring system is a platinum resistance immersion sensor and 400 ft of cable. Time constant of the sensor is 2.5 and the accuracy is ± 0.05 C. The four wire cable is marked with a color code and numbers to facilitate rapid depth identification of the sensor.

- Recorder

An Esterline Angus 6 in. recording Labograph with a servo potentiometer measuring element was used to record the temperature. Response of this instrument is $1/8$ full scale, accuracy 0.5% of full scale and sensitivity $1/8\%$ full scale. Depth was recorded on the chart at each 0.2 C temperature change throughout the depth of the profile.

Commencing April 15, 1964, flights were made weekly, monitoring the ten stations. At each letdown, the equipment was checked against a certified thermometer and recording began until the probe bottom was manually indicated. A complete data run took less than 5 hr. The entire operation, based at Seattle, Washington, took less than 10 hr per trip. Some weather interference was encountered and wind caused drift errors on some days; however, the entire operation was quite adequate and exceeded expectation. The recording equipment performed satisfactorily and no runs were aborted for this reason. The aircraft and experimental apparatus are illustrated in Figures 1 and 2.

FIGURE 1

Cessna 180 Float Plane Used as Data Collection Platform

FIGURE 2
Apparatus on Bench

DISCUSSION

For several years, interest has centered on the development of improved heat budgets and better modeling of the density current behavior in reservoirs. The alteration of the normal temperature distribution has been described by Churchill⁽¹⁾ and J. C. Ward⁽²⁾. Commencing in the early 1950's, these and other investigators began a search for an appropriate model of density current regime. In 1958, Yih⁽³⁾ reported that for large densimetric Froude numbers there was no tendency for flow separation. As the Froude number decreases below a critical value of $1/\pi$, the conditions of the analysis predict that the entire depth of fluid

cannot be in motion toward the outlet and an internal current with a thickness less than the total depth results.

In 1959, using laboratory troughs, Debler developed a correlation for the Yih prediction that the dividing streamline in a stratified reservoir could be modeled as a function of the densimetric Froude number, F_i . Figure 3 illustrates this relationship and is produced from Debler's original paper in the ASCE Journal.⁽⁴⁾ The reader is encouraged to review the original reference for development of the mathematical analysis.

FIGURE 3

The Ratio of the Thickness of a Density Current to the Depth of Channel -Debler- 1959

A study of this work reveals that three rather unnatural conditions were adopted to simplify the laboratory work.

- The tests were commenced from a state of static equilibrium at Reynolds number essentially zero

- The flow outlet was located at the very bottom of the test trough
- The trough dimensions were chosen to minimize edge effects

While these conditions have application to a number of reservoirs, a study of many western reservoirs indicates that one or more of them does not exist. In Lake Roosevelt, none of the conditions exist.

Harleman, et al., ⁽⁵⁾ have reported on application of this method to Fontana Reservoir in support of other project activity. While good correlation of the density current boundary was obtained, complications were encountered in explaining the action of the lower boundary since this dam had an outlet some distance above the bottom.

During this period, commencing in 1958, the Richland Operations Office of the U. S. Atomic Energy Commission through General Electric Company, then sole operating contractor at Hanford, arranged to alter the delivery of water from Grand Coulee Dam to favor a cooler water regime both above and below the river affected by the plant. Efforts to account for the cool water inventory were never fully successful. As additional dams were completed, the flow regime was further confused. However, the original incentives still remain of interest to both the AEC and the Fish and Wildlife Service. The necessity to account for heat balance in the special releases and the inability to do so using existing theory lent special emphasis to improved understanding of density currents in Lake Roosevelt.

Work is continuing. A promising, dynamic river model programmed for the IBM 7090 computer is currently being debugged at Hanford.

Accepted theory, developed on the concept of static equilibrium (Figure 4) would lead the investigator to conclude that density currents should develop and flow through Lake Roosevelt. The cooling program initiated by General Electric was operated on the assumption that the stratified upper layers could be trapped by reducing spill to zero, and discharging all cool water through the penstocks at the 1030 ft elevation.

FIGURE 4

Expected Density Currents and Other Reservoir Data

Data collected in 1963, however, indicated that this expected density pattern was being interfered with by the dynamic flow conditions through the reservoir. The net effect was to cause dumping of warmer water while holding the cooler water. Replenishment of water from the North produced what appeared to be displacement flow rather than density flow. However, computation of the density interface using the Yih-Debler correlation indicated the presence of a dividing streamline. Clearly some additional influences were operating to alter the expected pattern.

As the 1964 data were compiled and density current boundaries computed, it became evident that the conditions of dynamic equilibrium were operating to create an additional sharply defined lower limit to the density flow regime. This lower limit appeared to cut through isotherms and further, rose and fell in response to the overall energy balance.

On September 3 and 4, 1964, a special set of data were taken at the 10 stations using both thermal detectors and velometers. The reservoir map, Figure 5, illustrates the unusual but not wholly unexpected result.

In Figure 5, the density current boundaries are located by velometer and defined as that portion of the stream having a velocity above the mean for any cross section. The original data and the derived boundaries are shown in Appendix 2. Appendix 3 shows a plot of the correlation between thermal gradients and observed shear zones and illustrates the technique used in defining "observed boundaries" using temperature traverse data. Velometer measurements were used only for the September 2-3 studies; the balance of the study is based on temperature depth recordings.

Further examination of the previous temperature data records confirmed the existence of both the upper and lower shear boundaries. The existence of a current band cutting through isotherms, but responding to static forces of stratification explained the tendency of the reservoir to drain like a dump truck using the drainage elevation of 1030 ft as a fulcrum.

FIGURE 5
Lake Roosevelt Flow Regime and Principal Isotherms

To illustrate the development of reservoir strata and the current path, Figures 6, 7, 8, and 9 (see pp. 14 through 25) are included showing a consecutive 12 wk period from July 27, 1964, until October 12, 1964. These illustrations, with the computed and observed flow boundaries, show the anticipated effects.

Efforts to correlate the bottom interface as a function of both static and dynamic forces are still underway at Battelle-Northwest. It is expected that the additional related work will be completed in 1965, but we felt that this material would be of sufficient interest to warrant publication before all findings are in.

CONCLUSIONS

As a result of this program, it appears that the following conclusions are appropriate:

- The correlation of the upper boundary predicted by Yih and demonstrated by Debler in trough experiments is sufficiently correct to be applied generally to stratified reservoirs. This applies to rapidly flowing reservoirs as well as relatively quiet systems.
- The bottom of the flow path created in a reservoir by discharge from a point below the surface does not necessarily remain below the elevation of the point of discharge. Rather, because of the conditions imposed by dynamic forces, the flow path separation layer or shear zone follows dynamic influences similar to the upper boundary and rises as necessary to maintain dynamic equilibrium.
- In the regime studied, the term stagnant zone is purely relative. At no time were velocities less than 0.05 ft/sec measured at any elevation. Velocity distribution both above and below the flow path was essentially the same. Velocities in the flow path were from 3 to 4 times those in the so-called stagnant zones.
- Operational concepts which envision use of the storage capacity of Lake Roosevelt to alter thermal conditions either expected from

storage upstream in Canadian Treaty Reservoirs or currently existing must be designed to cope with the actual flow regime discovered. It is quite apparent that the reservoir does fill by displacement from the North and does not develop a true density current regime of any significance. This does not preclude operational plans which would save cold water by curtailment of the annual spring draw-down for flood control if sufficient upstream storage volume can be found to supplant the volume currently drained each spring. Retention of this cold water now discharged for flood control would restore some of the seasonal imbalance in Columbia River temperatures currently existing.

- Downstream activities sensitive to dissolved ion and turbidity content are affected by reservoir flow path which bypasses cooler chemically rich Spokane River in flows. Temporary holdup of this in flow, bearing a large percentage of the dissolved material sensitive to activation by downstream nuclear processes, may account for the annual diminution of P^{32} content normally observed below the Hanford Plant.

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FIGURE 6a
Development of Density-Flow Regime - July 27, 1964

FIGURE 6b

Development of Density-Flow Regime - August 4, 1964

FIGURE 6c

Development of Density-Flow Regime - August 11, 1964

FIGURE 7a
Development of Density-Flow Regime - August 17, 1965

FIGURE 7b
Development of Density-Flow Regime - August 24, 1964

FIGURE 7c
Development of Density-Flow Regime - August 31, 1964

FIGURE 8a
Development of Density-Flow Regime - September 9, 1964

FIGURE 8b
Development of Density-Flow Regime - September 15, 1964

FIGURE 8c
Development of Density-Flow Regime - September 21, 1964

FIGURE 9a
Development of Density-Flow Regime - September 28, 1964

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FIGURE 9b
Development of Density-Flow Regime - October 5, 1964

FIGURE 9c
Development of Density-Flow Regime - October 12, 1964

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Additional Material of Interest

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ROOSEVELT LAKE TEMPERATURE (C) SURVEY
CONDUCTED ON SEPTEMBER 3, 1964
(United States Fish and Wildlife Service)

Depth - Meters		Station									
		0	1	2	3	4	5	6	7	8	9
Surface		18.1	18.1	18.0	17.6	17.9	16.8	16.7	16.2	14.8	14.5
10	3.05	17.7	18.1	17.8	17.1	16.8	16.5	16.3	16.2	14.8	14.5
20	6.1	17.6	17.6	17.5	16.8	16.6	16.3	16.2	16.1	14.8	14.5
30	9.15	17.6	17.5	17.4	16.7	16.5	16.2	16.2	16.0	14.8	14.5
40	12.2	17.5	17.5	17.4	16.7	16.4	16.2	16.2	15.7	14.8	14.5
50	15.3	17.5	17.4	17.4	16.6	16.4	16.2	16.1	15.6	14.8	14.5
60	18.3	17.5	17.4	17.3	16.6	16.4	16.2	16.1	15.5	14.8	14.5
70	21.3	17.5	17.3	17.2	16.6	16.4	16.2	16.1	15.4	14.8	14.5
80	24.4	16.9	17.0	16.8	16.5	16.3	16.2	16.1	15.4	14.8	14.5
90	27.4	16.7	16.6	16.5	16.4	16.3	16.2	16.0	15.4	14.8	
100	30.5	16.6	16.4	16.2	16.3	16.3	16.2	16.0	15.4	14.8	
110	33.5	16.5	16.3	16.2	16.2	16.3	16.2	16.0	15.3	14.8	
120	36.6	16.4	16.3	16.1	16.2	16.3	16.2	15.8	15.2		
130	39.6	16.3	16.2	16.1	16.2	16.3	16.2	15.8	15.2		
140	42.6	16.2	16.2	16.0	16.1	16.2	16.2	15.8	15.2		
150	45.7	16.2	16.2	16.0	16.1	16.2	16.2	15.8	15.2		
160	48.8	16.2	16.1	15.9	16.1	16.1	16.2	15.8	15.2		
170	51.8	16.2	16.0	15.8	16.0	16.0	16.2	15.8	15.2		
180	54.8	16.1	16.0	15.8	16.0	16.0	16.1	15.8	15.2		
190	57.9	16.1	16.0	15.8	15.8	16.0	15.9	15.7	15.2		
200	61	16.0	15.9	15.7	15.7	16.0	15.7				
210	64	16.0	15.9	15.7	15.6	15.8	15.5				
220	67	15.9	15.8	15.6	15.5	15.7					
230	70	15.8	15.8	15.6	15.4	15.6					
240	73	15.8	15.8	15.5	15.4						
250	76	15.8	15.7	15.4	15.4						
260	79	15.7	15.6	15.2							
270	84.3	15.6	15.5	15.1							
280	85.3	15.6	15.4	15.0							
290	88.4	15.4	15.2	14.7							
300	91.5	15.4	15.0	14.6							
310	94.5	15.2	15.0	14.6							
320	97.5	15.0	14.4	14.5							
330	100.3	15.0	14.1								
340	103.6	15.0									
350	106.8		Bottom Mud								
Time		3:15 p. m.	2:40 p. m.	2:00 p. m.	1:25 p. m.	12:45 p. m.	12:10 a. m.	11:35 a. m.	10:35 a. m.	10:00 a. m.	8:40 a. m.
Station	0 - Plum Point 1 - Keller Ferry 2 - Whitestone Rock 3 - Spokane 4 - Log Dump				Station 5 - Hunters 6 - Gifford Ferry 7 - Chalk Cliffs 8 - Colville River 9 - Evans						

APPENDIX 2

ROOSEVELT LAKE SURVEY CURRENT SPEED DATA*

September 2, 3, 1964

Depth	Station									
	0	1	2	3	4	5	6	7	8	9
Surface	0.20	0.05	0.025	0.20	0.150	0.150	0.175	0.250	0.20	0.450
10	0.10	0.05	0.025	0.250	0.050+	0.150	0.250	0.075	0.30	0.475
20	0.10	0.05	0.050	0.150	0.050	0.150	0.125	0.150	0.25	0.50
30	0.15	0.15	0.075	0.050	0.20	0.125	0.325	0.175	0.175	0.50
40	0.10	0.025	0.350	0.050	0.20	0.10	0.325	0.30	0.075	0.50
50	0.05	0.05	0.025	---	0.20	0.075	0.175	0.40	0.20	0.450
60	0.05	0.05	0.20	0.025	0.20	0.125	0.20	0.375	0.275	0.40
70	----	0.10	0.075	0.050	0.175	0.10	0.250	0.350	0.25	0.325
80	0.05	0.15	0.325	0.150	0.20	0.125	0.30	0.40	0.150	0.175
90	----	0.175	0.325	0.250	0.20	0.20	0.250	0.425	0.175	Bottom
100	0.075	0.10	0.250	0.30	0.20	0.20	0.250	0.450	0.225	
110	0.05	0.10	0.30	0.275	0.175	0.150	0.225	0.450	0.150	
120	0.15	0.10	0.350	0.275	0.175	0.125	0.10	0.450	Bottom	
130	0.30	0.075	0.375	0.20	0.20	0.125	0.30	0.50		
140	0.25	0.025	0.30	0.150	0.075	0.050	0.275	0.50		
150	0.15	0.025	0.375	0.075	0.075	0.050	0.250	0.450		
160	0.20	0.050	0.20	0.125	0.075	0.025	0.250	0.425		
170	0.20	0.025	0.20	0.075	0.075	----	0.175	0.425		
180	0.20	0.050	0.250	0.100	0.025	0.025	0.050	0.325		
190	0.15	0.050	0.250	0.150	----	----	Bottom	Bottom		
200	0.15	0.050	0.200	0.125	----	----				
210	0.20	0.050	0.10	----	----	Bottom				
220	0.20	0.050	0.05	Bottom	Bottom					
230	0.15	0.075	0.150							
240	0.20	0.075	0.150							
250	0.20	0.075	0.150							
260	0.20	0.075	0.150							
270	0.20	0.075	0.050							
280	0.10	----	0.025							
290	0.15	0.075	0.025							

End of Cable

---- Indicates 0 Reading

+ Surface Eddys

*Velocity in Feet per Second

Station 0 - Plum Point
 1 - Keller Ferry
 2 - Whitestone Rock
 3 - Spokane
 4 - Log Dump

Station 5 - Hunters
 6 - Gifford Ferry
 7 - Chalk Cliffs
 8 - Colville River
 9 - Evans

APPENDIX 3

VELOCITY AND TEMPERATURE VERSUS DEPTH
September 3, 1964

APPENDIX 4

DENSITY CURRENT BOUNDARY CALCULATION

(DATA: LAKE ROOSEVELT; SEPTEMBER 3, 1964)

(1) Evaluate: $F_i = \frac{Q}{W_o D_o^2} \sqrt{\frac{\rho_o}{g \beta}}$

(2) Determine: D_o/D_1

	<u>STATION</u>									
Width, ft at D_o	2100	1350	1000	1900	2000	1500	1800	2400	2100	800
Flow, ft ³ /sec	70,000									
Estimated Depth of Density Current, Average, ft	260	250	240	230	220	210	200	160	130	90
D_o^2	6.75×10^4	6.25×10^4	5.75×10^4	5.3×10^4	4.8×10^4	4.4×10^4	4.0×10^4	2.56×10^4	1.64×10^4	0.81×10^4
Temperature at D_o , C	15.8	15.7	15.5	15.4	15.8	15.6	15.7	15.2	14.8	14.5
(1) $\frac{Q}{W_o D_o^2} =$	0.514×10^{-3}	1.017×10^{-3}	1.245×10^{-3}	0.705×10^{-3}	0.744×10^{-3}	0.520×10^{-3}	0.99×10^{-3}	1.164×10^{-3}	1.02×10^{-3}	10.31×10^{-3}
Surface Temperature, T, C	18.1	18.1	18.0	17.6	17.9	16.8	16.7	16.2	14.8	14.5
Density at D_o lb/ft ³	62.370	62.371	62.373	62.375	62.370	62.374	62.372	67.377	62.381	62.384
Density at D_1 lb/ft ³	<u>62.343</u>	<u>62.343</u>	<u>62.344</u>	<u>62.349</u>	<u>62.345</u>	<u>62.359</u>	<u>62.360</u>	<u>62.366</u>	<u>62.381</u>	<u>62.384</u>
$\Delta \rho$	0.027	0.028	0.029	0.026	0.025	0.015	0.012	0.011	0	0
$\beta = \frac{\Delta \rho}{\rho_o}$, lb/ft ⁴	10.4×10^{-5}	11.2×10^{-5}	12.1×10^{-5}	11.3×10^{-5}	11.3×10^{-5}	7.15×10^{-5}	6×10^{-5}	6.9×10^{-5}	0	0
(2) $\frac{\rho_o}{g \beta}$	136	131	126	131	131	161	180	167	-	-
(1) (2) = F_i	0.070	0.132	0.156	0.090	0.046	0.092	0.178	0.196	$> \frac{1}{\pi}$	$> \frac{1}{\pi}$
D_o/D_1 From Deblor	0.53	0.71	0.77	0.60	0.61	0.60	0.83	0.86	1.0	1.0
Depth Fraction	0.47	0.29	0.23	0.40	0.39	0.40	0.17	0.14	0	0
Depth, Meters	36	22	17	28	26	26	10.5	9	0	0

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1	AIR FORCE INSTITUTE OF TECHNOLOGY	3	DEFENCE RESEARCH MEMBER
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1	ALLIS-CHALMERS MANUFACTURING COMPANY, BETHESDA	1	DOW CHEMICAL COMPANY, ROCKY FLATS
1	ARGONNE CANCER RESEARCH HOSPITAL	3	DU PONT COMPANY, AIKEN
10	ARGONNE NATIONAL LABORATORY	1	DU PONT COMPANY, WILMINGTON
1	ARMED FORCES RADIOBIOLOGY RESEARCH INSTITUTE	1	EDGERTON, GERMESHAUSEN AND GRIER, INC., GOLETA
2	ARMY CHEMICAL RESEARCH AND DEVELOPMENT LABORATORIES	1	FRANKFORD ARSENAL
1	ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORIES	1	FUNDAMENTAL METHODS ASSOCIATION
1	ARMY MATERIALS RESEARCH AGENCY	2	GENERAL ATOMIC DIVISION
		2	GENERAL DYNAMICS/FORT WORTH
		2	GENERAL ELECTRIC COMPANY, CINCINNATI
2	ARMY NUCLEAR DEFENSE LABORATORY	1	GENERAL ELECTRIC COMPANY (MSVD)
1	ATOMIC BOMB CASUALTY COMMISSION	1	GENERAL ELECTRIC COMPANY, SAN JOSE
1	ATOMIC ENERGY COMMISSION, BETHESDA	1	GOODYEAR ATOMIC CORPORATION
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1	AEC SCIENTIFIC REPRESENTATIVE, JAPAN	1	IIT RESEARCH INSTITUTE
3	ATOMIC ENERGY COMMISSION, WASHINGTON	1	*INTER-AMERICAN INSTITUTE OF AGRICULTURAL SCIENCES
4	ATOMIC ENERGY OF CANADA LIMITED	1	IOWA STATE UNIVERSITY
	ATOMIC ENERGY OF CANADA LIMITED, TORONTO	1	JET PROPULSION LABORATORY
2	ATOMIC ENERGY OF CANADA LIMITED, WHITESHELL	1	KNOLLS ATOMIC POWER LABORATORY
4	ATOMICS INTERNATIONAL	1	LING TEMCO YOUGHT, INC.
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Ptd.	Standard Distribution	Ptd.	Standard Distribution
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1	OFFICE OF ASSISTANT GENERAL COUNSEL FOR PATENTS (AEC)	1	UNIVERSITY OF CHICAGO, USAF RADIATION LABORATORY
10	OFFICE OF NAVAL RESEARCH	1	UNIVERSITY OF HAWAII
1	OFFICE OF THE CHIEF OF NAVAL OPERATIONS	1	UNIVERSITY OF PUERTO RICO
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