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ANALYSIS OF SCALE CONTROL IN  
FLUIDIZED-BED/HEAT EXCHANGERS

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Civil Engineering Laboratory (Navy)  
Port Hueneme, California

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)  An experimental study was made to determine the scale control effectiveness of fluidized-bed heat exchangers in heating seawater. A fluidized bed consists of granular solids suspended in vertically oriented heat exchangers. The purpose of the granular solids is to enhance the deposition of any precipitating salts on the granular solids which present a large surface area in the solution. A further purpose was to investigate whether the mild scouring action produced by the granular solids would eliminate and prevent the formation of actual		

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scale and its buildup on the heat exchanger surface or on the bed particles themselves. The favorable results of this study revealed that scale and its buildup can be eliminated by utilizing the fluidized-bed technique for temperatures above 240°F.

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## INTRODUCTION

Present-day plants for seawater distillation are limited by the imposed maximum temperature, approximately 240°F, to which the solution may be heated without inducing scale on the heat-exchanger surfaces. The twin achievements of scale control at a reasonable additional cost plus the extension of the upper operating temperature of the distillation plant to over 300°F would advance considerably present desalination technology. The economic significance of this process is self-evident: it leads to higher thermal efficiencies with greater yield of freshwater per unit of energy input.

The Naval Civil Engineering Laboratory (NCEL)\* undertook the study and test of this concept of utilizing fluidized beds for scale control in heat exchangers.

The concept of using fluidized beds for scale control in heat exchangers is not a recent one. Prache [1] in 1926 proposed the circulation of abrasive material past the heating surface as a means of continuous removal of scale deposits. More recently, Brookhaven National Laboratories [2] have experimented extensively with such a process. Their studies concluded that fluidized-bed heat exchangers provided scale-free operations for temperatures ranging to 400°F. however, the fluidized-bed technique was not pursued further as a high-temperature, scale-control device because another technique, ion-exchange desulfation, promises larger returns in terms of capital investment when used at the 50 to 100 mgd plants. In ion exchange desulfation, scaling salts are removed before reaching the still. Salable by-products result, yielding a profit from the operation of large desulfation facilities. On the other hand,

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\* On 1 January 1974 redesignated the Civil Engineering Laboratory (CEL) of the Naval Construction Battalion Center, Port Hueneme, CA.

the size of plant that is of interest to the Navy will not yield a profit; and, accordingly, a fluidized bed seems very suitable.

Although many other factors must be considered in operating distillation plants at such high temperatures, the overall potential of cost reduction with this process is clearly apparent. For Navy operations, a flash distillation plant incorporating a fluidized bed would require less weight, volume, and maintenance for the same freshwater output of a conventional flash unit.

#### METHODS OF DESALINATION

The principal desalination processes presently used are tabulated below, and Reference 3 gives explanations of these various techniques. Since the fluidized-bed technique applies primarily to the multistage flash-distillation concept, a brief discussion of that process is in order.

##### Distillation:

- Vertical tube
- Multistage flash
- Multieffect multistage
- Vapor compression
- Solar

##### Membrane:

- Electrodialysis
- Transport depletion
- Reverse osmosis

##### Crystallization:

- Vacuum freezing-vapor compression
- Secondary refrigerant freezing
- Hydrate formation

##### Chemical:

- Ion exchange

The flash-distillation process, illustrated in Figure 1, is based on the fact that water boils at progressively lower temperatures as it

is subjected to progressively lower pressures. The distillation unit consists of a series of chambers, each at a pressure lower than the previous one. As the hot seawater from one chamber flows into the adjacent lower-pressure chamber, some of that water flashes into steam.

Heat can be added to the feed water prior to its entry into the highest temperature chamber by various means, e.g., steam boiler, waste heat from diesel engines, or coil-type heaters. The flashing steam condenses as it comes in contact with the heat exchanger through which the incoming seawater flows. Vaporization of some of the water lowers the temperature of the remaining brine which then flows into the next stage where more water is flashed into steam at the lower pressure, and the process continues. This arrangement is quite efficient insofar as recovery of heat energy is concerned since 90% of the heat required to evaporate the flashing brine is transferred to the incoming seawater as it flows through the condenser tubes toward the heater.

#### SCALE AND ITS FORMATION

The flash process discussed earlier is subject to scale on the seawater side of the heat-exchanger surfaces. The scale problem is more severe at higher temperatures. True scale, as defined in a chemical engineering sense, is a deposit formed by precipitation from solution of a substance which has a solubility that decreases with an increase in temperature [4]. By this definition, the solubility of a scale-forming material is lowest at a heated surface. Consequently, deposition in an evaporator or heat exchanger will occur on the surface through which the heat is transmitted. This scale deposit will form an insulating blanket on such a surface, severely impeding the flow of heat and causing a reduction in efficiency or capacity, or both.

The principal scale-forming salts in the seawater are calcium carbonate ( $\text{CaCO}_3$ ), magnesium hydroxide ( $\text{Mg}(\text{OH})_2$ ), and calcium sulfate ( $\text{CaSO}_4$ ). As explained in Reference 5, formation of the carbonate and

hydroxide scales are caused by the chemical decomposition of the bicarbonate radical, together with the release of carbon dioxide ( $\text{CO}_2$ ), as the temperature is raised. For seawater temperatures of  $150^\circ$  to  $180^\circ\text{F}$ ,  $\text{CaCO}_3$  scale predominates, while  $\text{Mg}(\text{OH})_2$  is formed at the higher temperature range of  $180^\circ$  to  $240^\circ\text{F}$ . In present distillation plants, however, carbonate and hydroxide scale can be avoided by the addition of acid to the seawater. Such treatment maintains the pH level at the point where scale will not form [5,6].

Other means of reducing potential scale at temperatures below  $240^\circ\text{F}$  that have been used in industry, or have been suggested for seawater distillation, include the following:

1. Chemical treatment to precipitate (as a more insoluble compound) one of the ions forming the scaling compound
2. Preheating by direct steam injection to reduce the solubility of the scaling component
3. Heating and aeration of the feed to drive off carbon dioxide, thus increasing the pH and precipitating the scaling component, prior to passage through the heat exchangers

The formation of calcium sulfate scale, on the other hand, follows directly at temperatures above  $240^\circ\text{F}$  due to its own inverse solubility-temperature relationship, and the scaling problem becomes progressively worse with temperature increase. Due to the extreme difficulty in eliminating this scale, current requirements limit the upper solution temperature in desalination plants to about  $240^\circ\text{F}$ . For a more comprehensive study and review of scale formation and its prevention, Reference 6 is recommended.

#### EXPERIMENTAL APPARATUS AND PROCEDURES

Five heat exchangers like those shown in Figure 2 were constructed out of 90-10 Cu-Ni\* to use in the investigation at NCEL. The fluidized beds of two of the heat exchangers contained bronze balls 1/8-inch in

\* See the Appendix for properties of 90-10 Cu-Ni.

diameter, and two others contained No. 7 lead shot 0.100-inch in diameter. The fifth heat exchanger did not contain any fluidized bed and served as a control unit. The five test units were then connected in series, shown schematically in Figure 3. A steam boiler supplied heat while a turbine pump fed raw seawater through the system. Figure 4 shows the actual setup in the laboratory.

The experiment consisted of three separate tests as discussed below.

#### Test No. 1

Initial efforts during this test were directed toward general operating procedures and possible limitations imposed by the existing equipment. During this phase of the test it was found that the seawater preheater could not withstand pressures desired for the experiment. Furthermore, the seawater could not be heated to temperatures exceeding 300°F because of the inability of the boiler to supply adequate steam pressure at the desired water flow rates. A final limitation was insufficient back pressure in Unit No. 5 to prevent boiling at the high temperatures existing in that unit.

Before any tests were conducted, it was believed that boiling would enhance contact between the fluidized-bed particles and heat-exchanger walls by the increased turbulence and, thus, provide a more effective means of scale prevention. The tests showed, however, that boiling tends to blow these particles out of the test unit. To avoid loss of the fluidized-bed particles in Unit No. 5, a screen was installed at the exit end of this unit. Within a few hours at temperatures around 280°F, scale deposited on the screen (as shown in Figure 5) and reduced the flow to virtually zero. The screen and fluidized-bed particles were then removed. A pressure relief valve could have been incorporated at the exit end of Unit No. 5, but the added pressure requirement would have been beyond the allowable limit of the preheater.\* Therefore, Unit No. 5 was used as the control unit. Test Unit No. 4 reached temperatures beyond

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\* See Figure 6 for the Pressure Temperature equilibrium relationship.

270°F without boiling and could be used for comparison with Unit No. 5. In a practical sense, however, boiling should be avoided in the heat exchanger since this boiling action should occur in a controlled fashion by the subsequent flash chambers.

Throughout all the test runs, Units No. 1 and 3 contained the lead shot, and Units No. 2 and 4 contained the bronze balls. The ball checks used to prevent the downward migration of the bed particles were 3/4-inch type 316 stainless steel. Unit No. 5 contained a 7/8-inch chrome alloy type E52100\* in addition to the type 316 stainless steel. The purpose was to study erosion behavior of the two materials. The fluidized beds in the first four units were expanded by a factor of three with the top of the bed reaching halfway through the heat exchangers (see Figure 3). This was done for two reasons: (1) to promote scale formation in the top half of the heat exchangers and study the effect of the fluidized bed in the bottom half and (2) to allow establishment in later tests of a fluidized bed along the entire length of the tubes to determine if the presence of the particles would prevent further buildup of scale and possibly eliminate the deposits already formed.

Figures 7 through 9 depict these tests graphically. Upon termination of Test No. 1, the units were dismantled and were inspected with a borescope. The lower portions of the first four heat exchangers where fluidized-bed action was present were shiny clean while the upper portions showed a continuous coating of scale. Figure 10 shows a sample of 1/32-inch-thick scale obtained from Unit No. 5. Later tests with sulfuric acid solution revealed the type of scale to be calcium sulfate.

#### Test No. 2

For this test, more bed particles were added to achieve a bed expansion ratio of three with the top of the fluidized bed appearing in the sight glass. After 25 hours, the system was shut down, and the tubes were again inspected. Evidence of scale removal was observed since portions of shiny metal could be seen along the upper half of

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\* Type E52100 contains 0.98/1.10C, 0.25/0.45 Mn  
and 1.30/1.60 Cr.

the tubes. Unit No. 5, as expected, had a continuous coating of scale all along its inside surface.

### Test No. 3

This test was essentially a continuation of the previous one to ascertain that all of the existing scale could be removed. After 80 additional hours of fluidized-bed action, the heat exchangers were completely disassembled and inspected. The inside of all the tubes of Units No. 1 through 4 were shiny clean and free of deposits except for the top few inches of Unit No. 4 where patches of thin scale still persisted. Unit No. 5, which utilized no fluidized bed, showed a continuous coating of scale along the whole length of the tube's inside surface.

To further carry out the inspection, Units No. 4 and 5 were cut open longitudinally. Figure 11 is a photograph of the inside surfaces of both heat exchangers halfway up the tubes. Figure 12 shows a view of the top ends. The thin patches of scale appearing in Unit No. 4 is explained by the premature shutdown of the system. It is believed that a few more hours of fluidized-bed action would have completely eliminated this scale, purposely formed in the initial phase of the experiment.

### DISCUSSION OF RESULTS

The favorable results obtained during this experiment tend to correlate with the more extensive tests conducted at Brookhaven National Laboratory [2]. It appears from these data that the scaling problem in seawater distillation can be eliminated, at moderate additional cost, to permit extension of upper temperatures from about 200°F to one in the range of 350° to 400°F. This raising of the upper temperature along with absence of scale would lead to higher thermal efficiencies and increased freshwater production per unit of supplied heat energy.

As indicated earlier, the first phase of the test was to purposely induce scale in the upper portions of the heat exchangers by limiting fluidized-bed action in only the lower half. Upon termination of the

first phase, an inspection of the tubes revealed a continuous scale along the surfaces where fluidized-bed action was not permitted. This fact signifies that the principal-forming scaling salts precipitated from solution and were carried in suspension by the seawater stream whenever fluidized-bed action was present. However, in the absence of such action, these salts readily precipitated on the inside walls of the heat exchanger as the results show. In an actual distillation plant the suspended salts would most likely precipitate as they exit the fluidized-bed heater. Since only limited information is at hand, the extent of this precipitation problem is not known. However, the primary concern in desalination plants is keeping the heat-exchanger surfaces clean.

Another aspect which should not be overlooked is erosion of the fluidized-bed material and heat exchanger walls. Tests conducted at Brookhaven National Labs [2] show the following results. Type 316 stainless steel exhibited superior performance throughout over other materials used such as bronze and lead shot. After 3,636 hours of continuous fluidized-bed action at 300°F, a weight loss of only 1.59% was observed for 1/8-inch 316 stainless steel balls. On this basis, a bed material of this type would realize a weight loss of 3.5% per 8,000 hour year. Furthermore, no reduction in wall thickness of the 90-10 Cu-Ni heat exchanger was observed after the 3,626-hour test.

Due to the short duration of tests conducted at NCEL, one conclusive result was obtained concerning erosion. Figure 13 shows a 3/4-inch 316 stainless-steel ball and a 7/8-inch chrome-alloy steel ball before and after a 150-hour test at an average temperature of 265°F. The stainless steel ball did not exhibit any apparent weight loss while the chrome-alloy steel lost 45% of its original weight.

Based on the information acquired, a multistage fluidized-bed heat exchanger like that shown in Figure 14 can be constructed and incorporated in a flash distillation plant shown in Figure 15.

Estimates reveal that a 20-stage pilot plant similar to the one in Figure 15 can be designed to produce 5,000 gallons of fresh water per day and have the following specifications:

Component	Total Height (ft)	Outside Diameter (in.)	Total Weight (lb)
Multistage fluidized-bed heat exchanger	12	15	2,000
Flashing stages	12	12	1,500

The feed rate of raw seawater would be 25,000 gallons per day. A 400,000 BTU/hr boiler supplying steam at 100 psia would be adequate.

#### CONCLUSION AND RECOMMENDATIONS

The results of these tests show that a fluidized-bed heat exchanger is a technically feasible means for continuous elimination of scale and prevention of its formation. Also, troublesome acid addition requirements would probably be eliminated. The initial step in designing the flash plant as envisioned in Figure 14 would be the construction and testing of the fluidized-bed heat exchanger. Next would be the design of the flash chambers and testing of the pilot plant.

It is recommended that a flash distillation plant be built similar to the one shown in Figure 15. The development of such plants will be as follows:

1. Design and fabricate the multistage fluidized-bed heat exchanger
2. Test performance of the heat exchanger
3. Design and fabricate the flash chambers
4. Completely assemble the flash distillation plant
5. Test performance of the pilot plant

## CUPRO NICKEL, 10% 706

This Cupro Nickel alloy, with a 10% nickel content, was developed by Anaconda American Brass Company to answer the need for metal less costly than the richer copper-nickel alloys but still offering much of Cupro Nickel's tough reliability. This was achieved by the addition of controlled quantities of iron, resulting in Cupro Nickel, 10% 706.

Cupro Nickel, 10% 706 offers, to a good degree, the properties inherent in 30% nickel alloys but with a savings of nickel, and with a consequent reduction in costs. It is strong, rugged, durable, ideal for use in condenser tubes where superior stamina is called for, but understandably not to the extent offered by Cupro Nickel, 30%. Also worth noting . . . this low nickel alloy has heat transfer properties almost as efficient as those of admiralty.

Nominal composition of this metal is 88.35% copper, 10.00% nickel, 1.25% iron, 0.40% manganese. The inclusion of controlled quantities of iron in Alloy 706 has given this metal an extraordinary resistance to general corrosion and stress corrosion cracking, as well as to erosion and impingement due to turbulent water containing air bubbles and silt flowing at high velocities.

As indicated above, it is primarily a condenser tube alloy that also finds ready application in process heat exchangers. Cupro Nickel, 10% 706 is furnished in light drawn temper which, though naturally soft, is sufficiently rigid for easy handling and installation. This temper fully meets the expanding test and permits the metal to be roll-expanded into tube sheets and flares.

Although pre-eminently used in salt water lines, Alloy 706 is not especially adapted to handle heavily polluted waters containing sewage and industrial wastes.

Alloy 706 finds its greatest application in marine service in oil refineries for condensers and evaporators, in tidewater steam power plants, in sugar refineries, in distilleries, and in the chemical processing industries.

In sheet form, it is used extensively in the manufacture of hot water tanks for domestic service. In small tube form, it is often fabricated into tips for welding torches, for distillers' tubes and for ferrules.

Standard forms available: sheet, strip, plate, tube, rod and bar.

When so specified, Cupro Nickel 10% 706 will be manufactured to the following current specifications: ASTM Specifications B402, B171, B111, B395; SAE Specification CA706, and Military Specifications MIL-C-15726E, MIL-T-16420J, and MIL-T-15005E.

### FORMING AND FABRICATION

Cupro Nickel, 10% 706 lends itself well to cold working and hot forming. It is readily fabricated by heading and forming and welding.

### JOINING

This alloy is one of the most weldable copper-metals and is readily joined by all arc welding processes. The filler metal is a specially-alloyed 70-30 copper-nickel composition. The metal is excellent for all types of resistance welding. It is readily brazed and soldered.

**COMPOSITION, FORMS AND PROPERTIES OF  
CUPRO NICKEL, 10% 706**

Nominal Composition: 88.35% Copper  
10.00% Nickel  
0.40% Manganese  
1.25% Iron

Standard Forms: Sheet, strip, plate, tube, rod and bar

Approximate Relative Machinability: 20 (based on Free Cutting Brass 360 arbitrarily rated at 100)

Tensile Strength, psi:	Plate	Tube	Sheet	Rod	Wire
(Hard*)	—	60,000	—	Consult	Mill —
(Soft)	42,000	44,000			

Yield Strength @ 0.5% Extension Under Load, psi:	Plate	Tube	Sheet	Rod	Wire
(Hard*)	—	57,000	—	Consult	Mill —
(Soft)	18,000	22,000			

Elongation, % in 2 in. (except wire, which is % in 10 in.)	Plate	Tube	Sheet	Rod	Wire
(Hard*)	—	15	—	Consult	Mill —
(Soft)	35	46			

Rockwell Hardness No.:	Plate	Tube	Sheet	Rod	Wire
(Hard*)	—	B68	—	Consult	Mill —
(Soft)	B15	B25			

Melting Point (Liquidus): 1145C 2100F

Density: 0.323 lbs. per cu. in.

Average Coefficient of Linear Thermal Expansion per °F (77-572 F): .0000093

Electrical Conductivity, % IACS @ 68 F (volumetric): 9.2 (for soft annealed metal; slightly lower for hard temper)

Thermal Conductivity, Btu per sq. ft. per ft. per hr. per °F @ 68 F: 26

\*Values are for soft sheet reduced about 37% in thickness by cold rolling, or for commercial hard-drawn rod, wire and tube.

Mechanical properties are based on the following forms, as they apply: Sheet, 0.040 in. thick; Plate, 1 in. thick; Rod and Shafting, 1 in. diameter; Wire, 0.080 in. diameter; Tube, 1 in. diameter x 0.086 in. wall thickness.

Additional information about this metal, its properties and applications, is included in the Ansoconda American Brass Company publications, available upon request: B-2 Ansoconda Tubes and Plates for Condensers and Heat Exchangers; B-36 Corrosion Resistance of Copper Metals, and Technical Publication 60 Copper Metals for the Process Industries. Write to: Sales Promotion Department, Ansoconda American Brass Company, Waterbury, Connecticut 06720

## REFERENCES

1. Prache, C., U.S. Pat. No. 1,581,545, April 20, 1926.
2. Brookhaven National Laboratory. R&D progress report no. 571: Scale control in high temperature distillation utilizing fluidized bed heat exchangers, by L. P. Hatch, and G. G. Weth. Upton, NY, Jul 1970.
3. U.S. Department of the Interior, Office of Saline Water. The A-B-seas of desaling. Washington, D.C., U.S. Government Printing Office, 1968.
4. W. L. Badger. Chemical engineering handbook, 3rd ed. New York, McGraw Hill, 1950, p. 518.
5. Langlier, W. F., Caldwell, D. H., and Lawrence, W. B., Institute of Engineering Research, University of California, final report. Contract W-44-009 Eng.-499, Engineer Research and Development Laboratories, Ft. Belvoir, August 15, 1950.
6. U.S. Department of the Interior, Office of Saline Water Research and Development Progress Report No. 35: Critical review of literature on formation and prevention of scale, by W. L. Badger and Associates, Inc., Ann Arbor, Michigan, Jul 1959.

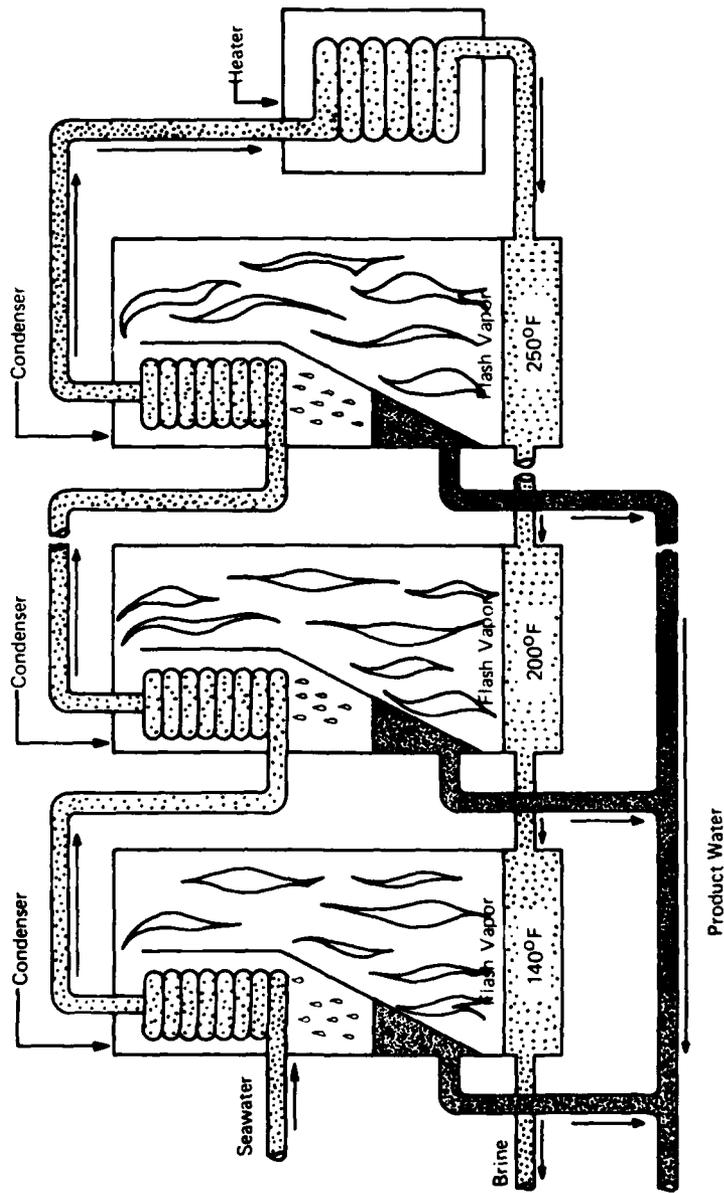


Figure 1. Multistage flash distillation process.

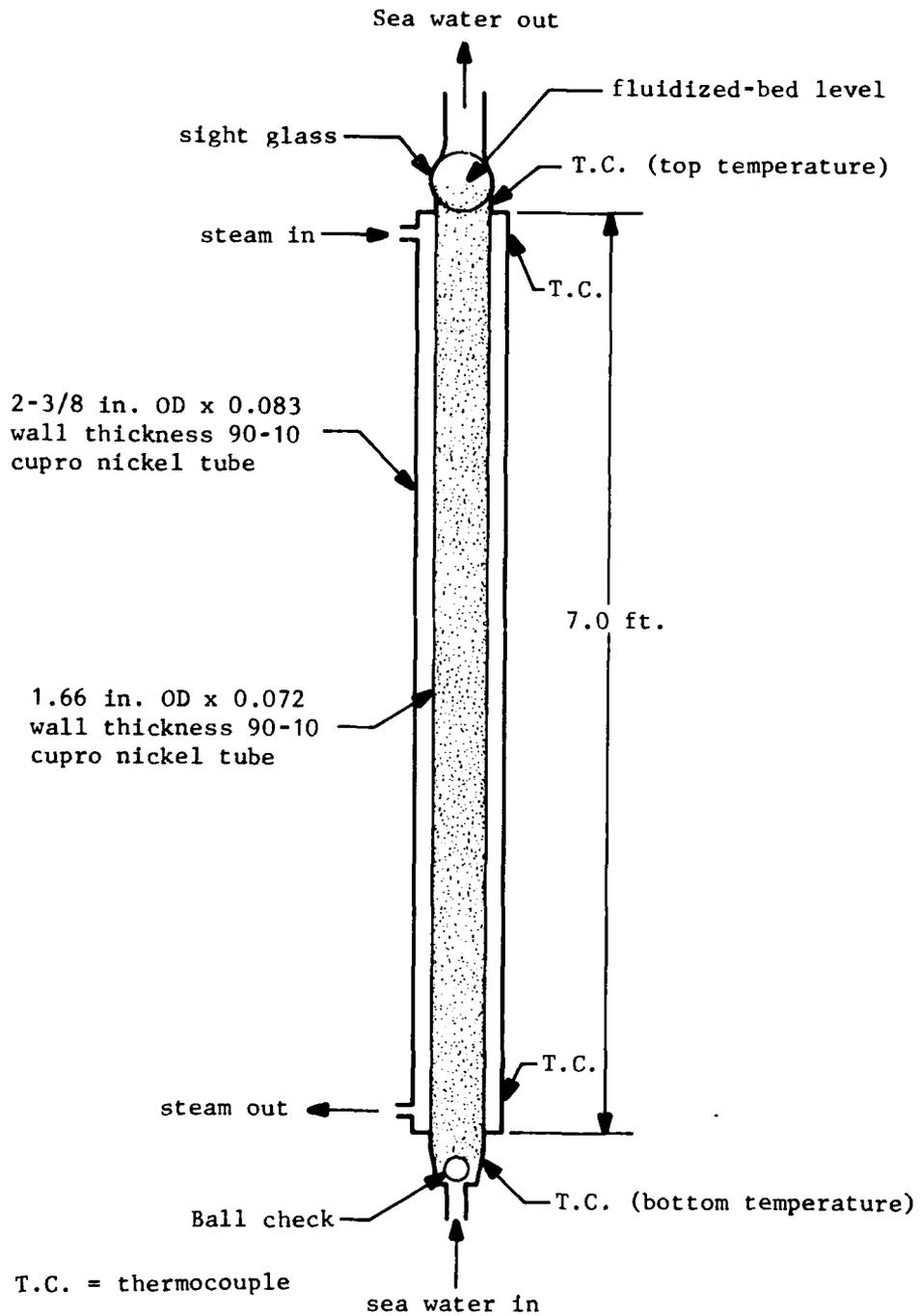


Figure 2. Fluidized-bed heat exchanger

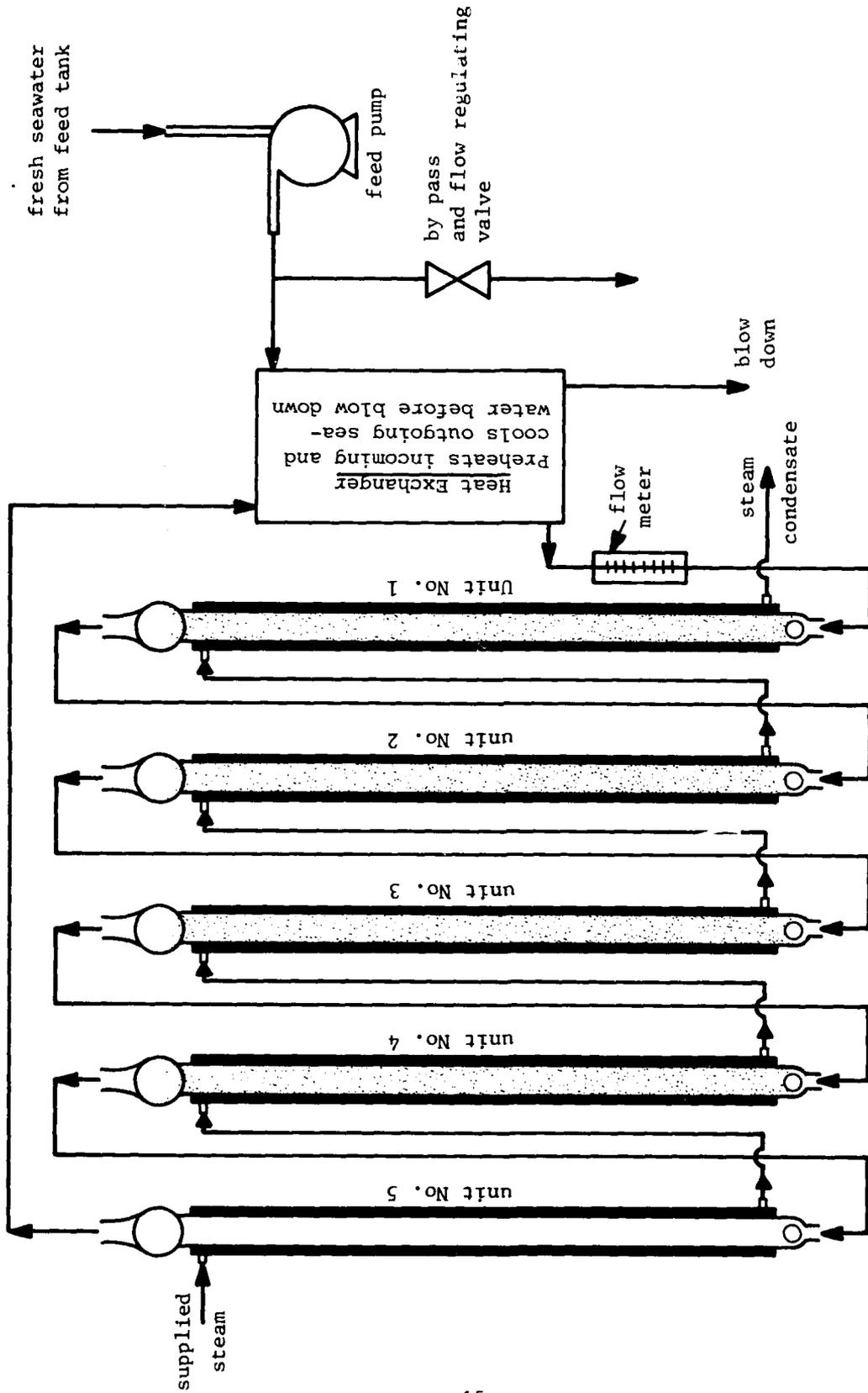


Figure 3. Complete series assembly of the fluidized-bed heat exchangers

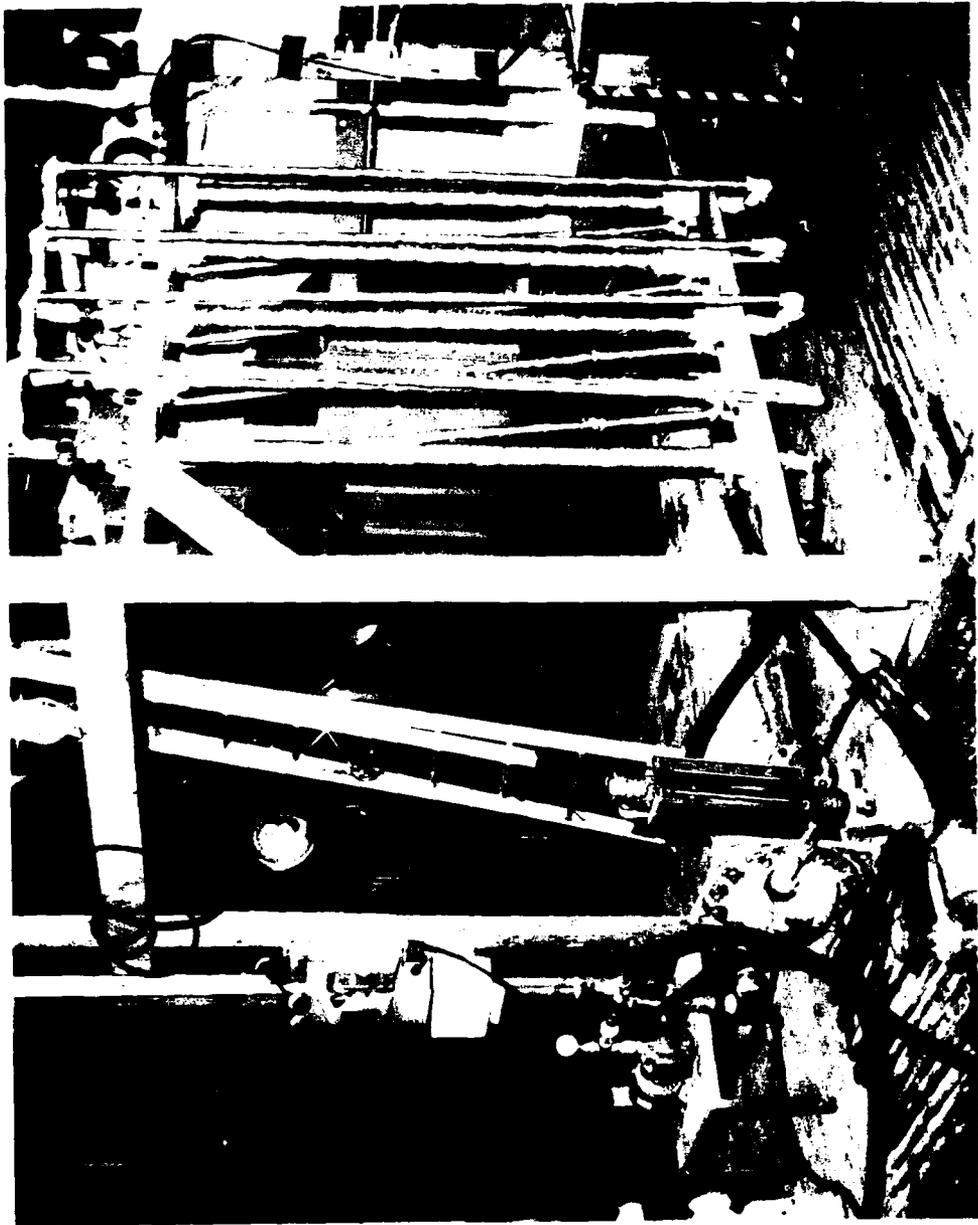


Figure 4. Actual experimental apparatus.

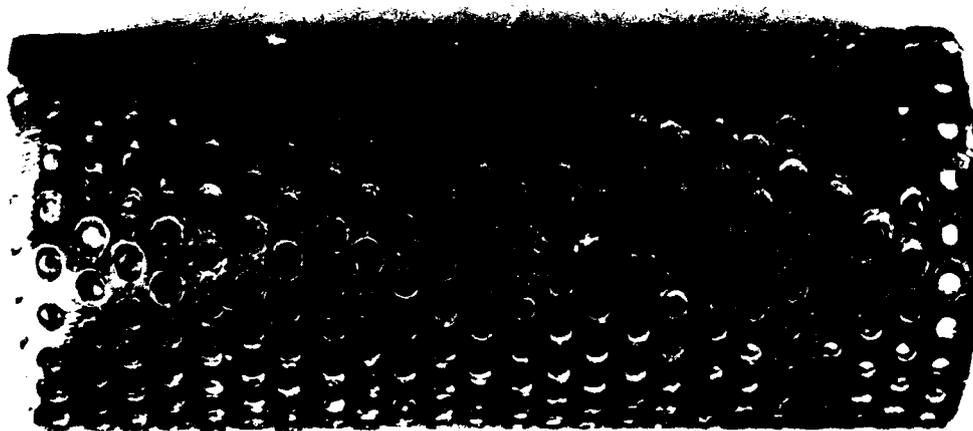
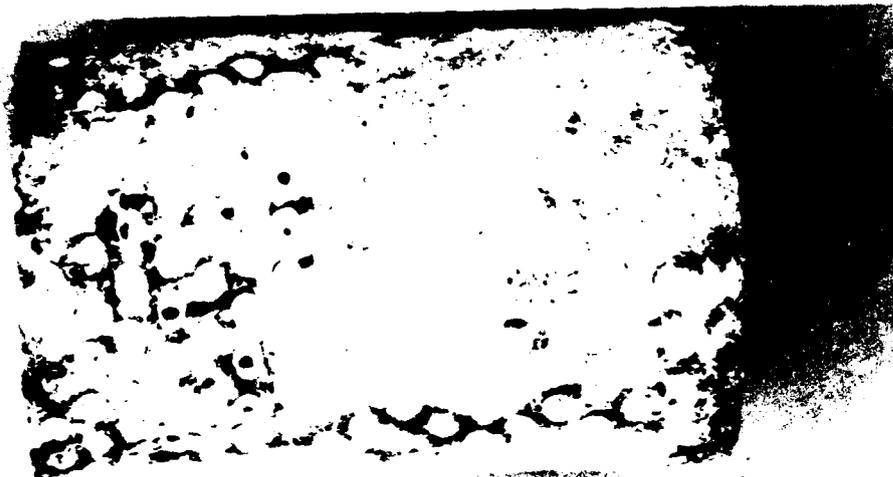


Figure 5. Similar screen devices before and after 5 hour test at 280°F.

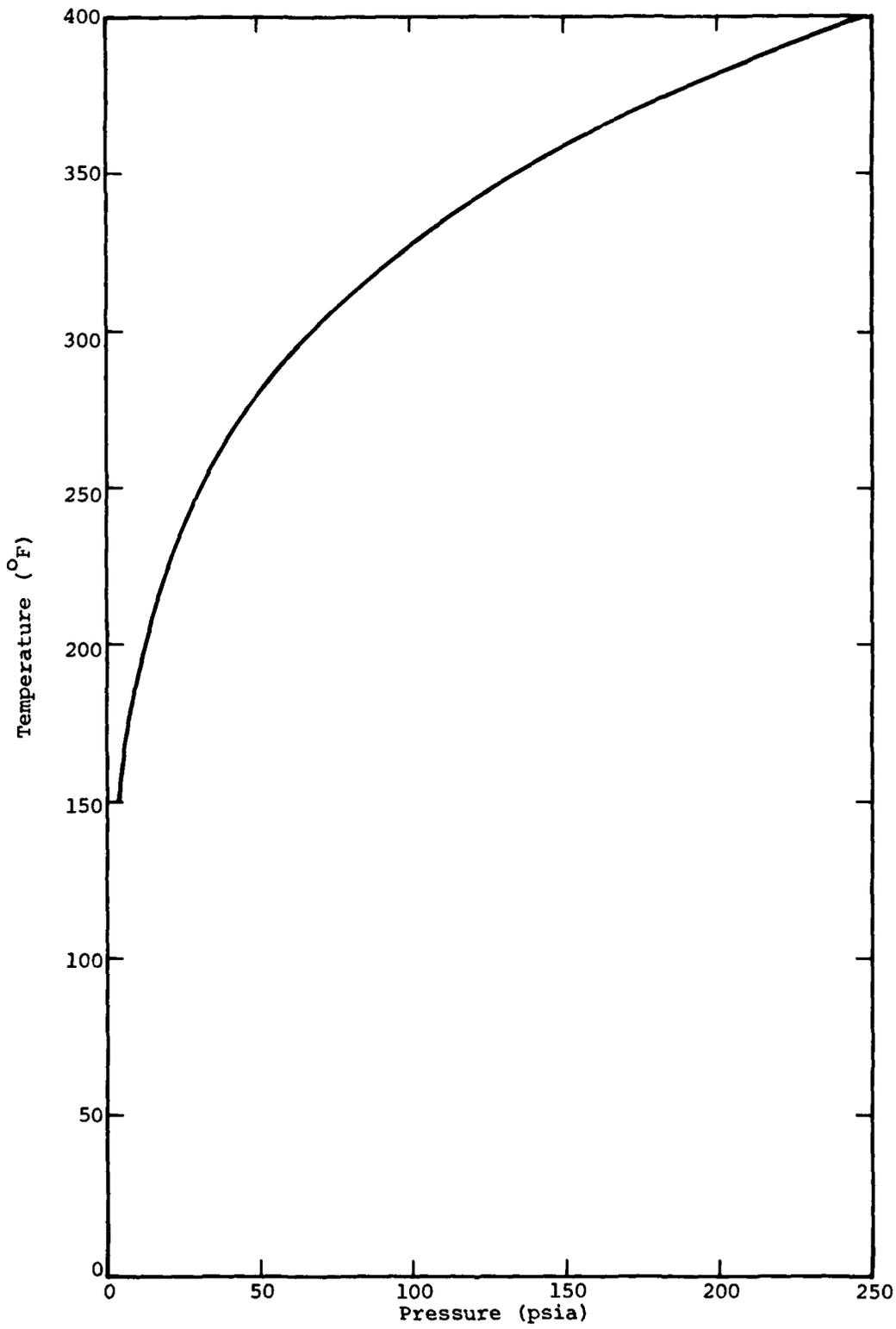


Figure 6. Absolute pressure versus temperature for dry saturated steam.

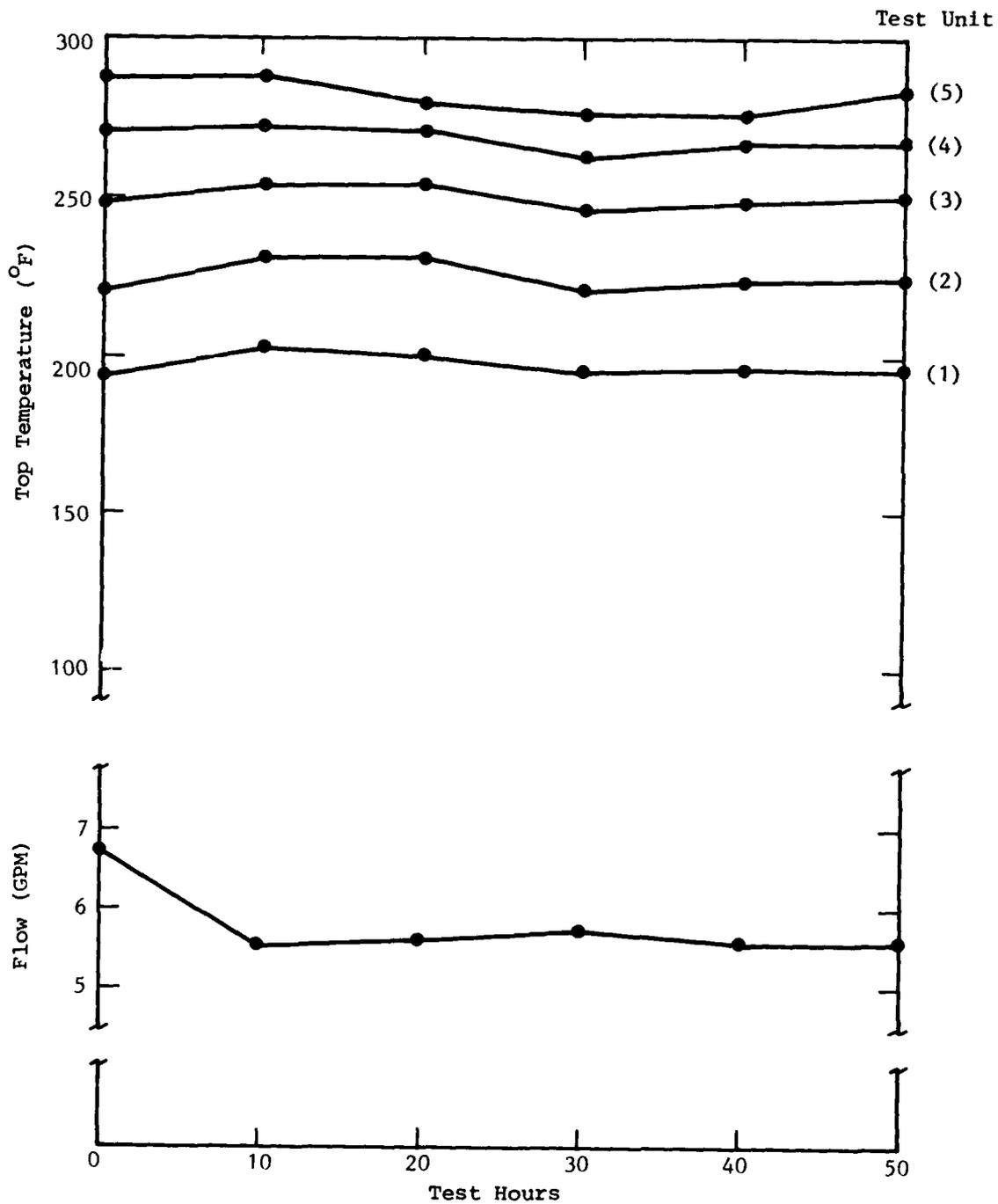


Figure 7. Test No. 1.

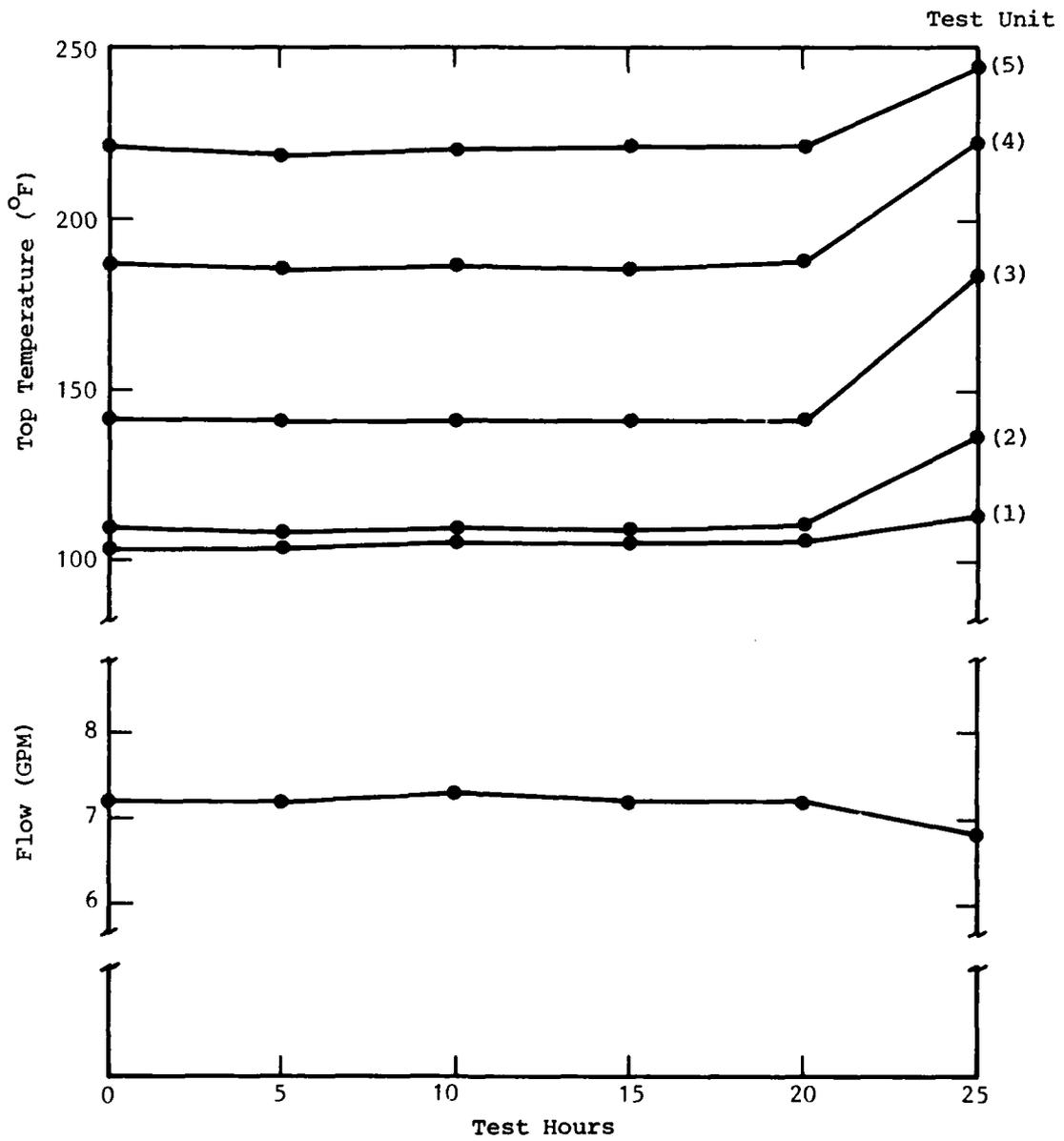


Figure 8. Test No. 2.

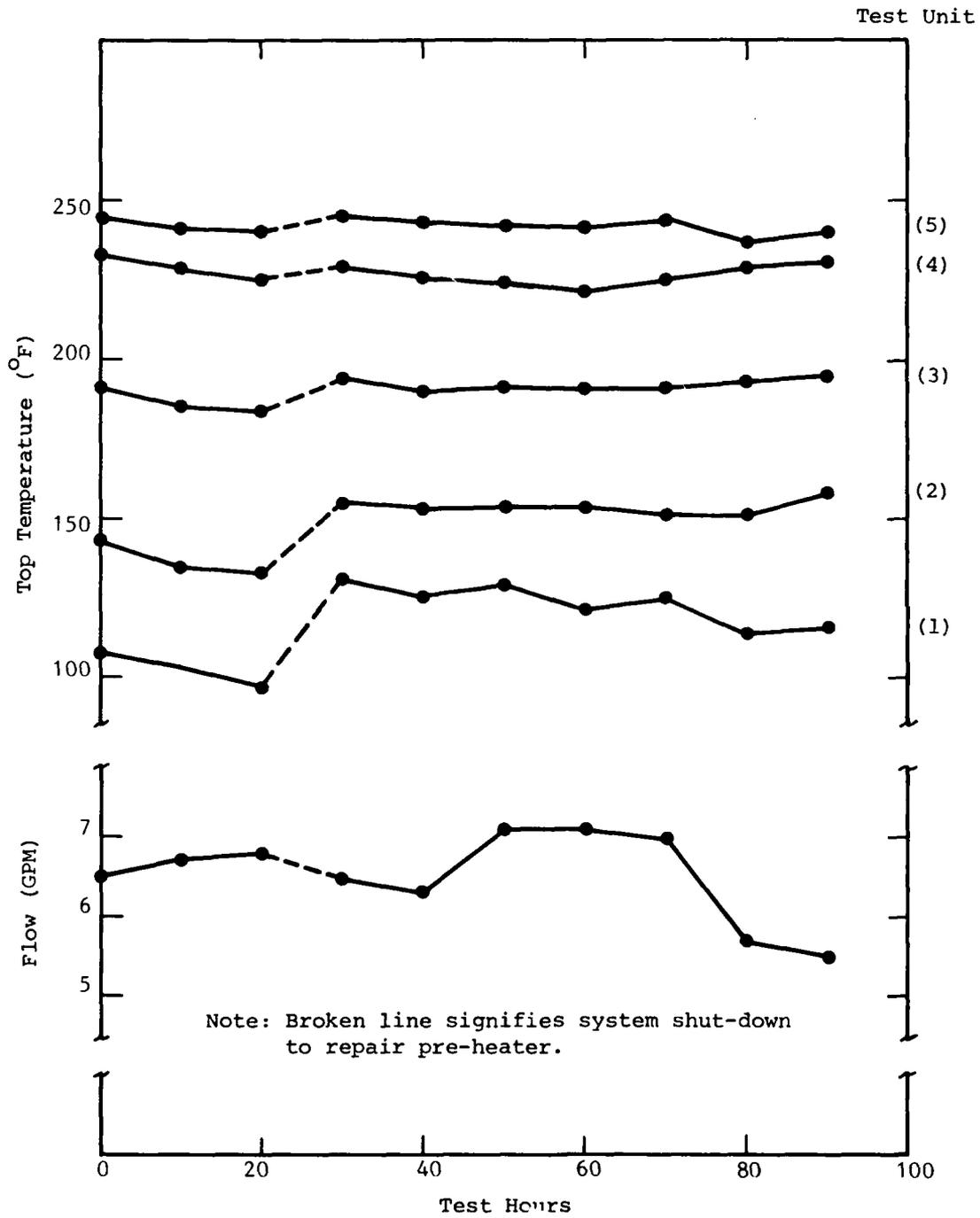


Figure 9. Test No. 3.

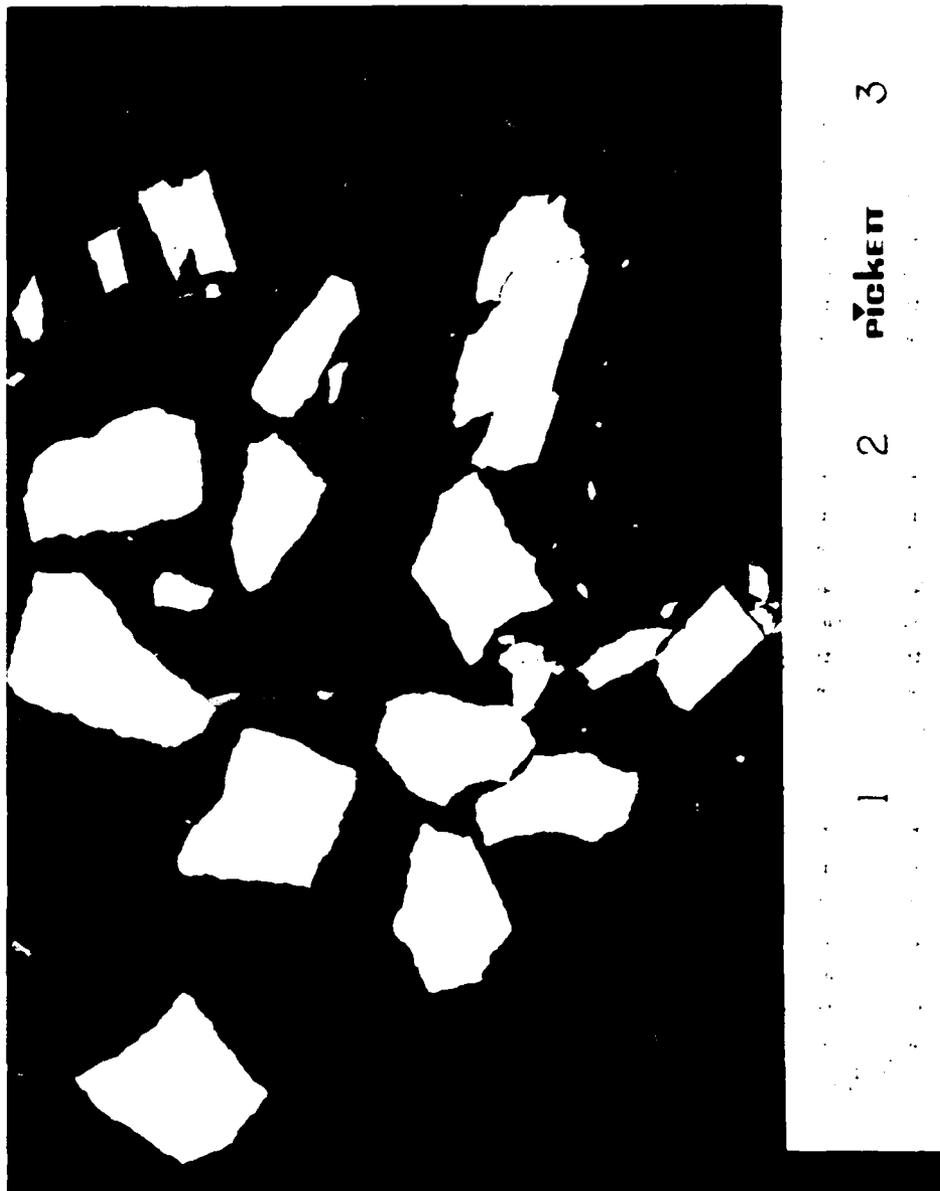


Figure 10. Typical calcium sulfate scale after 50 hours at 280°F.

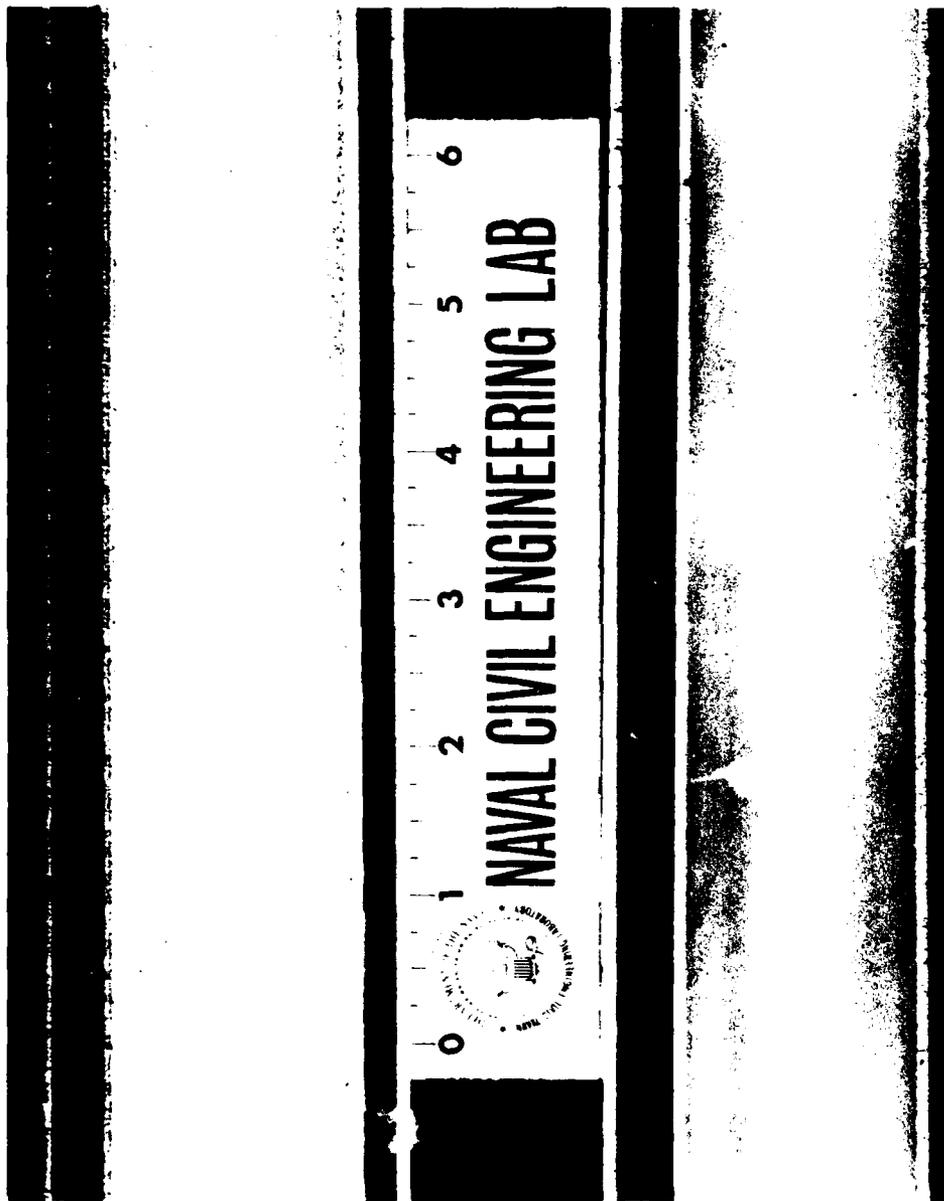


Figure 11. Mid-section of inside tube surfaces - test units no. 4 and 5.

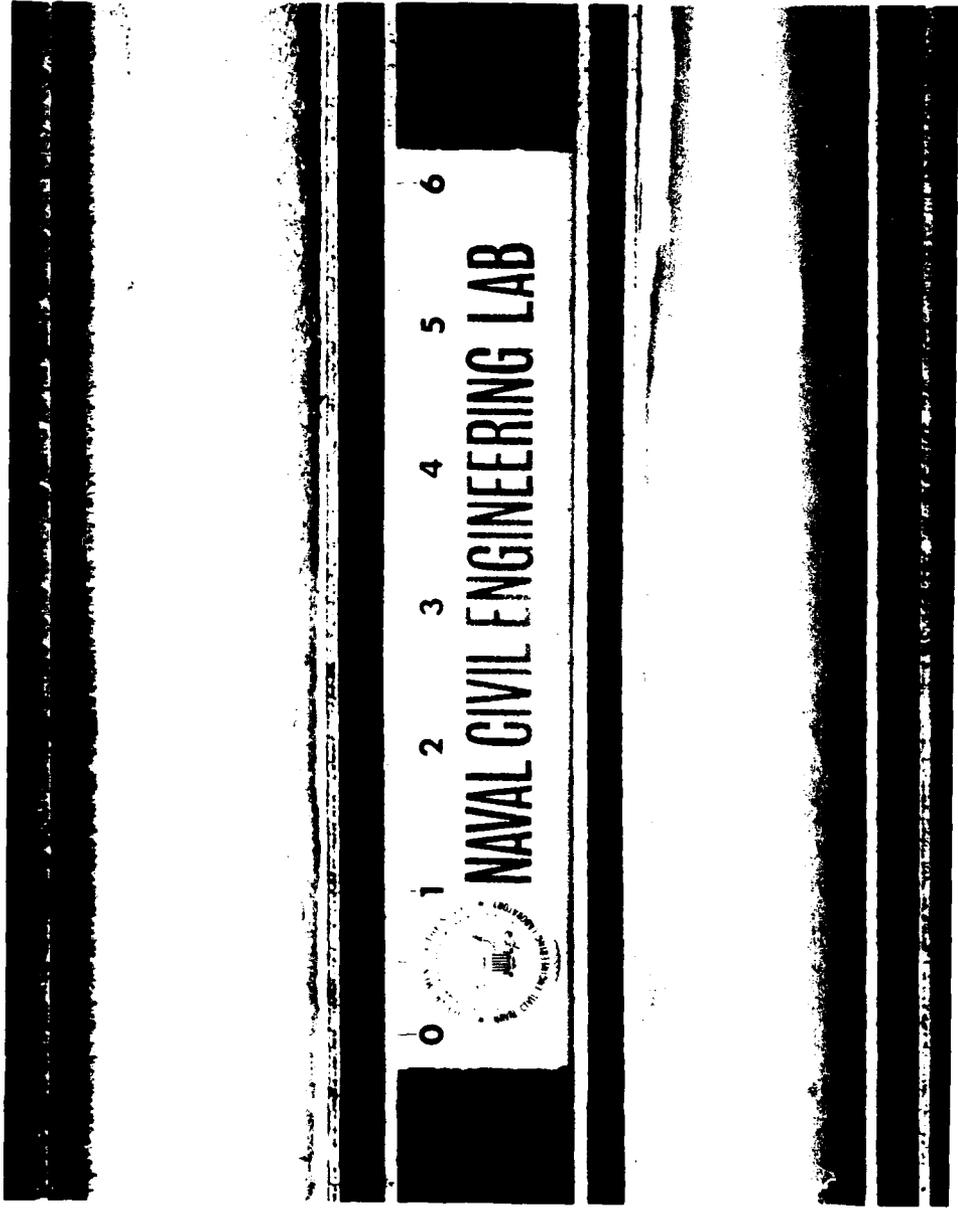


Figure 12. Top-section of inside tube surfaces - test units no. 4 and 5.

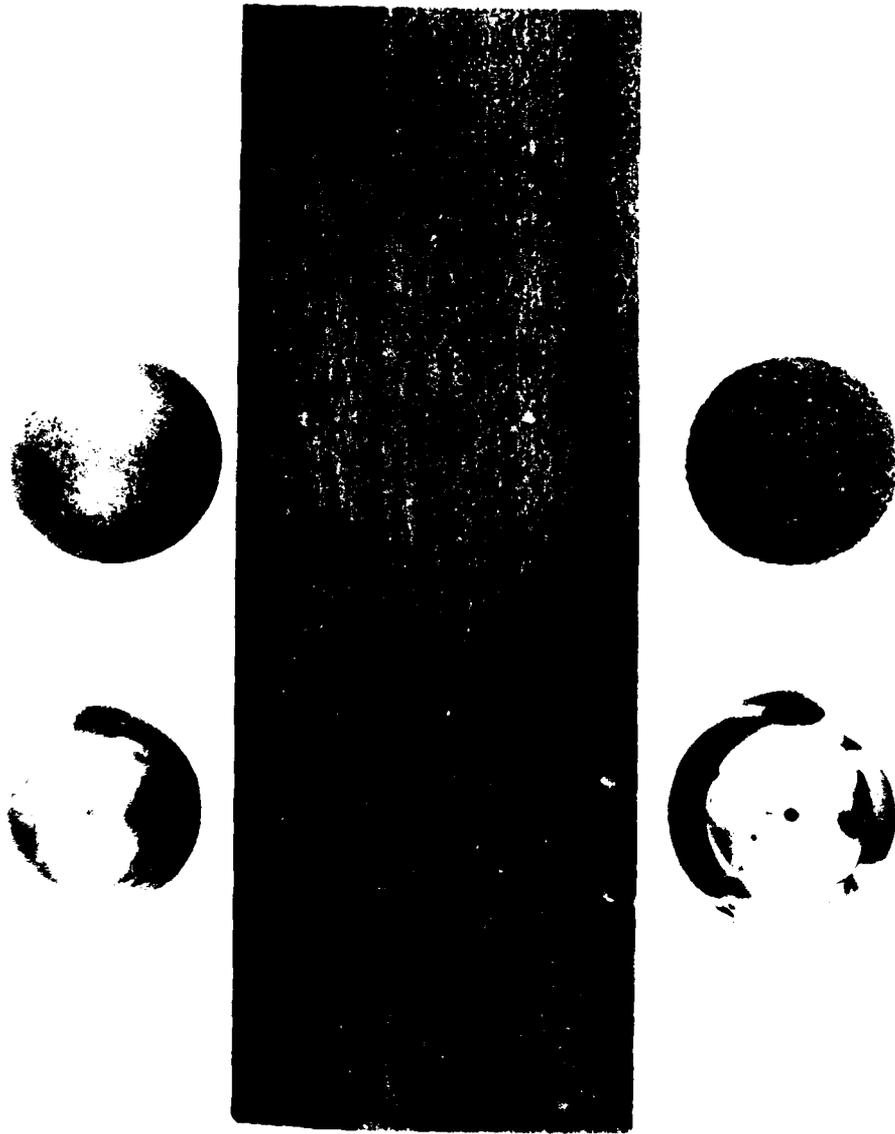


Figure 13. Erosion test on a 3/4"ss-type 316 and 7/8" chrome alloy steel balls after 150 hours at 2750f.

MULTI-TUBE STAGED FLUIDIZED BED  
HEAT EXCHANGER

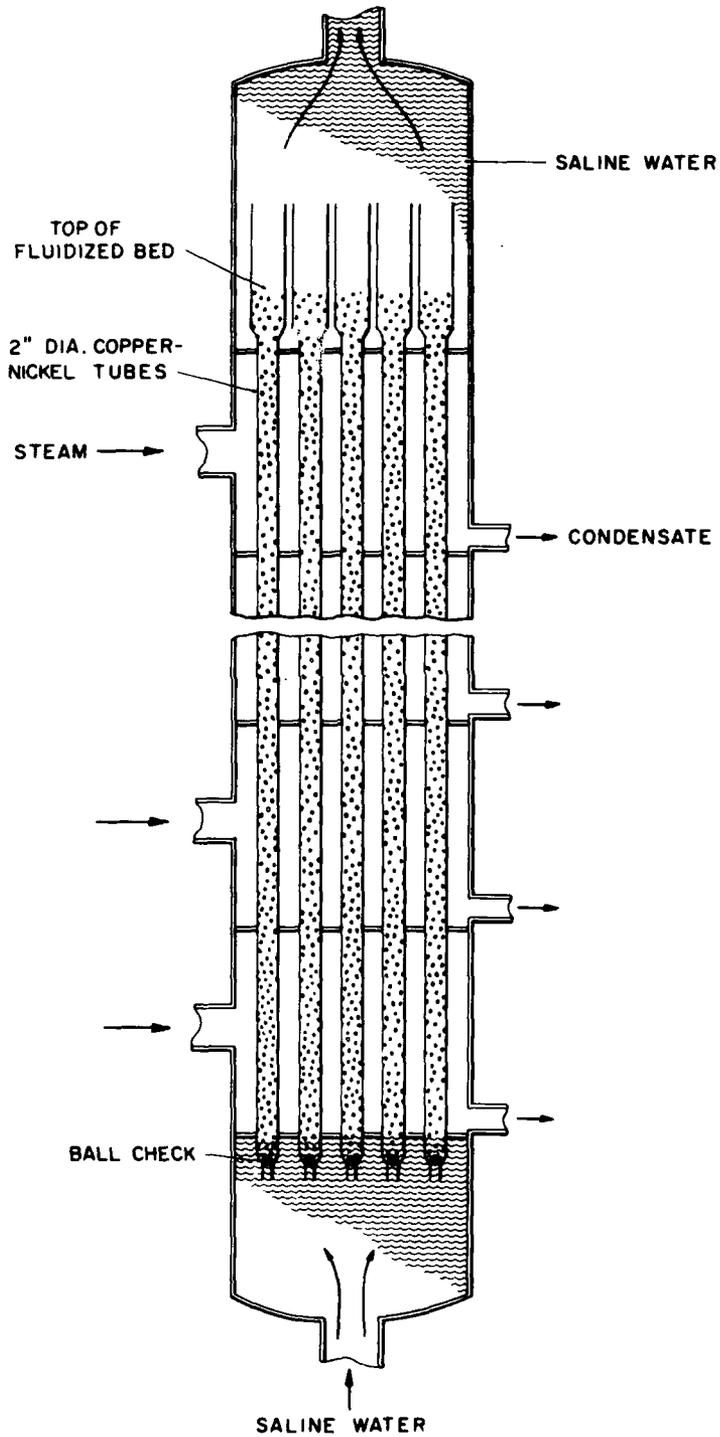


Figure 14. Multi-stage staged fluidized bed heat exchanger.

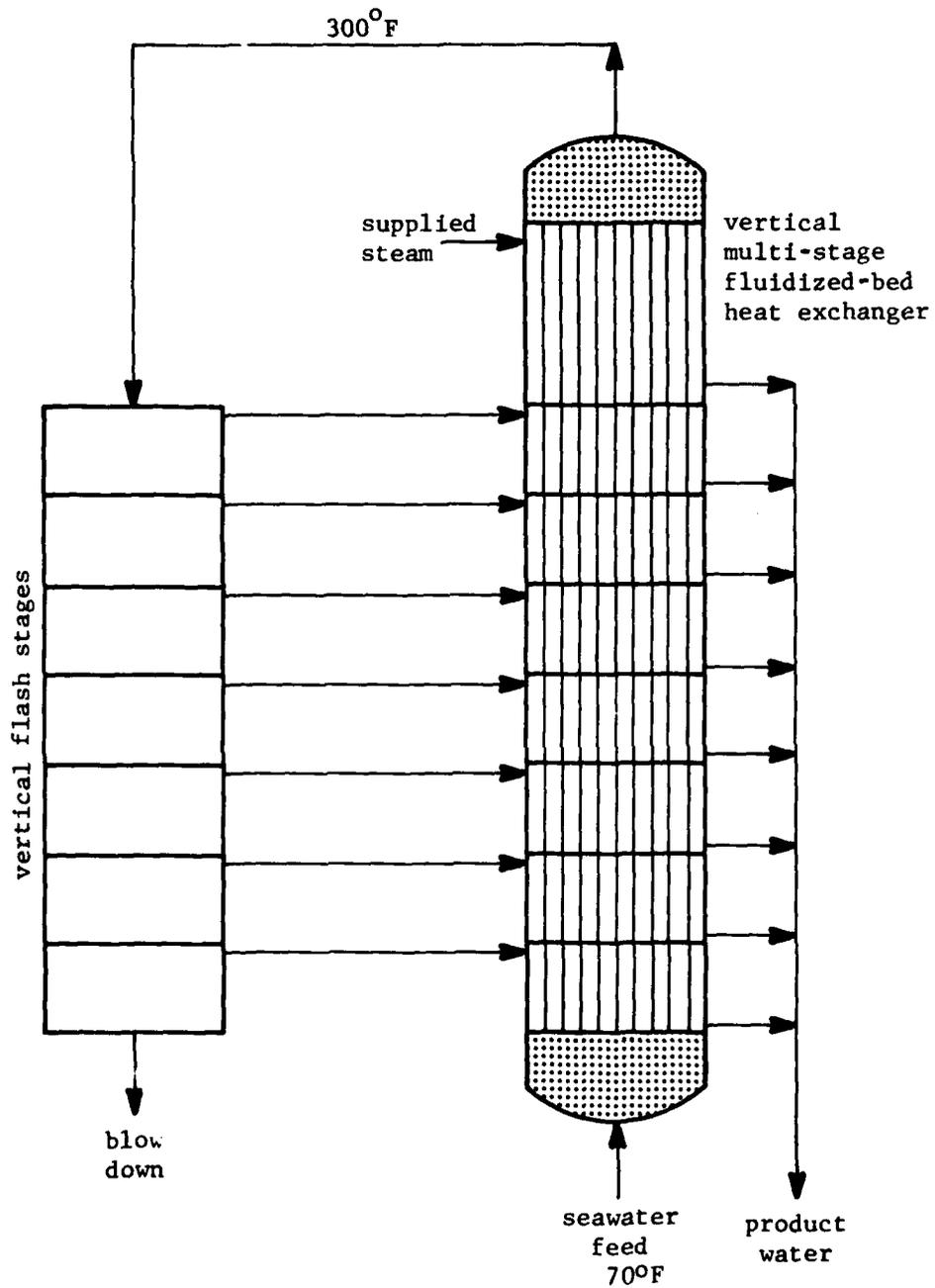


Figure 15. Multi-stage flash plant incorporating fluidized bed heat exchanger.