SODIUM AEROSOL TRAP DESIGN

by

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March 1972

Work performed under the auspices of the U. S. Atomic Energy Commission

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ABSTRACT

Based on a study of sodium aerosol trap technology, it is concluded that hot refluxing wire-mesh demisters can reduce the sodium content of argon to <2 μg/g for at least 100 days with oxygen contamination of 30 μg/g and several times longer at <10 μg/g. Compact, low-pressure-drop designs are proposed for the high-capacity EBR-II argon cooling system (21,000 cm^3/sec) and for monitoring systems requiring up to 1400 cm^3 of argon per second. Novel features include high-temperature operation for better wetting, installation of the mesh in a slanted annulus to ease return of molten sodium and to enhance heat transfer, and 25-50 μm wire mesh for improved interception.

I. INTRODUCTION

With the national commitment to the Liquid Metal Fast Breeder Reactor as a major energy source in the near future, the development of long-lived, reliable reactor-system components takes on renewed significance. Among the components for which completely satisfactory designs have yet to be proven are the cover-gas aerosol traps. These traps are used to remove the vapor and aerosol of sodium and its compounds in cover-gas systems.

Purified inert cover gas is needed to provide cooling and purge gas for reactor-cover components and isolate them from the liquid metal. Inert gas is used to control the pressure in the reactor systems. It is employed in blowing liquid metal from fuel subassemblies and as heating, cooling, and isolation gas in remote fuel loading and unloading. In addition, the cover gas is continually analyzed for fission-product gaseous contaminants for early detection and pinpointing of fuel-cladding failure. In all of these systems, cover gas is removed from above the liquid metal reservoir, filtered in a vapor and aerosol trap, processed, and recycled.

Previous workers have designed traps that provide either long-lived efficient vapor removal or short-lived efficient removal of both vapor and aerosol. The designs, however, have not accomplished the dual goal of long life and high efficiency in removing aerosol formed by the oxidation of alkali metal in impure cover gas.

The purpose of this work is to evaluate vapor-condensing and aerosol-trapping concepts and experience, and then, using recent technology, to recommend trap designs for future experimental appraisal. The designs are adapted to the EBR-II reactor systems, inasmuch as EBR-II has all of the above systems in current operation. EBR-II can thus provide historic operational bases and the opportunity for immediate inexpensive testing of longer-lasting and more efficient replacement traps under realistic operating conditions.

II. DESIGN CONSIDERATIONS

A. Aerosol Generation

Because of aerosol generation, cover gases over molten sodium in nuclear reactor systems can contain an order of magnitude more sodium than accounted for by vapor pressure. The aerosol results from turbulence and, especially at temperatures exceeding about 570°K, from convection of sodium vapor from the sodium pool followed by condensation to aerosol. According to Ader and Kesser, this condensation occurs within a few millimeters of the surface if the gas is more than 50°K cooler than the interface.[1]

The physical state of the aerosol in a leaky system is important. For example, in argon contaminated with 500 μg air/g at 700°K, more than half of the saturation amount of sodium could be converted into solid sodium oxide aerosol. In addition, moisture in the air will produce solid sodium hydride (or hydroxide).

Typical sodium aerosol concentrations in argon cover gas are shown as a function of sodium pool temperature in Fig. 1. The 10^{-3} weight-fraction value calculated from the normal plugging time of the vapor trap in the EBR-II primary argon cooling system agrees with the bench-scale data of Kesser.[2]

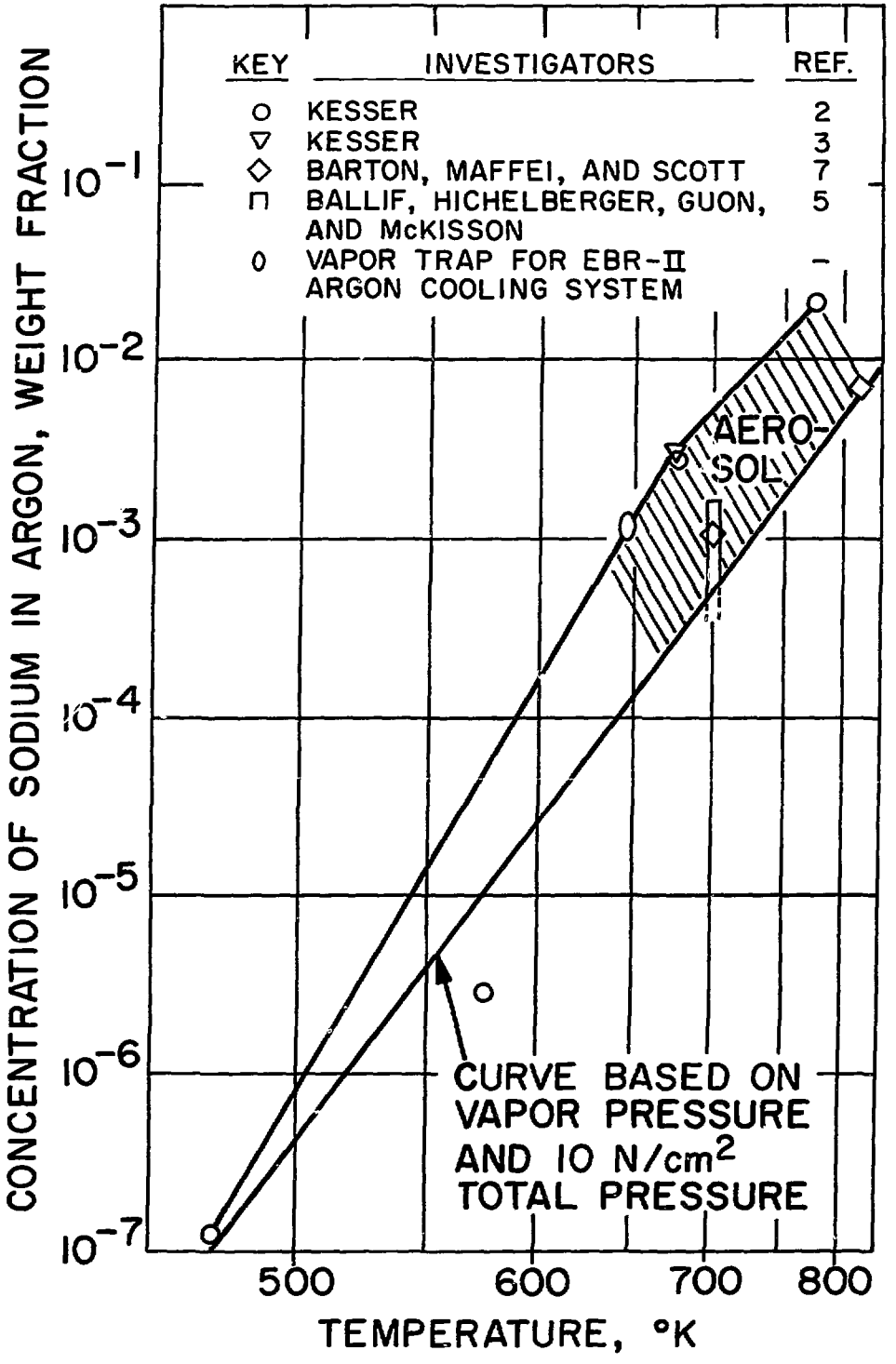

Fig. 1. Sodium Aerosol Concentrations in Argon Cover Gas as a Function of Sodium Pool Temperature

A representative particle-size distribution of cooled sodium aerosol in argon above sodium at 673°K has been presented by Kesser.[3] The mass-mean diameter was 4 μm. The distribution could be represented by the following averaged diameters:

Average Particle Diameter, μm	Weight %
30	0.5
18	5
10	14.5
6	30
3.5	29
2	15
1	5.5
0.6	0.5

The larger particles tending to form at higher temperatures would be expected to be returned to the sodium pool by gravitational settling or be more easily separable in aerosol traps. At lower sodium temperatures, nucleation processes may promote smaller particles, which are difficult to remove in aerosol traps.

B. Aerosol Removal

Several transport mechanisms can be used to remove sodium aerosol from cover-gas streams. A comparison of the magnitudes of the driving forces involved aids in selecting the best mechanisms for separating 1-μm sodium particles in argon at 645°K. As a borderline basis of comparison, 30-μm particles can be completely separated in a baffled settling chamber 0.5 m high and 1.5 m long with a gas velocity of 0.3 m/sec. The gravitational force per particle is 10^{-11} newton,* and the momentum corresponding to its terminal settling velocity of 10^{-3} m/sec is 10^{-14} kg-m/sec. But for

*Newton, the unit of force in the International System of Units, is abbreviated hereafter as N in this report.

a 1-μm particle, the gravitational force is only 10^{-16} N and its terminal velocity and momentum are insignificant at 10^{-6} m/sec and 10^{-21} kg-m/sec, respectively. The average velocity and momentum of the argon atoms are 635 m/sec and 4×10^{-23} kg-m/sec, respectively, indicating that Brownian motion can disrupt the transport of the 1-μm particles.

Impingement and coalescence of 1-μm particles by diffusion is also negligible as a separating mechanism. Only about 10 of the 10^5 particles present per cubic centimeter collide with each other per second.

Thermal precipitation is no more effective than gravitational settling, since the thermal force exerted on a 1-μm particle is only 10^{-16} N in a 22,000°K/m gradient.

In common electrostatic precipitators, the force on a 1-μm particle can exceed the single-electron-charge force of 10^{-13} N by many orders of magnitude depending on the charge acquired, indicating the separating potentiality of these precipitators. However, the resistivity of liquid sodium is 10^{-7} ohm-meter, which is much lower than the 10^2- to 10^8-ohm-meter range for particles effectively separated in precipitators. The particles readily lose their charge on the collecting electrode and may be reentrained. Prevention of shorts between the electrodes by plated-out sodium remains a most difficult problem.

The magnetic force on a flowing 1-μm sodium particle with 10% of its atoms charged is significant at 10^{-11} N in 0.4-tesla magnetic-flux density. This force can be used to project the particles perpendicular to the direction of flow to separate them from the flow stream. However, the accompanying electrostatic force parallel to the direction of flow is 10 times stronger, even at potentials less than 0.5 V. An electromagnetic device has the same disadvantage as an electrostatic device; a cathode-anode pair is needed to unbalance the charges on the droplets, and these electrodes are prone to shorting out by plated sodium.

The momentum of a 1-μm particle traveling at 1.8 m/sec is 10^{-15} kg-m/sec. The centripetal force exerted on the particle in forcing it to turn sharply (1-mm radius) is 10^{-12} N. At these magnitudes, impaction as a separating mechanism is insignificant. However, for particles 4 μm in diameter, the momentum is 10^{-13} kg-m/sec and the force is 10^{-10} N, and at these values, the impaction mechanism becomes significant. Consequently, this mechanism should be considered in the design of sodium aerosol traps.

The mechanisms of straining and interception should be employed in trap design for providing large frontal collecting surfaces and as a finishing operation for small-particle removal. Porous metal filters operated hot can effectively coalesce molten sodium aerosol, but the capillary force to push the coalesced molten sodium out of the pores is high. The pressure drop required is 0.4 N/cm^2 (16 in. H_2O) for 165-μm-diameter pores and 13 N/cm^2 (1.3 atm) for 5-μm pores. Instead of porous filters, it is recommended that fiber meshes be used, inasmuch as they can separate particles effectively, can provide low flow resistance, and are not easily plugged. For hot sodium aerosol systems, the choice of fiber material is virtually limited to stainless steel wire. Bouncing of fine particles from the smooth metal surface should not be a problem at velocities near 1 m/sec. Demisting mesh made from 100-125-μm wire can be used to provide the frontal collecting surface, and finer mesh made from 25-50-μm wire can be used for removal of minute particles.

C. Trap Operating Experience

Vapor traps with 100-125-μm wire-mesh elements have been used for many years at EBR-II and other installations. These traps act as both condensers and aerosol interceptors. Large diameters are employed to provide extended frontal surfaces for particle retention, and as a result of the low gas velocities encountered, the principal mechanism for separating aerosol is interception. Some of the traps are operated at ambient temperatures, and consequently the frontal mesh quickly plugs with frozen sodium. Other traps are operated hot so that the condensed vapor and sodium aerosol are refluxed. These hot traps have long operating lives, unless the argon becomes contaminated with oxygen. A principal shortcoming is the large mesh thickness required to provide sufficient interception for complete aerosol removal. If the mesh is only 10-15 cm thick, aerosol, if present, quickly penetrates the traps and plugs the backup porous metal filters.

More recently, Kimont has developed a compact trap utilizing the mechanisms of interception, impaction, and condensation for removing sodium aerosol from argon.[4] The test model was a hot refluxing unit 5 cm in

diameter, with elements consisting of tight wire mesh and condensing baffles. The aerosol was generated at 920°K, entered the trap at 800°K, and exited at 370°K. Removal efficiencies of up to 99.8% were claimed at argon flowrates to 0.6 g/sec (0.7 scfm).

Ballif et al. scaled this trap up to 20 cm in diameter and operated it at argon flowrates of 0.3 to 4 g/sec.[5,6] The aerosol was generated at 700°K, entered the trap at 600°K, and exited at 340°K. In higher-temperature tests, the aerosol was generated at 840°K, entered the trap at 740°K, and exited at 500°K. The preliminary tests were made without a wire-mesh element and at flowrates above 0.8 g/sec. Performance was poor under these conditions. Improved performance was noted after installation of a wire-mesh element and operation at the lower flowrates. The sodium content of the argon effluent was reduced to 20 μg/g or less.

In other tests, high removal efficiency was attained in sodium vapor traps by heating the feed to vaporize the aerosol and then gradually cooling the gas within the trap to condense the sodium directly from the vapor state.[5,6,7,8] Controlled-temperature-profile traps packed with 0.63-cm Raschig rings were employed. Typically, the aerosol was generated at 700°K, preheated to 760°K, and discharged at 450°K. In higher-temperature tests, the aerosol was generated at 870°K, preheated to 920°K, and discharged at 510°K.

Preheating is useful, even if all the aerosol is not vaporized; the preheating reduces the number of troublesome, minute particles, which would be vaporized most quickly. A slow rate of subsequent cooling prevents the growth of aerosol nuclei and allows time for transport of sodium to the condensation surface to be absorbed.

Maffei and Nichols reported losses in trapping efficiency after 10-30 days of operation of a controlled-temperature-profile trap packed with 0.63-cm Raschig rings.[9] The original efficiency was reinstated by back-flushing the trap with liquid sodium. It was postulated that the reduction in trap efficiency was the result of reduced wetting of the trap surfaces caused by reaction of gaseous impurities with the wetting sodium film. The sodium flush removed the surface film and restored trap efficiency. Preheating the aerosol feed appeared to eliminate the need for rejuvenation for at least 50 days. They also showed that trap efficiency decreased when the air content of the argon was increased from 0 to 64 to 326 μg/g.

Todd and Turner showed that the transition from nonwetting to immediate good wetting of liquid sodium on acetone-washed stainless steel occurred upon heating to approximately 520°K.[10] Increasing the oxygen content of the sodium from 5 μg/g to 85 μg/g raised the transition temperature to about 590°K. The better wetting at high temperatures can be attributed to the reduction of the oxide layer by liquid sodium. In sodium vapor traps, the vapor might be capable of reducing the oxide layer.

The more successful trapping of sodium vapor and aerosol when they are generated at high temperature with minimum impurity and trapped at high temperature can be attributed to the more favorable physical state of the sodium and to improved wetting upon contact with the packing surface. The preheat-condenser concept is of limited usefulness in systems where the argon is relatively impure and solid aerosols are generated; such systems require the incorporation of efficient mechanisms for removing particulates.

III. PROPOSED TRAP DESIGN

In this section, components and operating characteristics for proposed future traps are first discussed, then two specific designs for testing in EBR-II are presented.

A. Components

A compact trap that can provide extended operating time at high efficiency contains the following consecutive units: (1) heated 100-125-μm wire mesh that vaporizes the smallest aerosol particles, intercepts and drains off the largest liquid aerosol, and has an extended frontal area to retain large solid aerosol, (2) compact high-velocity-impaction zone of 100-125-μm wire mesh for removal of the bulk of the aerosol, with the molten sodium being refluxed and drawn off, (3) gradient-cooled refluxing 100-125-μm wire mesh of extended frontal area for vapor condensation, and (4) annular-shaped gradient-cooled 25-50-μm wire mesh for residual vapor condensation and fine aerosol interception. All of the mesh is of the Metex demister type with a density of 320 kg/m^3. The frontal and impaction zones of the trap should be heated to at least 570°-590°K if possible to ensure immediate wettability. The gas should exit at less than 530°K to reduce the vapor content to less than 2 μg/g. An exit temperature of less than the 371°K melting point of sodium would be desirable to prevent

carryover of sodium in the liquid state (which is more apt to plug downstream units than solid aerosol).

Plugging is inevitable with air-contaminated argon even in a hot trap because of the presence of solid sodium oxide and sodium hydride aerosol. The solubility of sodium oxide in molten sodium at trap operating temperatures ranges from 1 to 1000 μg oxygen/g solution and that of sodium hydride is a factor of 10 less on the basis of μg hydrogen/g solution.[11] This is insufficient for removal of the compounds by dissolution in the amount of sodium refluxed from aerosols. Thus, valved conduits should be available to bypass plugged zones, or facilities should be present for flushing the frontal portions of the trap with molten sodium, or a parallel trap should be available for use while changing mesh in a plugged trap. Finally, a follow-up absolute filter should be employed, preferably with a cold porous-metal element.

B. Trap Operating Characteristics

The pressure drop per unit length was calculated as a function of velocity for wire meshes operated at the conditions in the proposed trap, using demister correlations.[12] In a refluxing trap, the throughput is limited by the flooding velocity, which is seen in Fig. 2 to be 3 m/sec in the impaction zone and 0.9 m/sec in the fine-wire interception zone.

Since the mesh will gradually plug with solid aerosol, an easier return path for the molten sodium should be provided to delay flooding. This can be done by changing the flow orientation from vertical to slanted to allow the sodium to return down the side. The packing will tend to stay drier, thus lowering the pressure drop to compensate for the loss in available liquid return head. For a 45° angle, a design velocity of 1.8 m/sec should be appropriate in the impaction zone.

In the fine-wire interception mesh, a velocity of approximately 0.25 m/sec is suggested to provide (1) flow that is laminar, (2) sufficient time for conductive cooling of the gas with the attendant gradual condensation of the sodium vapors throughout the mesh, (3) a sufficiently thin annulus for substantial conductive cooling, and (4) a moderately large cross-sectional flow area available for particle retention.

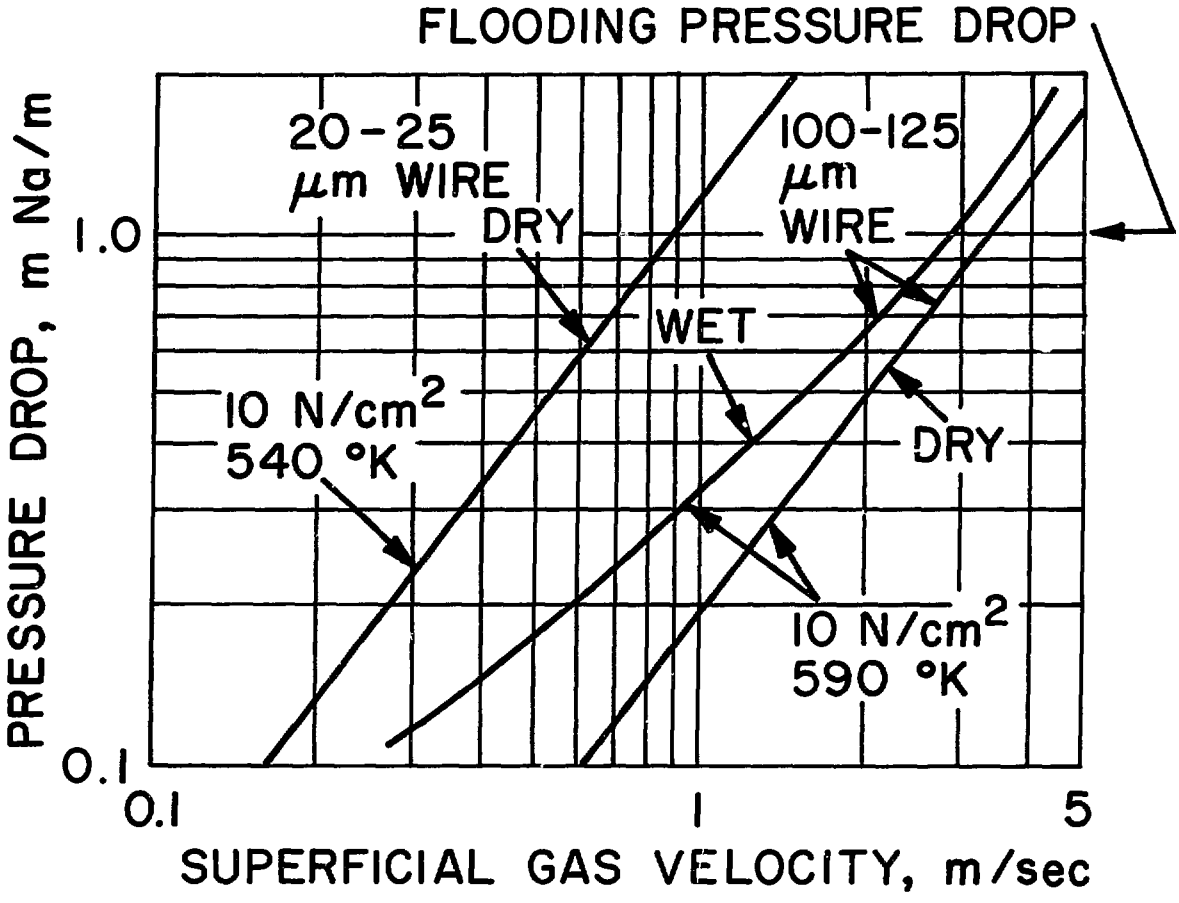

Fig. 2. Pressure Drop per Unit Length in Wire-mesh Demisters for Sodium-Argon Systems

The aerosol-trapping capabilities of 10-cm thicknesses of the meshes under the above conditions were calculated on the basis of demisting and air-filtration technology.[12,13] The 25-50-μm wire mesh is 30 times as effective (Fig. 3) as the 100-125-μm mesh, compensating for its 10 times higher cost of 5¢ per cubic centimeter ($1400/ft^3).

The following consecutive thicknesses of packing will reduce the sodium vapor and aerosol concentrations in argon from the EBR-II primary system to less than 2 μg/g: 10 cm of frontal and impaction 100-125-μm mesh and 25 cm of 25-50-μm interception and condensing mesh.

C. Trap for Cover-gas-monitoring System

Figure 4 shows a sodium aerosol and vapor trap designed for the supply line of the monitoring system for EBR-II primary cover gas. Confined headroom limits the tube slant to 20°, which restricts the design impaction velocity to 0.8 m/sec. Space will not permit installation of a mesh-bypass valve, a flanged exit end to ease mesh replacement, nor an isolation valve that could be shut without prior removal of the bayonet heater.

The inlet-zone temperature is to be maintained at 570°K at all times. This should keep much of the mesh hot and reduce hydrogen "gettering". The frontal-impaction mesh is shaped to gradually accelerate the gas to diffuse the collection of aerosol. The gradient-cooled interception zone is annular to provide sufficient conductive cooling in the flowing argon to reduce its temperature to about 430°K. External cooling is provided by natural convection of air. A draft tube is provided to amplify the flow of coolant air inside the annulus.

The trap capacity is specified as 2.5 g of argon per second at a pressure of 8.4 N/cm^2. On a standard volume basis this is 1400 cm^3/sec (3 scfm). The sodium content of the exiting argon is expected to be less than 2 μg/g. Initial pressure drop over the unit is projected as 80 N/m^2 (0.3 in. H_2O). For a cutoff pressure drop of 1000 N/m^2, the mesh life should be at least 100 days with an oxygen contamination of 30 μg/g and several times longer with an oxygen level of <10 μg/g.

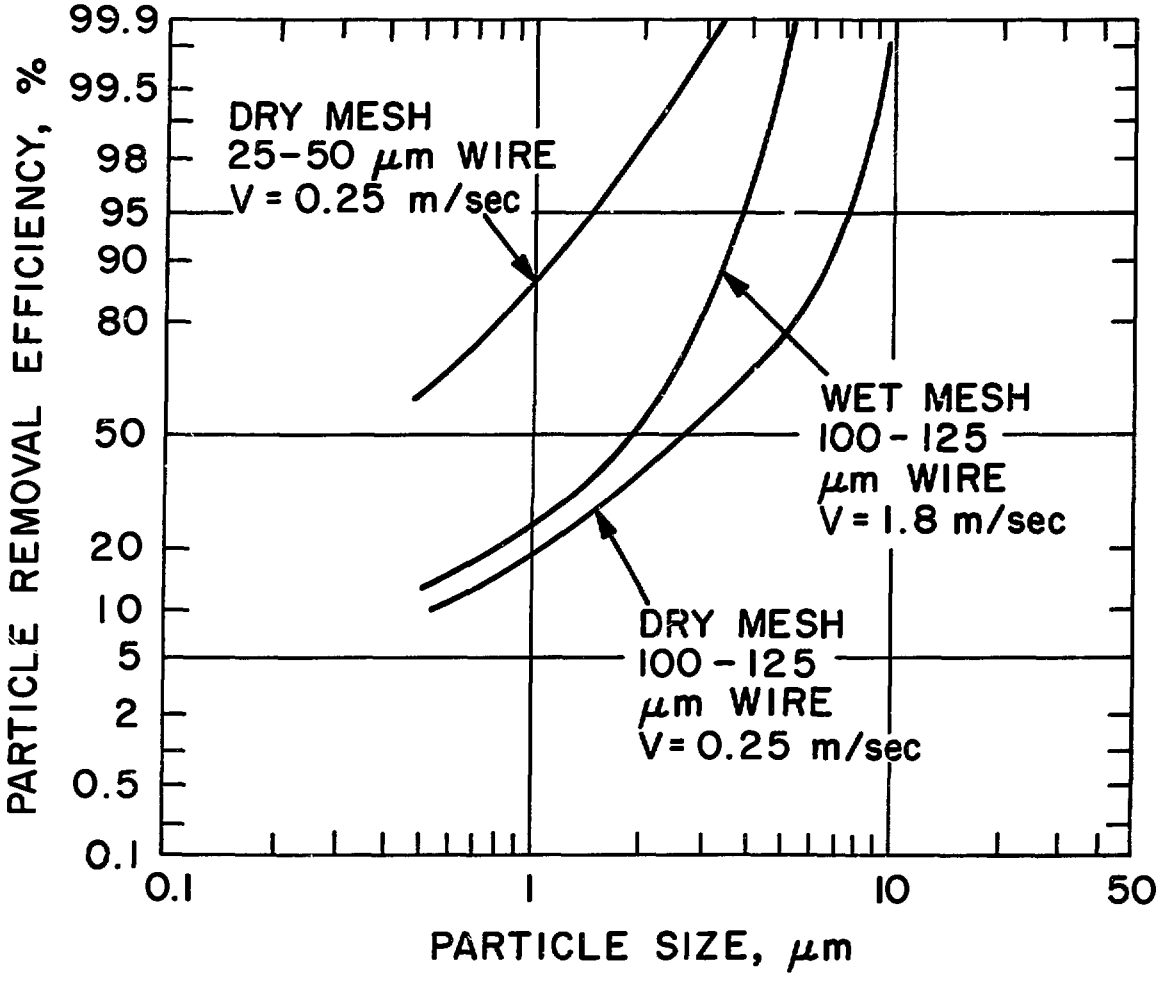

Fig. 3. Sodium Aerosol Filtration by 10 cm of Mesh

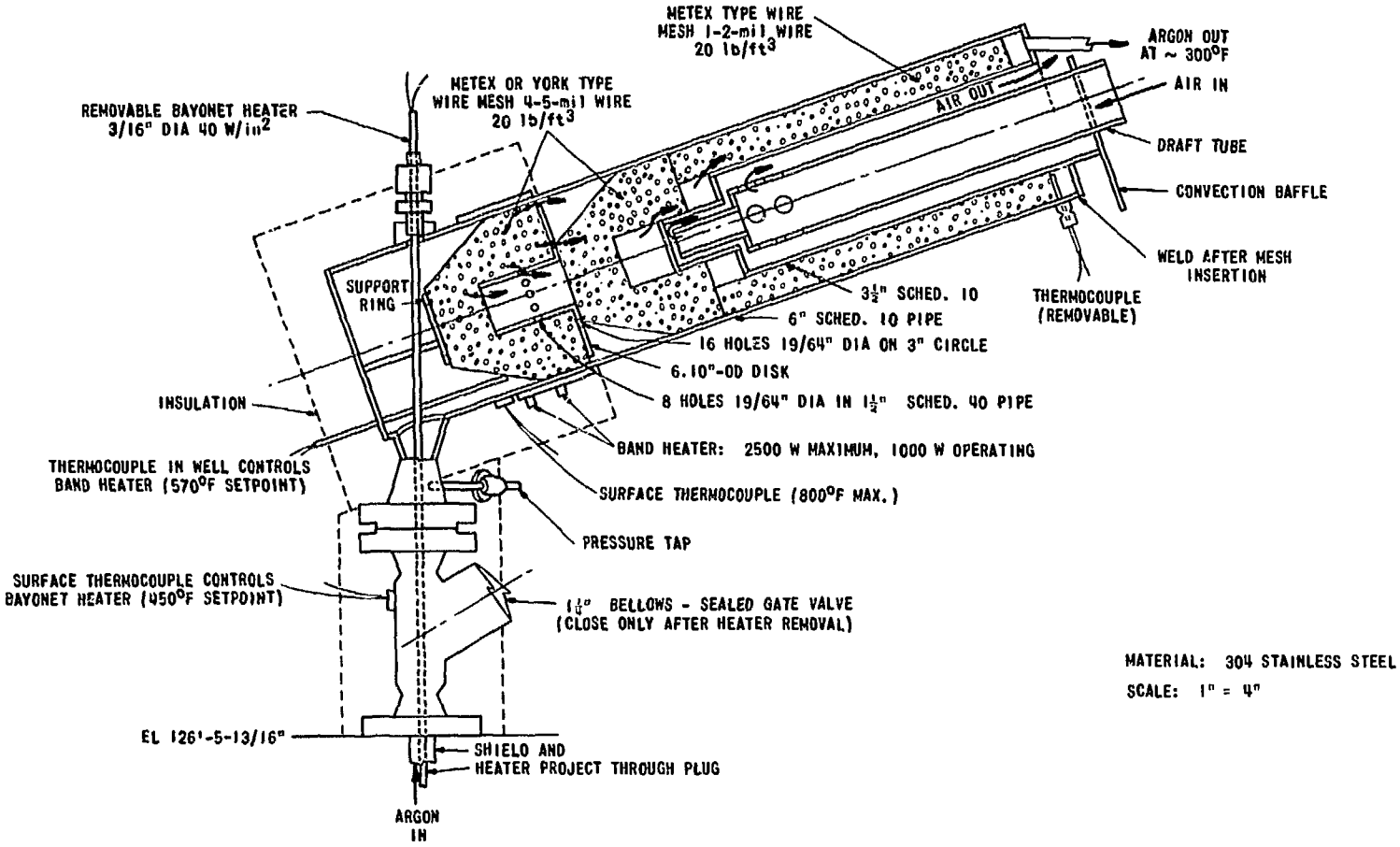

Fig. 4. Sodium Aerosol Trap for EBR-II Cover-gas-monitor Supply

D. Trap for EBR-II Argon Cooling System

Figure 5 shows this high-capacity unit. It can demist 37 g of argon per second at a pressure of 8.4 N/cm^2 to a sodium concentration of less than 1 μg/g. On a standard volume basis, this is 21,000 cm^3/sec (44 scfm). Initial pressure drop over the unit is 0.3 N/cm^2 (12 in. H_2O). With a cutoff pressure drop of 0.9 N/cm^2, the mesh life is projected to be about 500 hr or 1000 fuel handlings with argon contaminated by 30 μg oxygen/g and several times longer at <10 μg oxygen/g.

In order to fit into the location of the present trap, the proposed trap was designed as a horizontal unit in which the molten sodium drains off and is collected in a heated vessel of 83,000 cm^3. The inlet piping and frontal-impaction mesh are maintained near 500°K, the highest temperature practicable. After accelerating through the impaction zone to 1.8 m/sec, the argon is gradually cooled at 0.5 m/sec in annular mesh to approximately 470°K. Forced-air cooling is required on the outside, utilizing a shroud and a blower with a rating of 70,000 cm^3/sec at 0.22 N/cm^2.

IV. RECOMMENDATIONS

The data reported by Kesser have established the basis for quantitative design of sodium-vapor and -aerosol traps. His data made evident the need for improved interception of fine particles. This can be accomplished by the use of 25-50-μm wire mesh. Long life can be attained by hot refluxing operation in a slanted annular tube. It is recommended that traps employing these features be installed in the EBR-II systems for experimental verification and establishment of firm specifications for future applications.

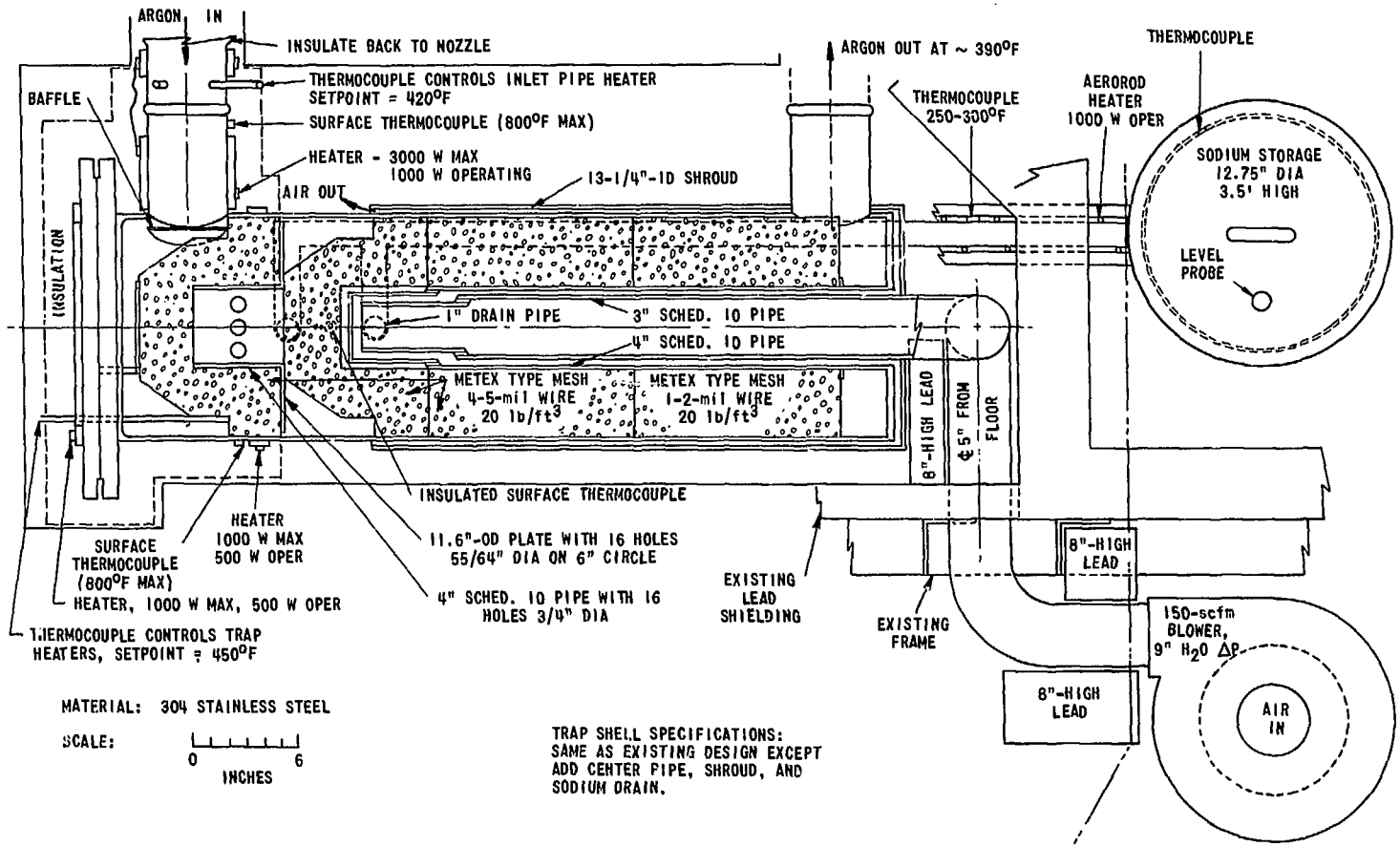

Fig. 5. Sodium Aerosol Trap for EBR-II Argon Cooling System

ACKNOWLEDGMENTS

The assistance of R. W. Kessie and J. G. Eberhart of Argonne National Laboratory and D. E. Lew and O. G. Jenkins of the Liquid Metal Engineering Center of Atomics International is appreciated.

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