Dawson

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SODIUM
TECHNOLOGY

Atomics International
North American Rockwell

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SODIUM TECHNOLOGY COURSE

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INTRODUCTION

Today's lecture is the first in an eight lesson series that is concerned with presenting the rudiments of the engineering application of sodium to nuclear reactor systems. Those who see or hear these courses will not automatically become experts. However, you will be introduced to this technology in such a way as to allow you to utilize the fundamental principles. The course is geared to college level engineers and scientists or equivalent. It is further assumed that most people who participate have a working understanding of nuclear reactor systems so that only a minimum of detailed explanation is necessary. This presupposes that some understanding of heat transfer, elementary chemistry and materials science is present.

The course is laid out in three broad areas.

1) The fundamentals, or information of value in understanding and working with a sodium system.

2) Sodium system design and application.

3) The operation, maintenance and safety of sodium systems.

Each lecture should be able to stand by itself as to content. An advance reading assignment will be assigned to provide an introduction to the work. A quiz will also be associated with each course lecture. You will be expected to complete this quiz on your own time. It will cover those points considered of major importance by your instructor.

A word about your instructors. These men are experts in their fields. In most cases they have had more than 10 years of experience in the technology of sodium. They were selected to share their particular expertise with you. One obvious advantage to you and a ground rule for the course is that they can and will answer questions for you as required. If there is something you don't understand, please feel free to ask for clarification.

A set of notes has been prepared for you to aid in the learning and recall process. They are complete, but I would urge you to take notes and highlight the points that are made. A second help is the video tape recordings that have been made of this course. These will allow you individually or in groups to review the course content for reenforcement of the lessons taught here. They are broken into one hour segments as a matter of convenience. We commend these to you — maximum value can be obtained from these by rechecking your class notes at the same time you review the video tapes.

Again, it is important that you realize that the answers are not all available in many areas of this technology. In many cases we can paint only a crude picture of some areas after more than 20 years of experience with sodium systems. It will in reality be your ingenuity and engineering curiosity that will optimize the systems which will use this coolant material.

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ADDITIONAL PROJECTIONS

Electrical Resistivity
Compressibility
Thermal Diffusivity
Surface Tension/Density
Prandtl Number
Radioactive Isotopes of Sodium
Neutron Reactions of Sodium

SODIUM TECHNOLOGY COURSE, SESSION I
PROPERTIES OF SODIUM
Dr. R. L. Eichelberger

This first session is intended to be an introduction to sodium for those who have not had previous experience with the material, and will serve as a brief review for those who have had some prior exposure. For discussion purposes the properties of sodium to be covered have been separated into three categories: chemical, physical, and nuclear. The classification of a property as chemical or physical is arbitrary in many cases, and is not meant to imply any real systematization.

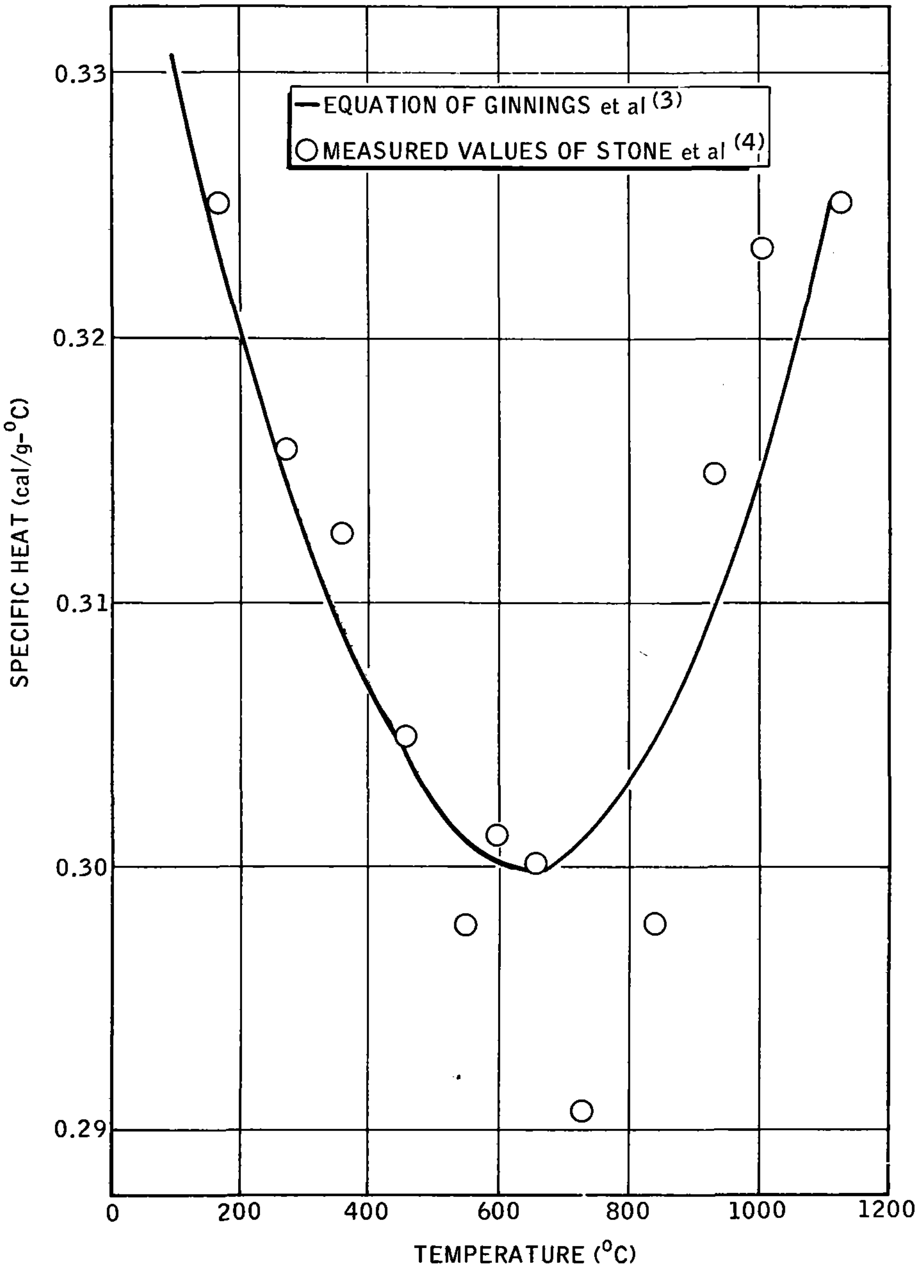
Chapter 1 of the new edition of the Sodium-NaK Supplement to the Liquid Metals Handbook(1) is recommended as a general reference on the properties of sodium. It serves as a comprehensive source of information on the properties of sodium and NaK which are of importance in using these liquids as high temperature heat transfer media.

A. CHEMICAL PROPERTIES

General — Sodium is a member of the alkali metal group (Group Ia of the periodic chart of the atoms), with atomic number 11 and a chemical atomic weight of 22.991. It is one of the more common elements in nature, forming about 2.8% by weight of igneous terrestrial rocks. Only oxygen, silicon, aluminum, iron, and calcium are more abundant in the earth's crust. Because of its reactivity toward other elements and compounds, it is never found free in nature, but is combined in stable compounds. A brief discussion on the reactivity of sodium toward other elements and compounds is included later in this series.

Sodium metal is metallic in appearance, if the surface is clean. An uncontaminated surface is specular, whether it is solid or liquid. Solid sodium is soft, compared to most metals, and can be deformed with the fingers or mechanically extruded. It cuts easily with a pocket knife or spatula, or with a wire "cheese cutter."

FIGURE 1. HEAT CAPACITY OF LIQUID SODIUM



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Melting Point — The melting point of sodium under 1-atm pressure is reported by Evans et al(2) as 97.82°C (208.1°F). The triple point, at which sodium melts under its own vapor pressure ($<1 \times 10^{-9}$ atm at the melting temperature), is 97.81°C. The melting point increases as the pressure is increased, reaching 294°C at 50,000 atm, but this phenomenon is not of any importance in applications at ordinary engineering pressures.

Heat of Fusion — The heat of fusion of sodium at its melting point is 27.05 cal/g, or 48.69 Btu/lb.(2) The heat of fusion per mole is therefore 621.9 cal/g-mol, or 1119.4 Btu/lb-mol. The heat of fusion was calculated from heat content curves for the liquid and solid.

Heat Capacity of Liquid and Solid — The heat capacity of liquid sodium is an important property to know for heat transfer calculations. The reported measurements of this property are not especially precise, however, with poorer agreement among experimenters than is desirable. Figure 1 shows the specific heat (heat capacity per gram) curve developed by Ginnings et al at the National Bureau of Standards,(3) and includes experimental points reported by Stone et al of the Naval Research Laboratories.(4) In Figure 1 it is important to note that the scale of the ordinate is expanded, with all points shown lying in the range 0.29 to 0.325 cal/g-°C.

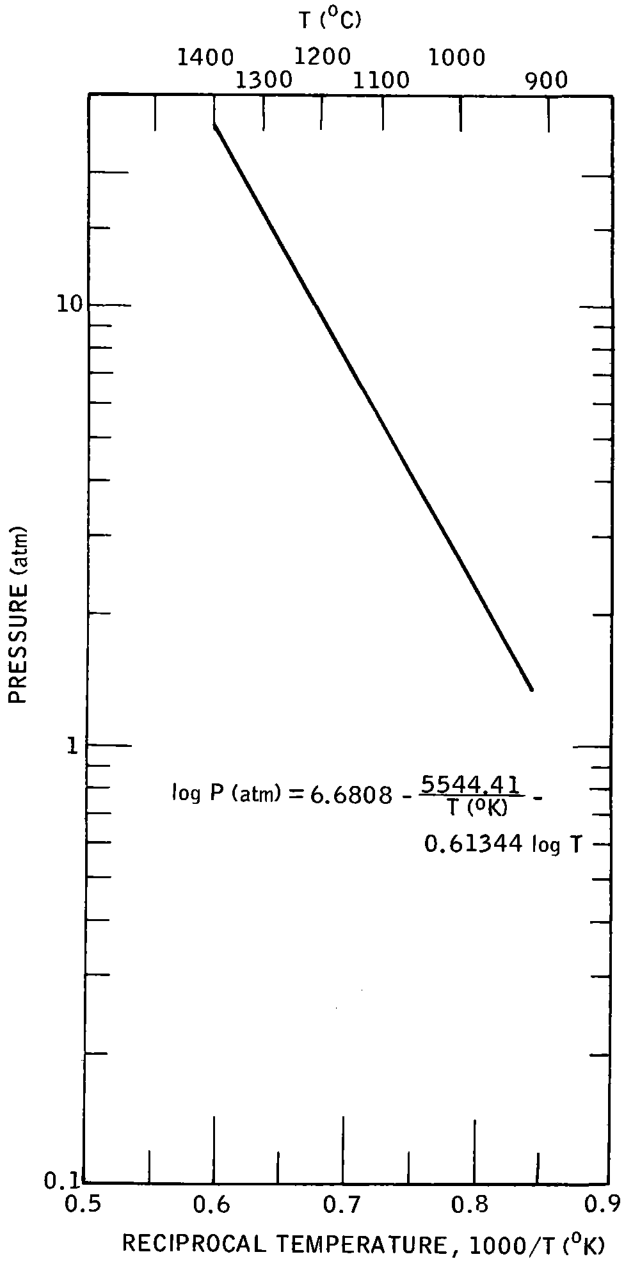
The heat capacity (specific heat) of solid sodium is 0.2 cal/g-°C from room temperature to the melting point.

Vapor Pressure — A knowledge of the vapor pressure of sodium and its variation with temperature is of great importance to designers and operators of sodium systems. Measurements of the vapor pressure have been made carefully by a number of investigators. Golden and Tokar(5) have made a critical evaluation of the work reported. Their conclusions are that for temperatures above 1250°K (~975°C), the vapor pressure is best represented by the equation of Stone et al(4)

$$\log P(\text{atm}) = 6.6808 - \frac{5544.41}{T(°\text{K})} - 0.61344 \log T \quad ; \quad T > 1250°\text{K} \quad . \quad \ldots(1)$$

At temperatures between the melting point and 1250°K, the expression of Ditchburn and Gilmour, is recommended.(6)

FIGURE 2. VAPOR PRESSURE OF LIQUID SODIUM ABOVE 1250°K (4)



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$$\log P(\text{atm}) = 6.354 - \frac{5567}{T(^\circ K)} - 0.5 \log T \quad ; \quad T < 1250^\circ K \quad . \qquad \ldots(2)$$

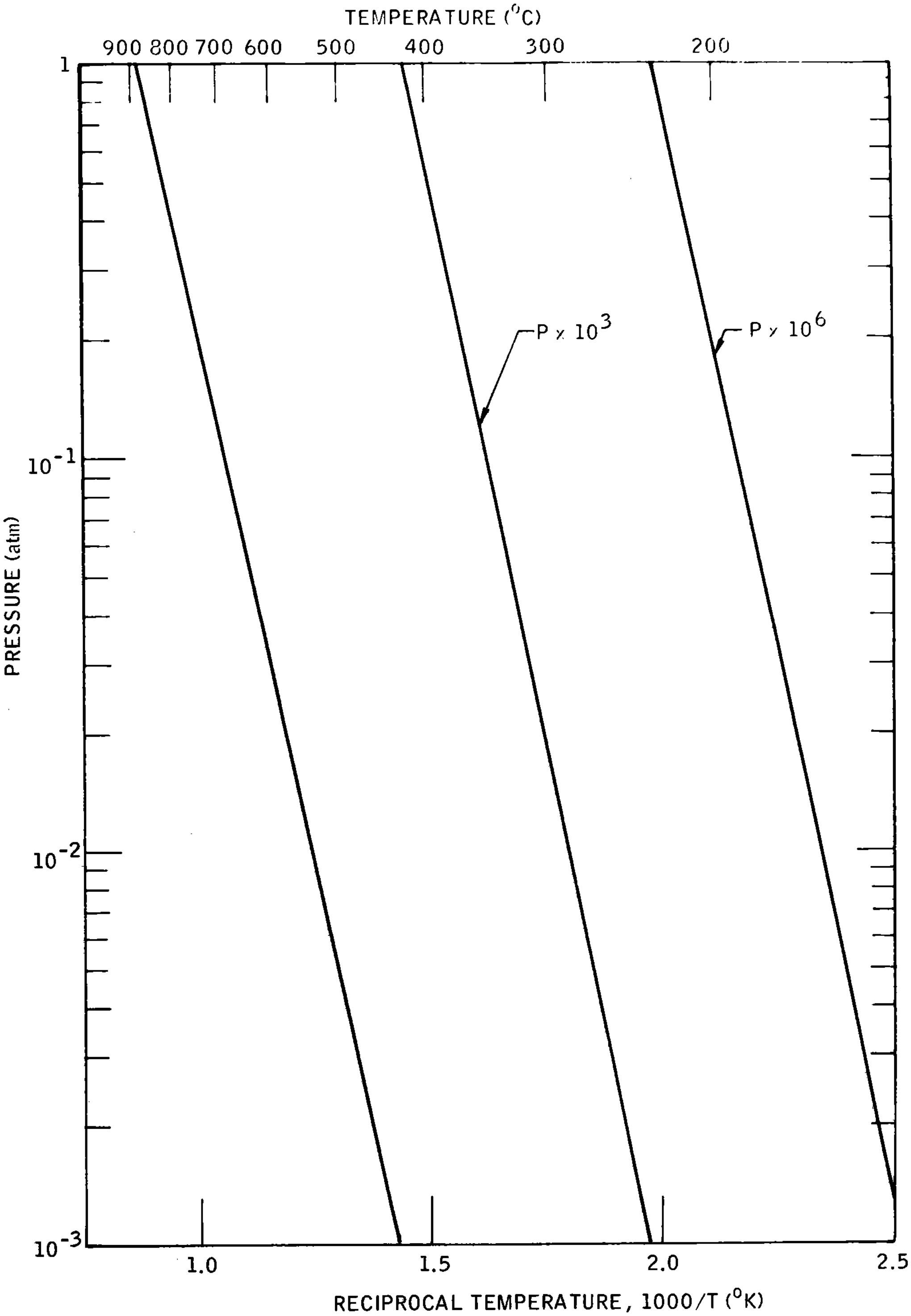
Equations 1 and 2 are plotted in Figures 2 and 3, respectively. The ordinate in Figure 3 has been folded twice to get the whole temperature range on one chart. The normal boiling point is that temperature at which the vapor pressure reaches 1 atm. This temperature for sodium is 881.4°C (1618.5°F).(4,7)

Although the vapor pressure of sodium is very low near the melting point ($\sim 10^{-9}$ atm), at system operating temperatures it is high enough to cause problems of vapor transport. Heated under vacuum to even modest temperatures — perhaps 400°C — sodium will move throughout a system in the vapor phase, and condense wherever there is a surface even slightly cooler than the sodium pool. Even when the system is pressurized with argon or helium, the vapor transport rate is high enough to cause significant problems through the formation of sodium frost. This phenomenon is discussed in a later presentation in this series. Briefly, however, a comparison may be made to the more familiar water system. At room temperature, the vapor pressure of water is about 25 mm of mercury. Sodium has an equivalent vapor pressure at about 600°C. In the purification of sodium by fractional distillation, it was found that a suitable process required a temperature of ~530°C,(8) at which temperature the vapor pressure is about 10 mm of mercury. The vapor transport phenomenon must always be considered in the design of cover gas systems, fuel handling apparatus, control mechanisms, and any other auxiliary which connects to or operates in the sodium vapor region.

<u>Heat of Vaporization</u> — The heat of vaporization of sodium at its normal boiling point (881.4°C, 1618.5°F) is 21.28 kcal/mol, or 925.6 cal/g.(9) In engineering units this is 1666 Btu/lb. Computer programs are available to calculate the heat of vaporization at temperatures other than the normal boiling point.(1,5) It is seen that the latent heat of vaporization of sodium is about 1.7 times greater, per unit weight, than that of water, at their respective boiling points.

<u>Heat Capacity of Vapor</u> — The heat capacity of sodium vapor is reported as 4.968 cal/mol (0.2161 cal/g or 0.389 Btu/lb),(2) and changes very slowly with temperature. The value given is satisfactory for most purposes, but for more

FIGURE 3. VAPOR PRESSURE OF LIQUID SODIUM BELOW 1250°K (6)



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precise computations the reference should be consulted. The relative contributions of sodium monomer and dimer to the heat capacity of the vapor are discussed in References 4 and 7.

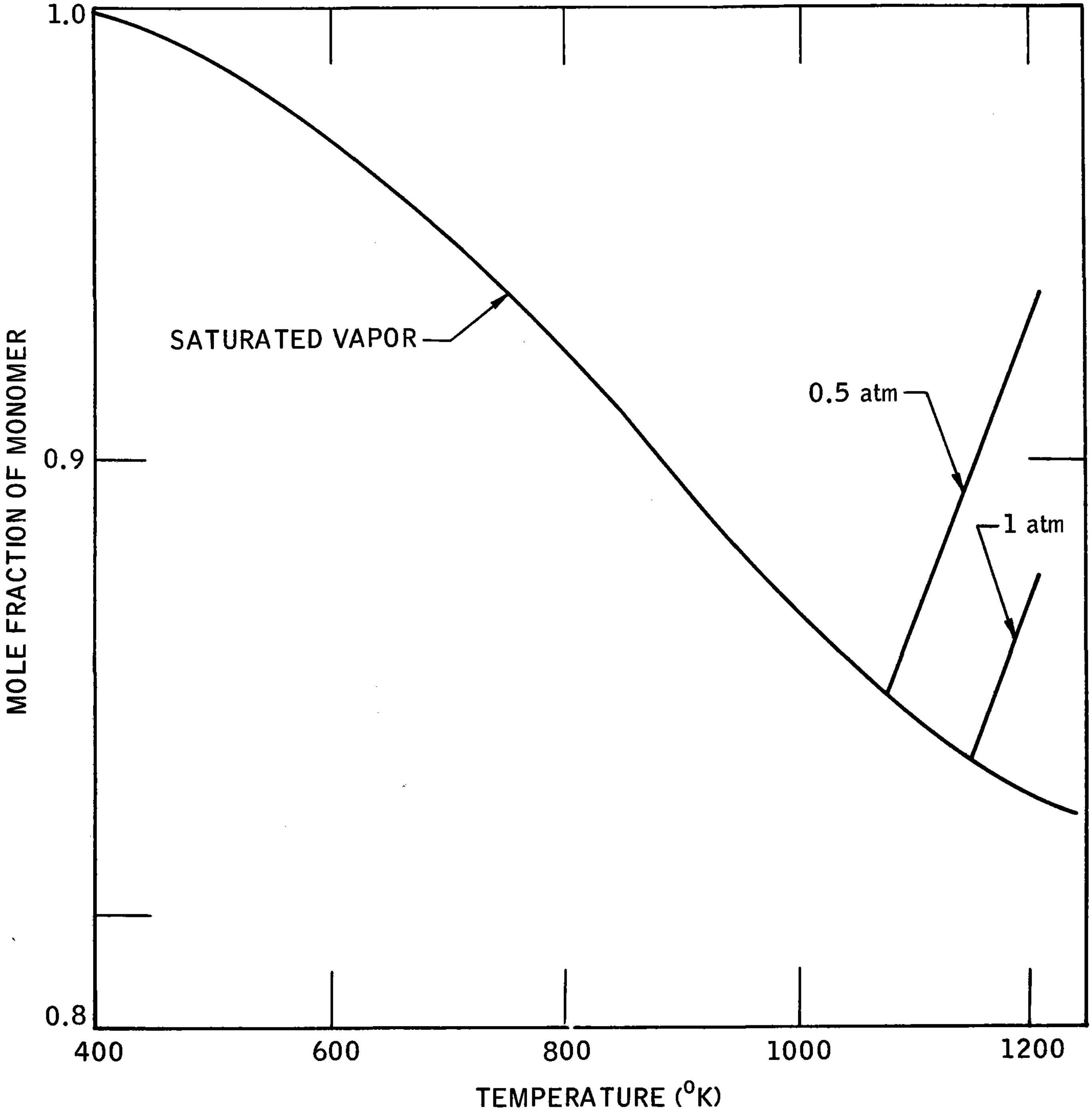
Composition of Sodium Vapor – Sodium vapor consists of a mixture of monomer (individual atoms) and dimer (pairs of atoms). Figure 4, which is taken from the 1955 Sodium-NaK Supplement to the Liquid Metals Handbook,(10) shows how the relative amounts of monomer and dimer change with temperature. The figure is probably not quantitatively accurate, but it gives a good qualitative representation of the composition of sodium vapor.

The top line in Figure 4 represents 100% monomer. Below ~400°K (125°C, 250°F), the vapor consists of individual atoms. As the temperature is increased, the vapor pressure increases, as discussed earlier, and the vapor composition follows the "saturated vapor" line on the chart. Isobars are shown for pressures of 1 and 0.5 atm. These show that if the vapor is isolated from contact with liquid at the temperature shown by the intersection of an isobar with the saturated vapor line, and subsequently heated at constant pressure, the dimer will decompose into individual atoms. The intersection of the 1-atm isobar and the saturated vapor line occurs at the normal boiling point. In a very early report, Feldman(11) stated that the vaporization of sodium occurs to form a monomeric gas, and dimerization occurs in the vapor phase.

Critical Constants – The recent values reported by Miller et al(12) are recommended as the critical temperature, pressure, and volume. Because of the difficulty in making measurements near the critical point, these properties are not known precisely. The recommended values are $T_{cr} = 2733 \pm 40°K$, $P_{cr} = 408$ atm, and $V_{cr} = 126\ cm^3/g\text{-mol}$.

The critical temperature is that temperature above which it is not possible to maintain sodium as liquid. The critical pressure is that which is needed to maintain liquid sodium at the critical temperature, and the critical volume is the volume of a mole of sodium at the critical temperature and pressure. The molar volumes of the liquid and vapor are identical at the critical point.

FIGURE 4. MONOMER-DIMER COMPOSITION OF SODIUM VAPOR (10)



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B. PHYSICAL PROPERTIES

Density — The density of liquid sodium, as reported by Stone at al,$^{(4)}$ is shown in Figure 5 as a function of temperature. There is nothing unusual about sodium in this respect, but it is seen that the density decreases rather rapidly as the temperature is increased. The slope of the line is constant, as plotted on this scale, although the reference represents the density as a power series expression. Figure 6 depicts the density of solid sodium, as it varies with changes in temperature, as reported in Sittig's useful monograph.$^{(13)}$ At cryogenic temperatures this curve shows a marked departure from linearity. The only region of the curve which is of engineering interest is the right end, between room temperature and the melting point. It is of passing interest to notice that the density reaches that of water at about -145°C.

The volume change on melting for sodium is about +2.7%. This must be considered in sizing certain components. The decrease in volume on freezing gives rise to the formation of a "pipe" in the solid sodium, particularly in small containers.

The experimental method used to determine the density values from which the curve in Figure 5 was drawn was not unique, but seems unusual in being applied to sodium. A pycnometer with a volume of 30 cm^3 was made from Cb - 1% Zr alloy, and used in the usual way, but at temperatures substantially higher than one usually associates with pycnometer density measurements. This procedure produces very accurate numbers.

Electrical Resistivity — A property of sodium which makes it unique among the customarily used heat transfer fluids is its electronic conduction. Sodium is a "good" metal, and conducts electricity well. Therefore it is possible to use such devices as electromagnetic pumps and flowmeters, and level sensors based on electrical continuity, in engineering systems. Bomelburg and Smith$^{(1)}$ have taken the experimental results of a number of investigators and derived the resistivity vs temperature curve shown in Figure 7. The values for the solid, taken from Dugdale and Gugan,$^{(14)}$ are represented in Equation 3.

$$\text{Solid, } r(\mu\Omega\text{-cm}) = 4.290 + 1.993 \times 10^{-2}\, t + 9.848 \times 10^{-6}\, t^2 ; \quad t = °\text{C}. \quad \ldots(3)$$

FIGURE 5. DENSITY OF LIQUID SODIUM (4)

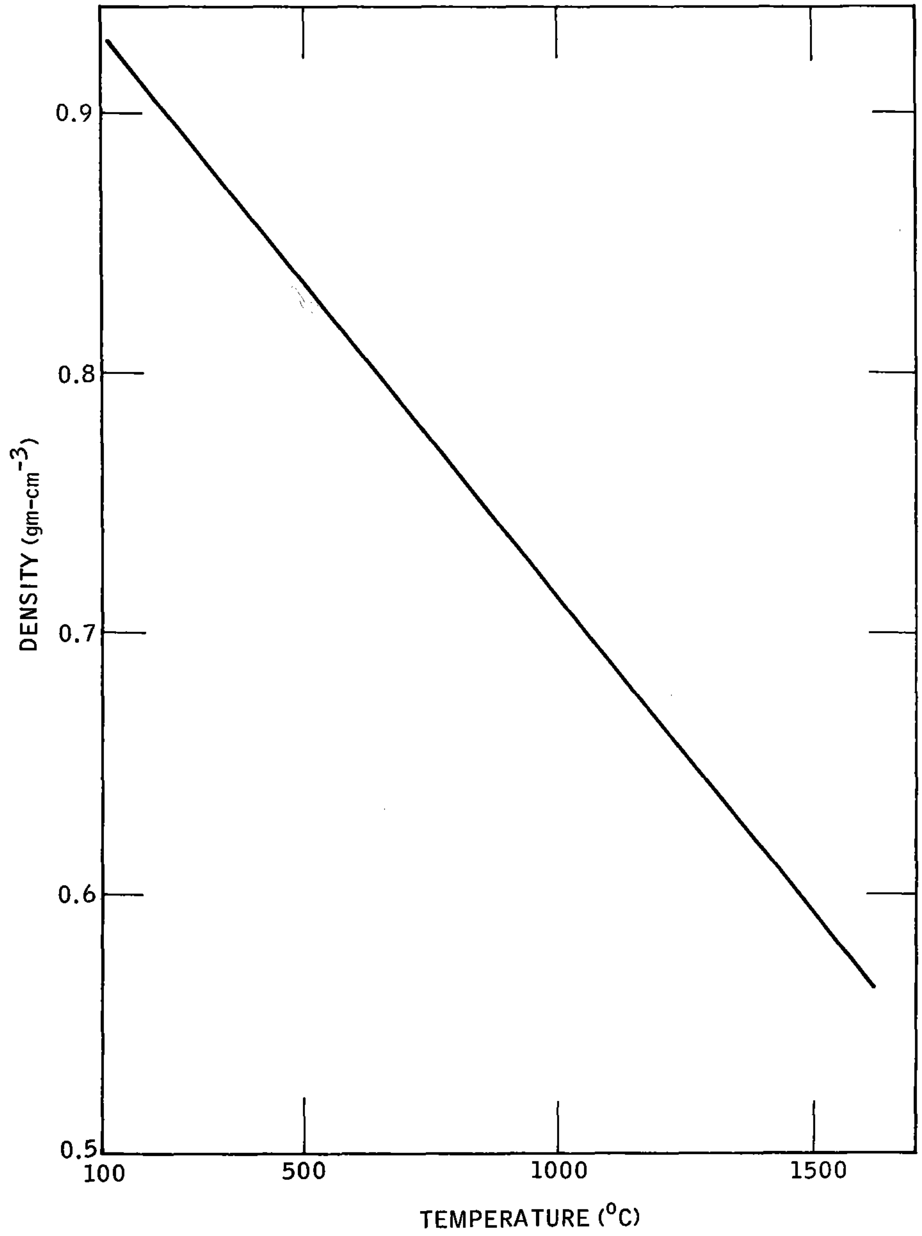

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FIGURE 6. DENSITY OF SOLID SODIUM (13)

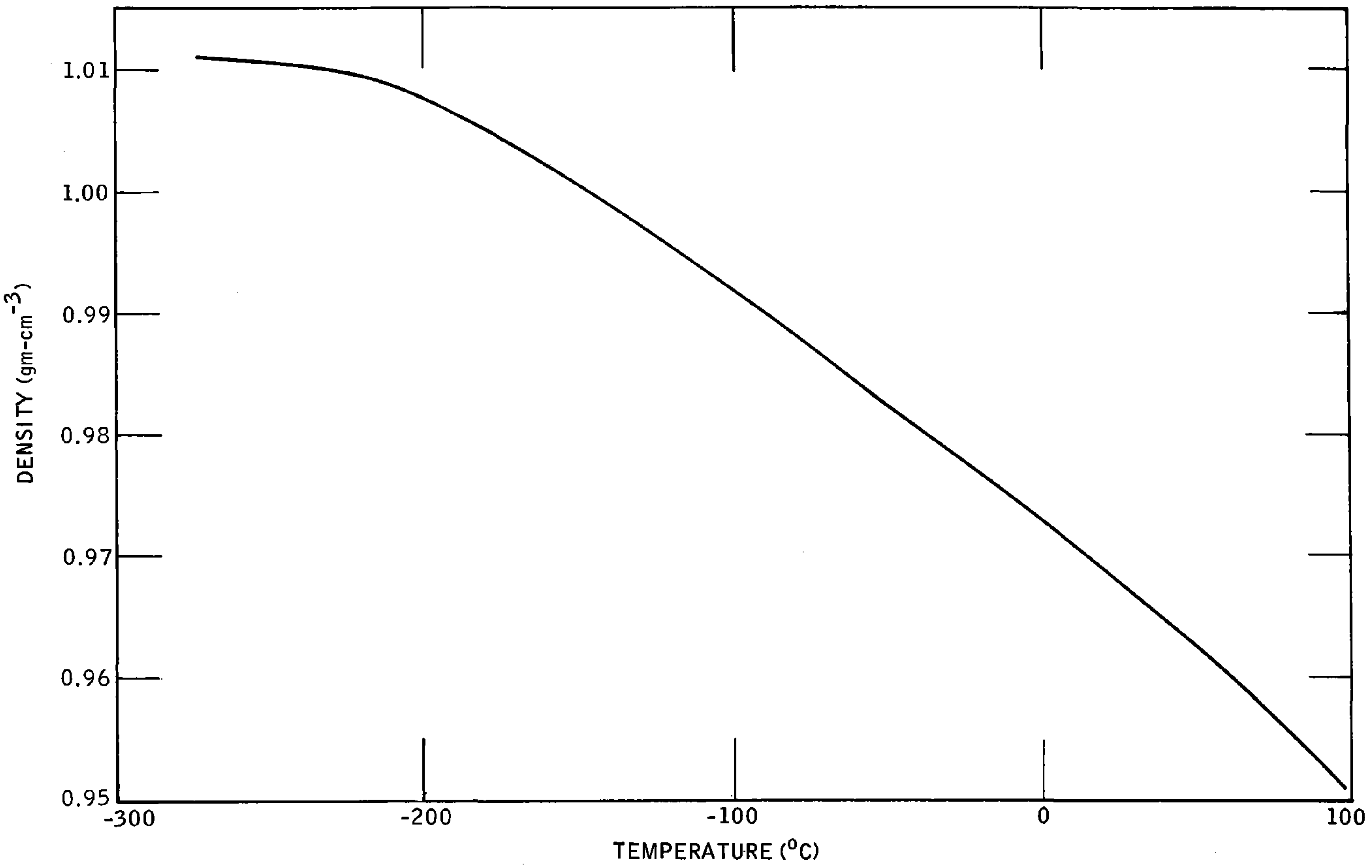

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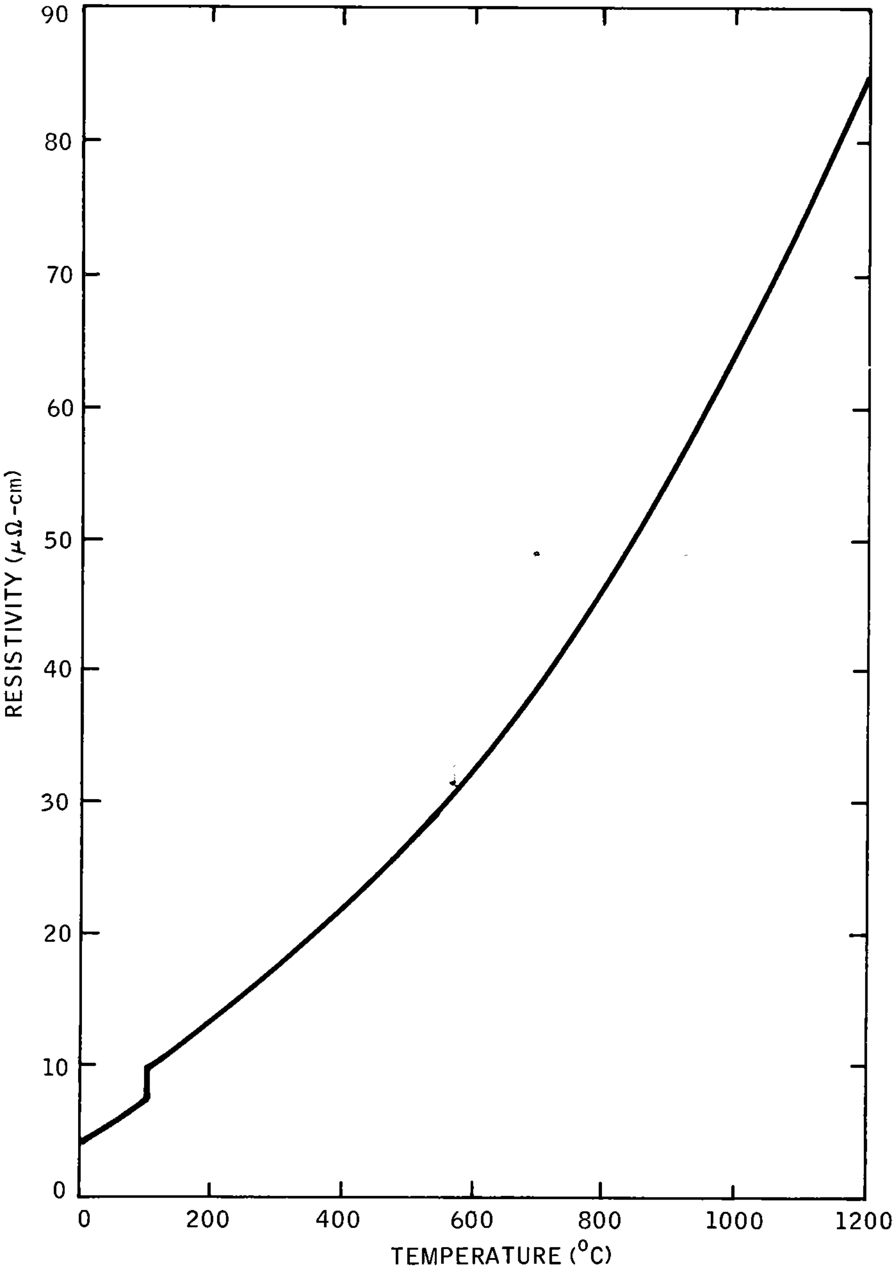
FIGURE 7. ELECTRICAL RESISTIVITY OF SOLID AND LIQUID SODIUM(1, 14)



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Equation 4 represents the liquid sodium portion of the curve.

$$\text{Liquid, } r(\mu\Omega\text{-cm}) = 7.756 + 2.054 \times 10^{-2} t + 3.481 \times 10^{-5} t^2 \;;\; t = {}^\circ C < 1200. \quad \ldots (4)$$

Table 1 shows how the resistivity of sodium compares with that of some more familiar metals. It is seen that at room temperature sodium is not quite as good a conductor as copper, aluminum, or gold, but that at its melting point it has a significantly lower resistance than the other metals have at their melting points. The high electrical conductivity of sodium is important in its application to heat transfer uses, and may find greater utility as technology advances.

TABLE 1

ELECTRICAL RESISTIVITY OF SEVERAL METALS

Metal	r at 20°C ($\mu\Omega$-cm)	r(liq) at Melting Point ($\mu\Omega$-cm)
Sodium	4.7	8.3
Copper	1.6	21.3
Iron	10	
Aluminum	2.6	20.5
Gold	2.4	30.8

Coefficient of Thermal Expansion — The specific volume of sodium at various temperatures, calculated from the density values of Stone et al(4) have been used by Bomelburg and Smith(1) to develop Equation 5 for the volume of any mass of liquid sodium based on the hypothetical volume of that mass at 0°C. It is seen from the form of the equation that the coefficient of volume thermal expansion is not constant with temperature. The expansion coefficient determined from Equation 5, expressed in the form dV/Vdt, which gives the fractional volume change per degree, decreases from $2.378 \times 10^{-4}\ ({}^\circ C)^{-1}$ at 100°C

$$V = V_o(1 + 2.418 \times 10^{-4}\, t + 7.385 \times 10^{-8}\, t^2 + 15.64 \times 10^{-12}\, t^3) \quad , \quad \ldots (5)$$

V_o = (hypothetical) liquid volume at 0°C

t = °C.

to 2.280 x $10^{-4}(°C)^{-1}$ at 1000°C. The coefficient for any desired temperature may be easily calculated to an accuracy of a few tenths of a percent by differentiating Equation 5 and substituting appropriately.

For solid sodium, the coefficient of linear thermal expansion, as calculated from data collected by Bomelburg and Smith,$^{(1)}$ is

$$\frac{d\ell}{\ell dt} = 6.893 \times 10^{-5} + 1.26 \times 10^{-7}\ t(°C) \quad . \qquad \ldots(6)$$

Effect of pressure on the thermal expansion is small, affecting it by <1% at a pressure of 50 atm.

The thermal expansion of sodium must be considered in both laboratory and industrial circumstances, particularly when equipment is loaded with sodium just slightly above its melting point, and additional heating is carried out after the system is sealed. Careless workers have had vessels rupture because of the force of expanding sodium which had no place to expand into, in an improperly sized container.

The thermal expansion of sodium is about one-half that of water, but it is still six times greater than that of steel, the most usual material in which it is contained. It must be remembered, also, that the temperature range over which sodium is used is much greater than that associated with aqueous processes and equipment.

<u>Compressibility</u> — The compressibility of a heat transfer fluid needs to be considered in the design of pumps and piping systems. The isothermal compressibility is defined as the change in volume with pressure, per unit volume, at constant temperature. This may be symbolically expressed as

$$k_T = \frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T \quad .$$

For solid sodium, Beecroft and Swenson$^{(15)}$ have evaluated this expression as

$$k_T(\text{atm}^{-1}) = -3.09 \times 10^{-5}\left(1 - \frac{V}{15.61}\right) ,$$

in which V is the molar volume in cm^3. This relation is good at pressures up to 20,000 atm.

Bomelburg and Smith(1) have calculated the isothermal compressibility of liquid sodium from the relation $k_T = k_S + T\beta^2/\rho c_p$, in which k_S is the adiabatic compressibility, β is the volume coefficient of thermal expansion, and ρ, T, and c_p have the usual meanings of density, Kelvin temperature, and heat capacity at constant volume (in ergs/°K-gram). The adiabatic compressibility was calculated from the speed of sound measured in sodium through the relation $k_S = 1/\rho c^2$, in which c is the sonic velocity in sodium. The value of k_T increases slowly with temperature. At 100 and 200°C the calculated values are 19.16 and 20.89 x 10^{-12} $(dynes/cm^2)^{-1}$, respectively, or 19.41 and 21.16 x 10^{-6} atm^{-1}.

Thermal Conductivity — The ability of a material to conduct electricity is often closely correlated to its ability to conduct heat. Since sodium is a good electronic conductor, it is not surprising that it is a good thermal conductor also. This property is of course what makes sodium so useful as a heat transfer medium in nuclear reactors and in other applications. Expressions relating the thermal conductivity to the temperature for solid and liquid sodium are shown in Equations 7 and 8, respectively. Equation 7 is from Sittig(13) and Equation 8 is from Bomelburg and Smith.(1)

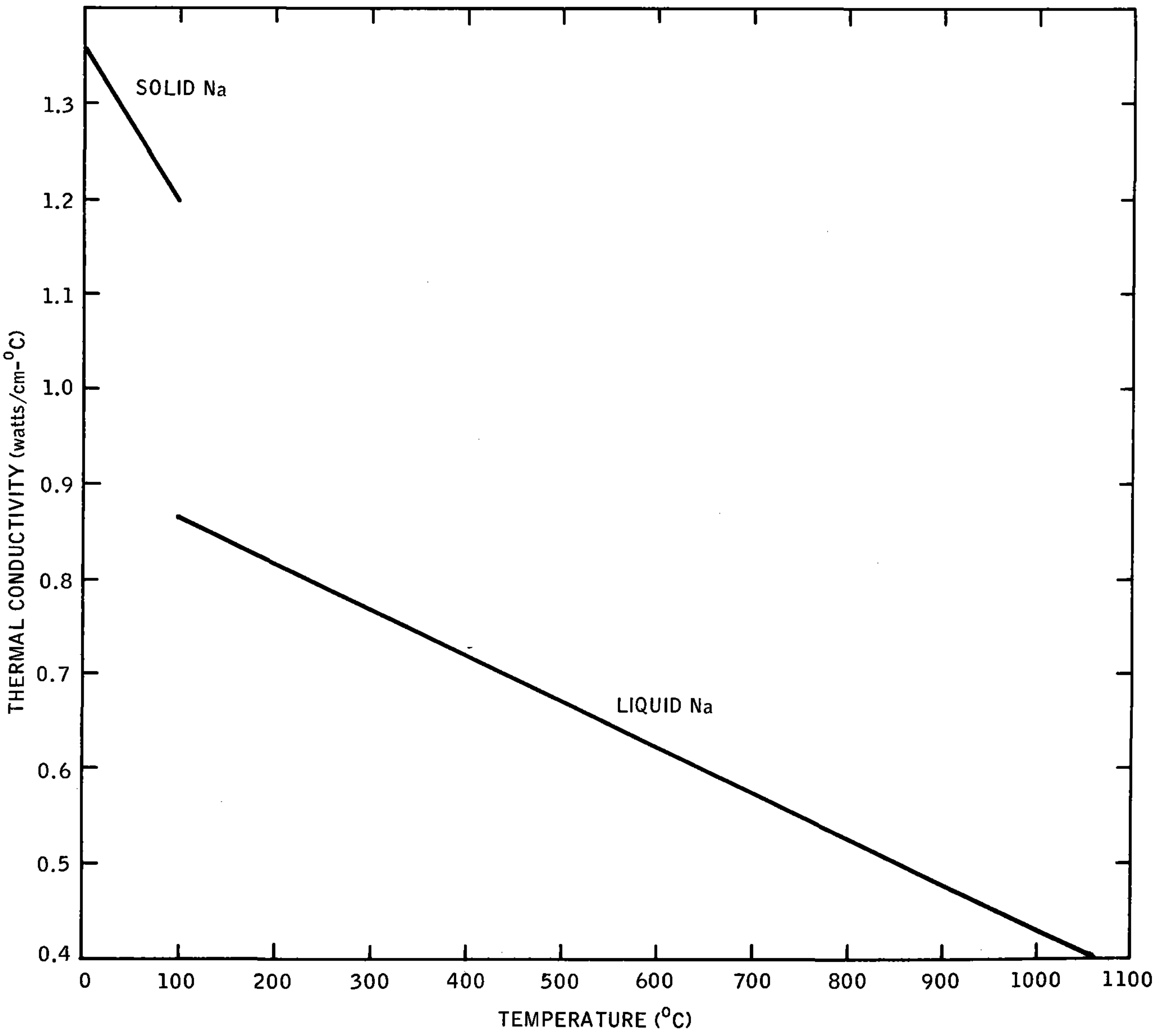
$$\text{(Solid) } k(\text{cal/cm-sec-°C}) = 0.324 - 0.0004t(°C) \qquad \ldots(7)$$

$$\text{(Liquid) } k(\text{cal/cm-sec-°C}) = 0.219 - 1.17 \times 10^{-4}t\ (°C) \qquad \ldots(8)$$

Equation 8, for liquid sodium, is accurate within 2% for temperatures below 832°C. To convert thermal conductivity in the units shown to Btu/ft-hr-°F, multiply the value by 241.8. Since it relates the heat flux density to the temperature difference in a system, the thermal conductivity is very useful in steady state heat transfer calculations.

Figure 8 shows the thermal conductivity of sodium from 0 to 1000°C, in watts/cm - °C.

FIGURE 8. THERMAL CONDUCTIVITY OF LIQUID AND SOLID SODIUM (1)



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Thermal Diffusivity — Another property useful in heat transfer work is the thermal diffusivity, which may be represented as $\alpha = k/c_p\rho$, in which $c_p\rho$ is an expression for the volume heat capacity, and k is the thermal conductivity. Alpha is a measure of the ability of the material to dissipate heat by conduction relative to its ability to retain heat, and is used in unsteady state heat transfer calculations to describe the heat distribution after a thermal pulse. Figure 9 shows the thermal diffusivity of sodium as a function of temperature.(1)

Viscosity — Many measurements of the viscosity of liquid sodium have been made. Figure 10 shows the values that Bomelburg and Smith(1) have chosen for the Liquid Metals Handbook. To obtain the kinematic viscosity from the dynamic viscosity, the value taken from Figure 10 may be divided by the density at the same temperature, the units then becoming centistokes.

Surface Tension — The surface tension of sodium may be expressed by

$$\sigma\,(\text{dynes/cm}) = 206.7 - 0.1t(^\circ\text{C}) \quad , \qquad \ldots(9)$$

which represents it as a linearly decreasing function of temperature. Equation 9 was derived from data of many investigators using the method of Golden and Tokar.(5)

Although the importance of the surface tension to the technology of sodium as a heat transfer fluid may not be immediately apparent, some recent experience at Atomics International suggests that it should not be ignored. Some observations with liquid lithium were especially dramatic in pointing this out. Lithium is an alkali metal with some similarity to sodium, but with a higher surface tension and a lower density. It was found in the course of experiments being conducted with lithium in a high vacuum that the liquid metal could not be poured out of a container an inch in diameter even by inverting it. The surface tension was sufficient to hold the metal in the container, and even vigorous shaking could not dislodge it. Lithium's low density made it easier to support than a higher density material would be, but it is seen from Table 2 that the problem could arise with other liquid metals. Designers must be alert to the possibility of filling small tubes with sodium, and not being able to drain them. This phenomenon could cause trouble with improperly designed bellows or freeze seals.

FIGURE 9. THERMAL DIFFUSIVITY OF LIQUID SODIUM (1)

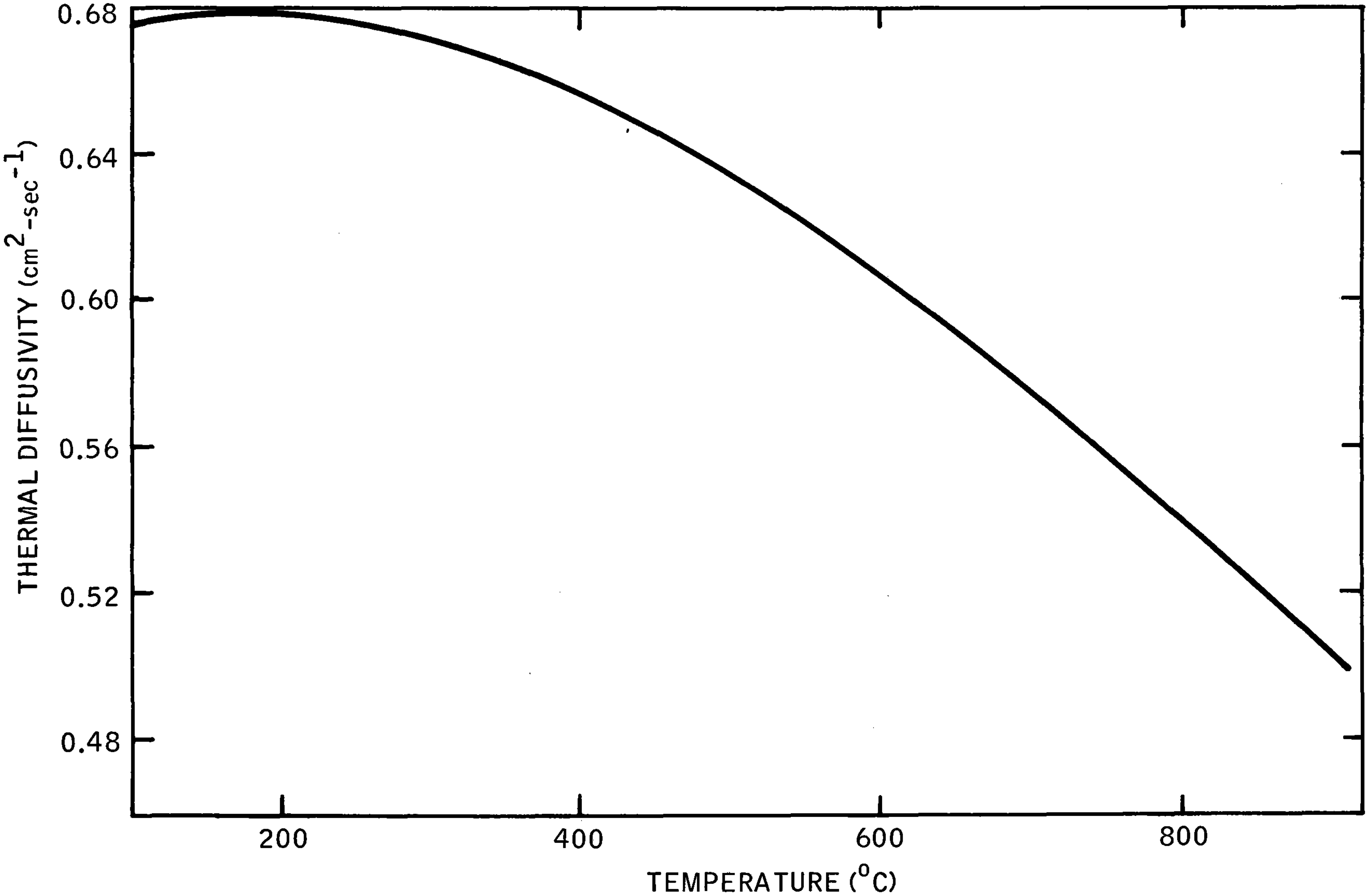

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FIGURE 10. DYNAMIC VISCOSITY OF LIQUID SODIUM (1)

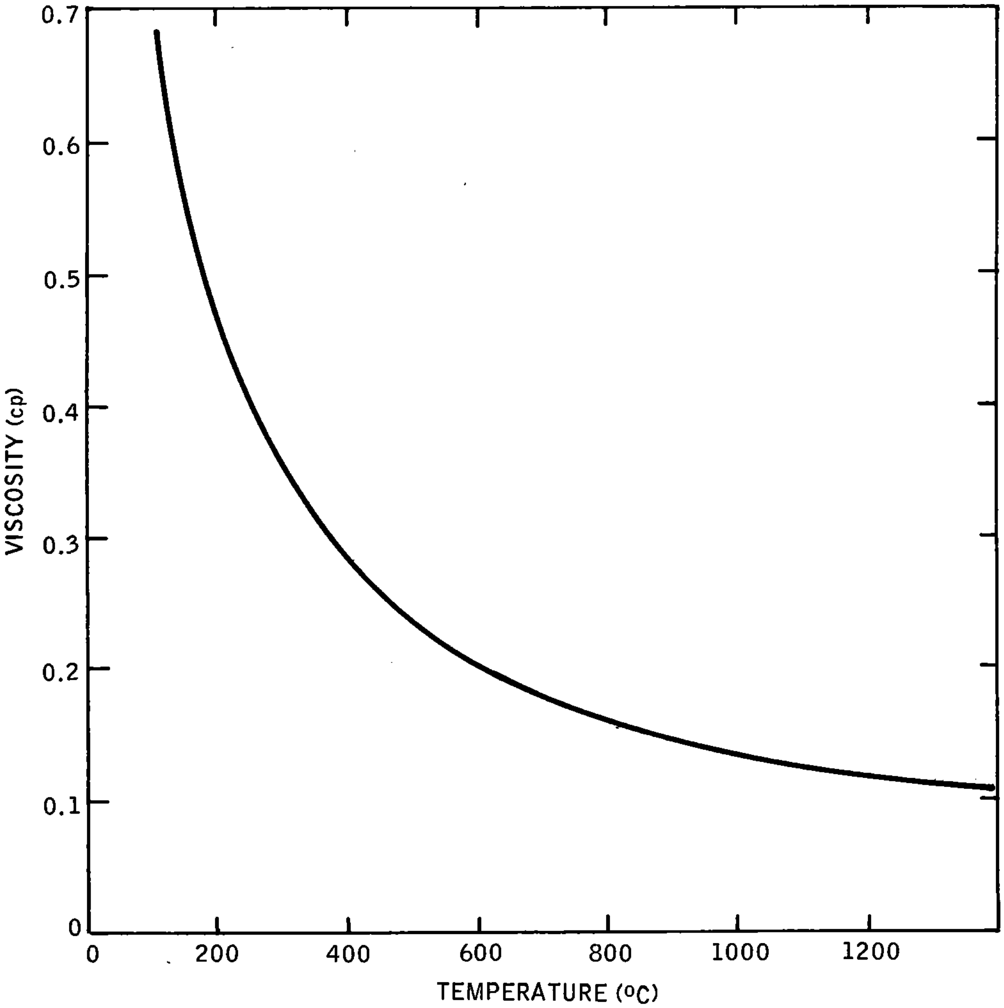

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FIGURE 11. PRANDTL NUMBER OF LIQUID SODIUM(1)

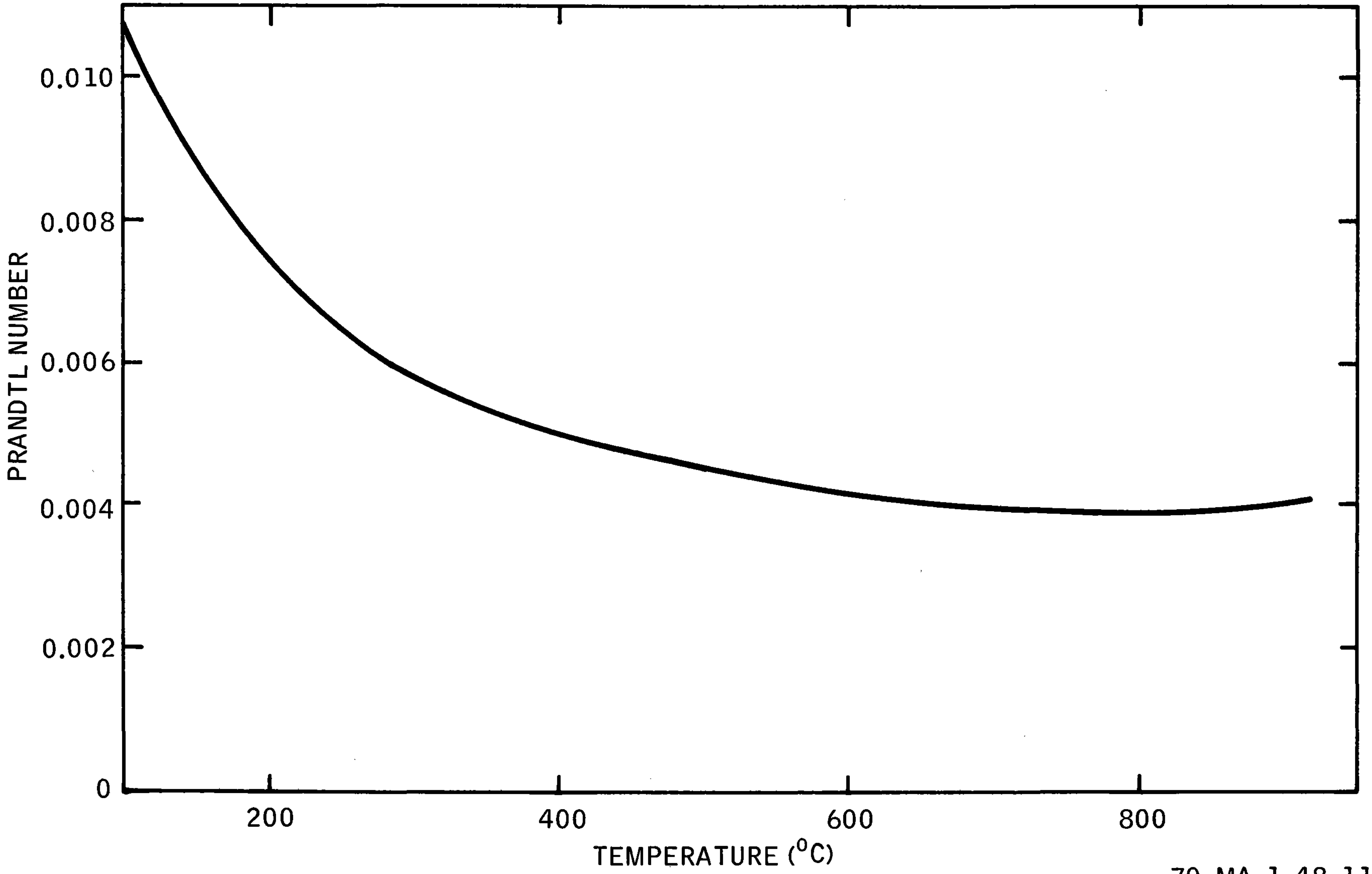

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TABLE 2

SURFACE TENSION/DENSITY RATIOS FOR METALS AND WATER

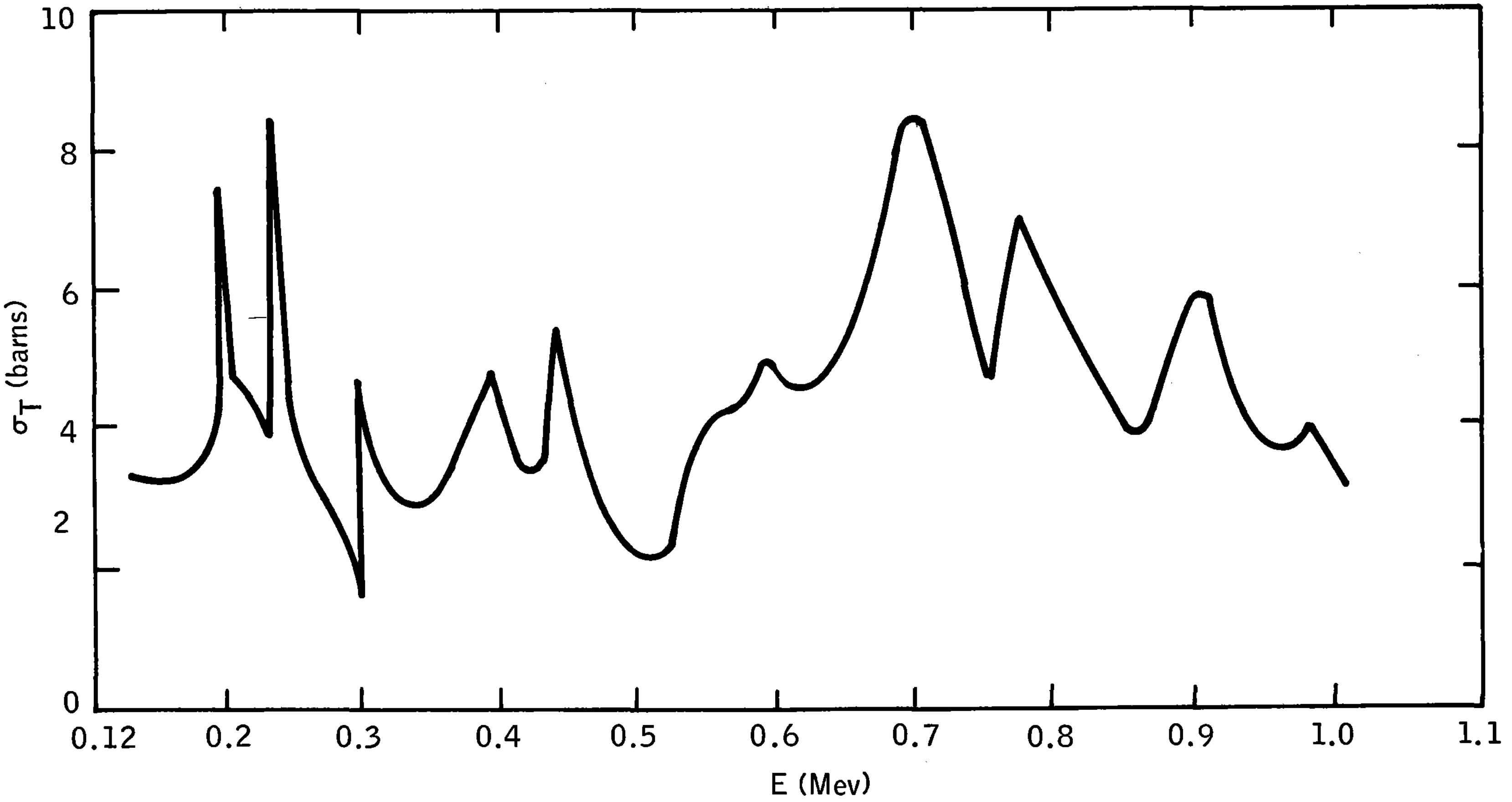
Liquid	(σ/ρ) (dynes/cm)/(gm/cm^3)	T (°C)
Li	720	550
Mg	360	680
Hg	320	300
Al	220	750
Na	210	550
K	120	550
H_2O	72	25
Pb	40	550

Prandtl Number – Among the dimensionless parameters used by engineers in making design calculations, one of the more important is the Prandtl number. The Prandtl number is the ratio of the kinematic viscosity to the thermal diffusivity, or the equivalent quantity absolute viscosity times heat capacity over thermal conductivity. The Prandtl number is a measure of the importance of turbulent heat transfer relative to conductive heat transfer for a material. Metals generally have low Prandtl numbers because of their high thermal conductivity. Figure 11 shows the Prandtl number plotted against temperature. The values shown are relatively low for Prandtl numbers. The curve in Figure 11 was plotted from the values published by Bomelburg and Smith.(1)

C. NUCLEAR PROPERTIES

Neutron Capture Cross Section – The neutron capture cross section of materials in the core of a nuclear reactor can greatly affect the economics and operation of the plant. In reactors operating in the thermal neutron region of the energy spectrum, this factor can be of overriding importance. Even in fast reactors, however, the propensity to absorb neutrons is very undesirable in core materials. The energy spectrum covered in Figure 12 is in the range encountered in fast neutron reactors. The figure shows the total neutron absorbance maxima characteristic of sodium. The energy range shown in Figure 12

FIGURE 12. TOTAL CROSS-SECTION OF SODIUM FROM 0.12 TO 1.0 Mev



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goes down to 0.12 Mev. Thermal neutrons have an average energy of 0.25 ev, less than the fast spectrum energy by a factor of 10^{-6}. To include thermal neutrons, the scale in Figure 12 would have to continue six decades to the left. The thermal cross section for sodium is 3.9 barns, about the same as in the fast region. At intermediate energies, however, there are some strong attenuations. For example, at 2.85 kev there is a scattering resonance of about 370 barns. The cross section of sodium is suitably low for reactor coolant use, but care must be taken to avoid impurities in it which have high cross sections. This subject will be covered briefly in a later presentation.

Nuclides — Sodium occurs in nature as only one isotope, or nuclide, with mass number 23. All other isotopes are artificially produced. These are listed in Table 3. Of these only the nuclides of mass 22, with a half-life of 2.58 yr, and mass 24, with a half-life of 15 hr, are of importance in reactor technology. The ^{22}Na activity will build up relatively slowly during reactor operation, but will likewise decay slowly. It therefore can pose a problem when accessibility to the sodium system is desired for repair or maintenance. The activity of ^{24}Na will be very high immediately after reactor shutdown, but a cooling period of 10 half-lives (about a week) will permit reasonable accessibility.

The neutron reactions of sodium are shown in Table 4, which indicates the way in which the isotopes of mass 22 and mass 24 are formed, as well as an isotope of neon and one of fluorine. The other nuclides of sodium shown in Table 3 are formed from other elements.

The foregoing pages offer a brief view of the properties of sodium that are of importance and interest to nuclear reactor designers and operators, but the discussion is not intended to be exhaustive either in scope or in depth. The one best source for more detailed information, and a discussion of other properties, is the new edition of the Sodium-NaK Supplement to the Liquid Metals Handbook, Chapter 1.(1) The other references listed are recommended as sources of greater depth for the subjects they cover.

TABLE 3

RADIOACTIVE ISOTOPES OF SODIUM

Sodium Isotope	Half-Life	Emitted Particle	Decay Product	Energy (Mev)
20	~0.39 sec	β^+, α	^{20}Ne, ^{16}F	$E_{tot}15$
21	23 sec	β^+	^{21}Ne	2.5
22	2.58 yr	β^+, EC*	^{22}Ne	Mainly 0.54
		γ		1.30
24^m	~0.02 sec	β^-	^{24}Mg	~6
		γ		0.472
24	15 hr	β^-	^{24}Mg	1.39
		γ		1.37, 2.75
25	60 sec	β^-	^{25}Mg	3, 8, 2.8, 2.4
		γ		0.98, 0.58, 0.40, 1.61, 1.96
26	1.04 sec	β^-	^{26}Mg	~5

*Orbital electron capture

TABLE 4

NEUTRON REACTIONS OF SODIUM

Target Nuclide	Natural Abundance (%)	Reaction	Product Formed	Half-Life	Type of Radiation Emitted	Energy of Radiation (Mev)
^{23}Na	100	n,γ	^{24}Na	15.0 hr	γ	1.37
		n,γ	^{24}Na	15.0 hr	γ	2.75
		n, p	^{23}Ne	38 sec	γ	0.44
		n, p	^{23}Ne	38 sec	γ	1.65
		n, 2n	^{22}Na	2.58 yr	γ	1.28
		n,α	^{20}F	11 sec	γ	1.63
		n,α	^{20}F	11 sec	β	5.4

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ELECTRICAL RESISTIVITY

METAL	$r_{20^\circ C}$ ($\mu\Omega$-cm)	$r(liq)_{m.p.t.}$ ($\mu\Omega$-cm)
Na	4.7	8.3
Cu	1.6	21.3
Fe	10	-
Al	2.6	20.5
Au	2.4	30.8

70-MA1-48-18

COMPRESSIBILITY

ISOTHERMAL: $k_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$

ADIABATIC: $k_S = \frac{1}{\rho c^2}$

$$k_T - k_S = \frac{T\beta^2}{\rho C_p}$$

THERMAL DIFFUSIVITY

$$\alpha = \frac{k}{C_p \rho}$$

70-MA1-48-20

SURFACE TENSION/DENSITY

LIQUID	(dynes/cm)/(gm/cm^3)	TEMPERATURE (°C)
Li	720	550
Mg	360	680
Hg	320	300
Al	220	750
Na	210	550
K	120	550
H_2O	72	25
Pb	40	550

70-MA1-48-16

PRANDTL NUMBER

$$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\eta C_p}{k}$$

70-MA1-48-17

RADIOACTIVE ISOTOPES OF SODIUM

SODIUM ISOTOPE	HALF-LIFE	EMITTED PARTICLE	DECAY PRODUCT	ENERGY (Mev)
20	~0.39 s	β^+, α	^{20}Ne, ^{16}F	E_{tot}15
21	23 s	β^+	^{21}Ne	2.5
22	2.58 y	β^+, EC*	^{22}Ne	MAINLY 0.54
		γ		1.30
24^m	~0.02 s	β^-	^{24}Mg	~6
		γ		0.472
24	15 h	β^-	^{24}Mg	1.39
		γ		1.37, 2.75
25	60 s	β^-	^{25}Mg	3, 8, 2.8, 2.4
		γ		0.98, 0.58, 0.40, 1.61, 1.96
26	1.04 s	β^-	^{26}Mg	~5

*ORBITAL ELECTRON CAPTURE

NEUTRON REACTIONS OF SODIUM

TARGET NUCLIDE	NATURAL ABUNDANCE (%)	REACTION	PRODUCT FORMED	HALF-LIFE	TYPE OF RADIATION EMITTED	ENERGY OF RADIATION (Mev)
^{23}Na	100	n, γ	^{24}Na	15.0 hr	γ	1.37
		n, γ	^{24}Na	15.0 hr	γ	2.75
		n, p	^{23}Ne	38 sec	γ	0.44
		n, p	^{23}Ne	38 sec	γ	1.65
		n, 2n	^{22}Na	2.58 yr	γ	1.28
		n, α	^{20}F	11 sec	γ	1.63
		n, α	^{20}F	11 sec	β	5.4

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Hydrocarbon Reactions
Oxygenated Derivatives
Halogenated Derivatives

SODIUM TECHNOLOGY COURSE, SESSION I
CHEMICAL INTERACTIONS
Dr. R. L. McKisson

The first session of this course reviewed the chemical and physical properties of the metal sodium itself. This section will review the interactions between various materials and sodium. First, the solubilities of metals, gases, and nonmetals in liquid sodium, and the factors which affect these solubilities will be presented. Then, the reactions of sodium with inorganic, ceramic, and organic materials will be summarized. Much of the material presented here can be found in the Supplement to the Liquid Metals Handbook, presently in press. References to other material will be given as is appropriate.

A. SOLUBILITY DATA – METALS

The solubility of iron, the most plentiful element in stainless steels, has been measured several times during the last twenty years beginning with Epstein(1) whose data are shown in Figure 1 (Plate 3). His studies were made by analyzing a sample of sodium equilibrated in an iron crucible contained in a glove box system. His studies extended over the temperature range 504 to 746°K, and the slope of the data as plotted on Figure 1 corresponds to a heat of solution of 2600 cal/mol. A few years later Rodgers et al(2) also carried out a measurement of the solubility of iron in sodium. These workers used two pumped loops, one made of nickel, the other of stainless steel. Their curves are also plotted on Figure 1, and show a ΔH(sol'n) of 2400 cal/mol. At about the same time, Bogard(3) investigated the solubility of iron in pure sodium, in sodium saturated with sodium oxide, and in sodium containing sodium oxide and hydroxide. These measurements were made using well purified iron which was then activated to produce radioactive ^{59}Fe. Distilled sodium was used and the test system was a closed nitrogen-filled vessel contained in an inert atmosphere chamber. Sampling was performed by withdrawing a sample through a 200-mesh nickel screen filter at the end of a sampling probe. The curves for these three measurements are also shown in Figure 1.

Bogard's ΔH(sol'n) of iron in pure sodium is 4700 cal/mol. Figure 1 thus shows the range of reported "solubility" data for iron in sodium as reported through the mid-fifties.

Some of the more recent measurements of the solubility of iron in sodium are shown on Figure 2 (Plate 4). The data of Epstein and of Rodgers et al., which data were obtained at lower temperatures, are also shown on Figure 2. The AI data were obtained by Eichelberger and McKisson(4) in the temperature range 600 to 1000°C, using distilled sodium and highly purified radioactive iron in a capsule experiment. Both the colorimetric and the radiochemical data were measured on the same samples using a Cb - 1 Zr collector crucible and a rod of irradiated iron as the sample. Both curves show the same heat of solution, 4600 cal/mol, but one interesting (but unexplained) finding was that the colorimetric analyses gave results which were nominally an order of magnitude higher than the radiochemical results.

Recent measurements by Singer and Weeks(5) of BNL are also shown in Figure 2. These were made at 486, 550, and at 600°C in a closed crucible made of electron beam zone-refined material which had been rolled into sheet and irradiated to produce radioactive ^{59}Fe as the sample. Dip samples of sodium contained in this crucible were taken after equilibration at temperature. In order to eliminate the effect of the oxygen in the sodium in the measured solubility values, Singer and Weeks performed measurements at a number of oxygen concentrations ranging up to full oxygen saturation (>1000 wppm O), but they found little effect below $\sim$100 wppm O.

Another series of tests has been carried out by Isaacs(6) at BNL. He used a uranium foil to thoroughly getter the oxygen from his test sodium, and took his samples in a molybdenum bucket. The oxygen concentration in the gettered sodium is believed to be <1 wppm. The test was performed using about 500 ml of distilled sodium in a closed chamber in a cleaned molybdenum crucible, with the sample being a 0.3-gram foil of irradiated iron which rested on the bottom of the crucible. Three samples were withdrawn simultaneously (at 650, 700, 750, and 800°C), and both radiochemical and colorimetric iron analyses were performed on them. The radiochemical samples showed <0.05 ppm for all four temperatures, but the colorimetric analyses showed only values of <1 ppm Fe. These values, 0.05 ppm Fe and 1 ppm Fe are the limit of detection values for the analytical techniques used.

Isaacs also measured the dependence of iron solubility on oxygen content at 650°C in the oxygen concentration range 0 to 1000 wppm O. His data, shown in Figure 3 (Plate 5), show a definite decrease in ppm iron as the oxygen concentration is lowered from 600 to 1000 wppm O to the lower values. This is in contrast to the findings of Singer and Weeks.(5)

It is thus quite clear that the "solubility" of iron in sodium is complicated, and perhaps none of the experiments thus far performed have been done without flaw. It is clear that oxygen does play a role, and that it is an important factor in the corrosion of steels. It is also clear that the effective "solubility" of the dissolving iron species responsible for material loss in a flowing system cannot reasonably be as large as a part per million at 600°C because such a value would cause much, much higher loss rates than are observed. However, it is also observed that flowing sodium systems do have iron concentrations of the order of a few ppm Fe.

Some relief from this dilemma may be found in the observation that at least one chemical compound of iron, sodium, and oxygen can be present in liquid sodium. This compound was first identified by Horsley(7) as $(Na_2O)_2\,FeO$, and has been found as a deposit in a number of systems. Recent evidence for its presence in a sodium-oxygen-iron system has been presented by Minushkin(8) of BNL. He studied the Na-O system using an electrochemical oxygen meter, and found that its normal behavior was perturbed when finely divided iron was present in the system. The nature of the observed changes clearly indicated that the iron was affecting the Na-O equilibrium, in a manner which indicated the formation of a Na-Fe-O compound. Further examination of this phenomenon should prove to be very important to the problem of the determination of the solubility of iron in sodium. If an Na-Fe-O compound is indeed soluble in sodium so that there are two (or more) iron-containing species present in solution, then the oxygen concentration will certainly be a critical factor in experimental measurements. Further, the presence of a soluble compound would perhaps account for the observation of ppm iron concentrations in loop systems in that the corrosion process could involve the "atomic solubility" of iron — a value which may well be two orders of magnitude lower.

In such an event, there remain two difficult experimental problems, the preparation of a pure "atomic iron" solution, and its analysis in the ppb Fe range.

The solubility of nickel in sodium has been measured by three sets of investigators, and the reported data are shown on Figure 4 (Plate 6). Although there is some scatter in the data from all of the laboratories, the complete set makes a rather convincing pattern. The data of Eichelberger(9) were obtained in capsule experiments in the temperature range 650 to 1000°C. Singer and Weeks(10) performed their measurements in a covered crucible in an argon box and using dip samples in the temperature range 490 to 595°C. Lee and Berkey(11) measured the solubility of nickel in sodium in the temperature range 298 to 445°C using a spark source mass spectrometer as an analysis tool. High purity solutes were exposed in sodium and a sample was taken using a syringe-type tool. (However, the sampling was done just above the M. P. of sodium, and the samples may not represent the higher temperature solubility equilibrium.) Their data were scattered, and the points shown represent the average values at the indicated temperature. The equation for the line drawn through all of the data is shown on the figure, and it indicates the ΔH(sol'n) of Ni in Na to be about 5000 cal/mol.

Solubility measurements of chromium in sodium have been made at AI by Eichelberger(9) and at BNL by Singer et al.(12) The AI data were measured in capsule experiments in the temperature range 700 to 1000°C and showed a considerable scatter ranging from 10 to 100 wppm Cr at 1000°C to 1 to 10 wppm Cr at 700°C. The BNL data consist at present of one point, measured at 650°C, of 0.4 wppm Cr. Eichelberger, in AI-AEC-12955, gives a tentative curve for these data,

$$\log_{10} S(\text{wppm})\,\text{Cr in Na}) = 5.876 - 5362/T\ (°\text{K})$$

Solubility measurements of niobium in sodium have been carried out by Kovacina and Miller(13) using a Cb - 1% Zr alloy as the solute sample material and a radioactive tracer analytical technique. Their data were measured in the temperature range 800 to 1360°C, and are shown on Figure 5 (Plate 7). More recent measurements have been made by Eichelberger(9) using distilled low-oxygen content sodium in capsule experiments. His data were obtained in the temperature range 600 to 950°C, and are also shown on Figure 5. A tentative solubility curve is shown; its equation is given on the figure, but the values shown are higher than one would expect to find for such a refractory metal. However, compounds of niobium and oxygen and alkali metals are known, so that even though there were attempts in both laboratories to minimize the amount of oxygen in the test systems, there could still be a niobate contribution to the measured solubility values.

The solubility of zirconium was measured by Eichelberger(9) and his three data points are shown at 600, 750, and 900°C on Figure 6 (Plate 8). Sodium having an oxygen content of <5 ppm O was used, and the work was done in sealed capsules. A tentative solubility curve which describes the data points is shown, but again, the levels of solubility are much higher than one would expect to find from such a refractory metal if the only solution process were atomic dissolution.

The solubility of titanium in sodium has been measured by Eichelberger(9) in the temperature range 400 to 830°C and his data points are shown in Figure 7 (Plate 9). The level of these data appears to be more reasonable, but there is considerable scatter at the temperature extremes. A tentative line is drawn through the points, and its equation is given in the figure.

The solubility of copper has been measured at three laboratories, AI, BNL, and LASL. The earliest measurements were made by Humphries(14) at 500, 600, and 700°C using irradiated copper. The other data were obtained following the discovery of copper in the sodium of the EBR-2. Eichelberger and McKisson(15) measured their data in the temperature range 250 to 726°C using a capsule technique with copper crucible and copper-rod solute samples in sodium containing <5 wppm O. Singer and Becker(16) measured the solubility of copper in the temperature range 255 to 547°C using a dip-cup technique and distilled sodium. About 35 data points were involved in the three sets, and they all very nicely defined the line shown on Figure 8 (Plate 10). The solubility expression defined by the line is also shown on the figure.

B. SOLUBILITY DATA – GASES

The solubility of oxygen has been measured many times during the past twenty years. Seven laboratories have reported their data in a total of nine reports. Eichelberger(17) reviewed all the information and established a set of criteria for the evaluation of the individual data in order to select those having the highest probability of being accurate. For example, low temperature data obtained by the use of the mercury amalgamation analysis technique were rejected because of the findings of Scarborough and DeVries(18) that there is a significant blank correction associated with the method. At low oxygen concentration, this must be taken into account in order that the analytical results not be prejudiced toward a high value. Since this blank correction was not known until 1967, the earlier data did not include this correction. Of course, the high values (>20 ppm) are less affected than the low ones. Second, it is known that sodium interacts with glass, and because the oxygen released would be expected to appear as dissolved oxygen, all oxygen solubility data obtained in glass were rejected. The final evaluation involved data from six different laboratories, and led to the curve and equation shown in Figure 9 (Plate 12). This curve is recommended over either of those of Claxton(19) who performed similar, but less critical, evaluation studies.

The solubility of hydrogen (or NaH) in sodium has been measured most recently by Addison et al,(20) in the temperature range 250 to 330°C, and earlier by Williams et al,(21) in the temperature range 240 to 445°C. The data of the two sets of investigators agree quite well, although Williams' low temperature data are slightly lower than Addison's. Addison et al have evaluated the two sets of data and conclude that the line shown in Figure 10 (Plate 13) is the best representation. The corresponding equation is shown on the figure.

Addison et al(20) also have presented data on the pressure-composition isotherms of NaH dissolved in liquid sodium. The previous figure showed saturation values of hydrogen (as NaH) dissolved in sodium, but Figure 11 (Plate 14) shows the partial pressure of hydrogen over unsaturated solutions of hydrogen in liquid sodium. The data are shown with temperature as a parameter, and each curve begins at a zero pressure of H_2 at a zero concentration of NaH in Na. As the hydrogen content of the sodium increases, at a given temperature, the partial pressure of hydrogen also increases until saturation is reached (precipitation of solid HaH). In the two-phase system (NaH plus hydrogen-saturated liquid sodium) the partial pressure of hydrogen remains constant, as is clearly shown by the 250, 300, and 315°C isotherms.

The solubilities of the inert gases helium, argon, and krypton and of nitrogen are shown in Figure 12 (Plate 15). These measurements were all made at ANL during the last two or three years. The helium data were measured by

Cafasso;(22) the argon, by Valeckis et al;(23) the krypton, by Dhar,(24) and the nitrogen, by Cafasso.(25) An evaluation of these data was made by McKisson (26) who also presents a technique for estimating the solubilities of the inert gases in other alkali metals. The data are interesting in that, because of the low solubilities of the gases, the entropy effects of their solution causes them to have positive temperature coefficients. This is a reason for concern in some reactor systems, because of the possibility of dissolution of cover gas over the core at the high sodium outlet temperature. Then the dissolved gas may separate out in lower temperature regions and produce gas bubbles which may tend to collect in equipment. If a really large bubble can be developed, and then it breaks loose to flow back through the reactor core, there will be heat transfer and nuclear reactivity perturbations which may be dangerous.

Nitrogen is seen to behave very much as though it were a large inert gas atom in that its solubility behavior is analogous to that of the inert gases, except it is less soluble. Cafasso,(25) using a ^{15}N tracer technique, has shown the solution and the release of nitrogen to be as diatomic nitrogen molecules. He saturated sodium with a mixture of $^{14}N_2$, $^{14}N^{15}N$, and $^{15}N_2$ molecules, and then found the released gas to have the same 28, 29, and 30 isotopic ratio as the source gas. Had the solution process produced atoms, the isotopic ratio would have changed.

C. SOLUBILITIES OF NON-METALS – CARBON

Carbon is the principal non-metal of concern in sodium reactor technology because of its effect on the mechanical properties of steels. The first studies of carbon solubility were made by Gratton.(27) Over the years since Gratton's work, Luner et al,(28) Cafasso,(29) and Gehri and Ott(30) have also attempted the measurement and have obtained rather scattered results. However, the most recent studies of Gehri(31) at AI, and of Longson and Thorley(32) have indicated the source of difficulty in the direct measurement of carbon solubility using elemental carbon is the rate at which graphite, or carbon, or diamond goes into solution in sodium. The rate is apparently very low. However, the rate of transfer of carbon from carbon-saturated nickel, or from a solid solution of carbon in nickel, into sodium is much faster. This phenomenon has been the basis for the most recent data at AI and at Harwell. Gehri's data are shown in Figure 13 (Plate 17). The equation of the line fitting the data is given in the figure.

A brief check of the effect of the oxygen content of the sodium was made by Gehri. The data points shown as squares and circles were made in sodium containing a nominal 10 ppm O, and those shown as triangles were made in sodium containing >25 ppm O. Since all of the points appear to belong to the same set, one must conclude that there was no oxygen dependence, at least in the range studied.

In summarizing the solubility discussion, it is of interest to compare the measured solubility values for metals in sodium at 600°C (1112°F). Values from the systems discussed here are shown in Table 1, together with additional more tentative values reported in AI-AEC-12955. The maximum value, 110 wppm for copper, seems reasonable enough, but the values for niobium and zirconium appear to be much higher than one would expect from such refractory metals. The chromium-iron-nickel group values seem odd in view of the preferred leaching of chromium and nickel from stainless steels. One would expect to find that the chromium value would be relatively higher. However, the following section may shed some light on these apparent anomalies.

TABLE 1

SOLUBILITY VALUES
(wppm at 600°C)

Copper	110	Cobalt	(<2)
Niobium	28	Vanadium	(<2)
Zirconium	27	Carbon	1.8
Titanium	7	Iron	1
Manganese	(<5)	Molybdenum	(0.5)
Nickel	2.3	Chromium	(0.3)

D. FACTORS AFFECTING SOLUBILITY

A basic problem faced by the experimenter who sets out to measure the solubility of a metal in sodium is to define what is meant by, for example, the "solubility of iron." Ordinarily, one expects that the solute atoms will separate from the solid and appear as individual entities in the solution, and in the thermodynamic sense this is the solubility value for iron, say. However, it is also customary that one measure the total amount of iron in the solution and to consider that value to be the solubility. Now, if the solution process is simple, these two numbers — 'atomic solubility' and 'total solubility' will have the same value. But, if dissolution occurs by more than one mechanism, they will be different. As was noted above, one factor in the measurement of the solution of iron is the oxygen content of the sodium, because it can react to form a sodium-iron-oxygen compound in solution. Thus, one has a mechanism for the solution of more iron than corresponds to the "atomic solubility." However, there are additional facets to solution by compound formation. First, the compound may be only marginally stable, so that its concentration will depend upon the oxygen concentration in the sodium. Then, one would see a large effect in high oxygen content systems, and perhaps essentially no effect below some threshold oxygen concentration. Further, the equilibrium will be sensitive to temperature, and in terms of a solubility measurement, there may be a temperature threshold as well. Second, there may be kinetic effects, so that varying amounts of compound may form in a sequence of tests, to add confusion to the data. One aspect of a kinetic problem was noted above in the carbon solubility measurements, in which it was found that elemental carbon goes into solution quite slowly, relative to the rate of transfer of carbon already dissolved in a metal such as nickel.

Therefore, one must be careful in using solubility values, to be certain that the system being studied corresponds to that in which the measurement was made, or one can be led to erroneous conclusions. In particular, it is prudent to view predicted corrosion rates of metals which form compounds such as ferrates, niobates, chromates or chromites, or vanadates with reservation; and to closely review the data and the corrosion mechanisms postulated.

1. Interactions With Inorganics

The reactions of sodium with selected inorganic materials will be treated briefly in the following. The reaction of sodium and water at low temperature is, I believe, very well known. Hydrogen gas and sodium hydroxide are formed. The reaction proceeds with some vigor, and the solution will get quite hot, but the most important aspect is the hydrogen gas production. If the reaction proceeds in air, the hydrogen and the oxygen in the air are almost always ignited because after a short time the sodium will usually burn and ignite the gas mixture. This can be rather severe and damaging if it occurs in a confined space.

At high temperatures, the products of the reaction will include sodium oxide and possibly sodium hydride, plus hydrogen. Again the potential for an explosion exists if the hydrogen can mix with air. Details of the reaction conditions and rates of the sodium-water interaction are given by Ford,(33) by Williams,(34) and in the forthcoming Supplement to the Liquid Metal Handbook.

The reactions of sodium and ammonia are summarized in the following equations,

$$Na_2O + NH_3(\ell) \rightarrow \text{Solution}$$

$$Na_2O + NH_3(\ell) \rightarrow NaOH + NaNH_2$$

$$Na + NH_3 \xrightarrow[\text{Fe, Al, Cr}]{\text{metal catalyst}} NaNH_2 + 1/2\ H_2(g).$$

The solution of sodium in liquid ammonia usually proceeds rather quietly to form the solution. A modest amount of heat is liberated, but it is dissipated in the evaporation of some of the ammonia. The oxide impurity in the sodium reacts as shown and forms sodium hydroxide and sodamide, which are only slightly soluble in the ammonia, and will appear as a precipitate, if they are present in excess.

If, during the dissolution process, a metallic catalyst is present, sodamide and hydrogen are formed. Again, one must guard against the possibility of a hydrogen explosion, although the immediate source of burning sodium is not likely to be present in this system, as it is when water is involved.

The interest in ammonia among reactor-oriented engineers stems from the search for a solvent suitable for removing sodium from reactor components in a regulated way, and of leaving the parts in a re-usable condition. Further information regarding these reactions may be found in the new Supplement to the Liquid Metals Handbook, in the book by Jolly,(35) and in a report by Alter and McManus.(36)

Jolly(35) has made a rather comprehensive study of the sodium-ammonia system, and his phase diagram is shown in Figure 14 (Plate 22). As one can see, it shows a region of two liquid phases, each of which is a sodium-ammonia solution. The low-sodium phase is blue and is more dense than the bronze-colored higher-sodium phase. The eutectic composition has about 17 at. % sodium, and the eutectic temperature is -111°C.

Other alkali metals show a similar behavior in ammonia, and it is found that the lithium-ammonia solution on the lithium-rich side of the two-phase region is the least dense liquid phase known.

As noted above, the impurities in sodium are much less soluble than is sodium in ammonia. This fact was at one time used as the basis for an analytical technique for impurities in sodium, but it was found that the method was less useful than the mercury amalgamation technique, so it has been abandoned.

The reactions of carbon monoxide and sodium are shown below:

$$\begin{aligned} \mathrm{Na + CO} &\rightarrow \mathrm{(NaCO)_6} \\ &\rightarrow \mathrm{Na_2C_6O_6}\ \text{(sodium rhodizonate)} \\ &\rightarrow \mathrm{Na_2CO_3} \\ &\rightarrow \mathrm{p(NaO)_4C_6O_2}\ . \end{aligned}$$

Sinclair et al(37) have studied these reactions and give an excellent exposition of them. It is interesting to note that the reactions which yield organic-like products all produce molecules containing the benzene ring (C_6) structure. Sodium carbonate, the most stable Na-C-O compound is, of course, always a by-product.

Carbon dioxide gas reacts with sodium to form a number of products,

$$\begin{aligned} \mathrm{Na + CO_2(g)} &\rightarrow \mathrm{Na_2CO_3 + C} \\ &\rightarrow \mathrm{Na_2C_2} \\ &\rightarrow \mathrm{Na_2C_2O_4} \end{aligned}$$

but solid carbon dioxide-sodium mixtures are reported to explode upon impact.(38)

The products of the reaction between gaseous CO_2 and sodium are primarily those shown: the carbonate, the carbide (or the acetylide), and the oxalate. Details of these reactions and the yields from them are given by various authors,(39-42) and in the new Supplement to the Liquid Metals Handbook (in press).

Sodium will react to form sodium cyanide by a number of reactions. The yields are not high, but it is of interest that NaCN does form from such mixtures as:

$$\begin{aligned} & Na + (NH_4)_2C_2O_4 \cdot H_2O \text{ @ } 500°C \\ & \quad + Na_2CO_3 + NaN_3 \text{ @ } 700°C \\ & \quad + C + N_2 \text{ @ } 700°C \\ & \quad + Na_2CO_3 + N_2 \text{ @ } 700°C \ . \end{aligned}$$

The studies from which these reactions were established were performed at ANL and are reported by Hobart and Bjork.(43) The ANL workers also measured the solubility of NaCN in sodium and found the surprisingly high value of 75 ± 110 wppm NaCN at 550°.(44)

Sodium carbide (sodium acetylide) is a marginally stable compound which cannot be formed by displacing the metal from any of the other metallic carbides. It can be formed, however, by reacting acetylene with sodium dissolved in liquid ammonia. The mono-acetylide NaC_2H is produced and forms a cake in the reaction vessel. This material can then be separated and heated to form disodium acetylide, or sodium carbide Na_2C_2.

Although sodium will not react with carbides, it does serve as a solvent and transport medium for carbon dissolved in metals. The transport of carbon from low-alloy steels to stainless steels is a well-known phenomenon, and recently, the transfer of carbon from one stainless steel to another has been identified.

2. Reactions With Ceramics

The question of the feasibility of using ceramics in a sodium system is an interesting one. In general, the answer is found in a comparison of the thermodynamic stability of the oxide with that of dissolved sodium oxide at the particular oxygen concentration in sodium. One must use the stability values for Na_2O as an unsaturated solute in sodium, because in this solution, Na_2O is more stable than is solid Na_2O. This is shown in the list below, which shows the free energies of formation of sodium oxide and of various ceramic materials at 800°K. In this list, the ΔF-values are shown per gram-atom of oxygen, so they are directly comparable. Note that while solid Na_2O has a ΔF_f of -73, a 5 wppm O solution of Na_2O in the Na has a ΔF_f of -83, showing an increased stability of 10 kcal/g atom O for the oxide dissolved in sodium. Further, the ΔF_f will become more negative as the oxygen concentration in the sodium is reduced below 5 wppm O.

OXIDE STABILITIES
F_f (800°K, kcal/g-atom O)

Oxide	ΔF_f	Oxide	ΔF_f
$Na_2O(s)$	-73	$ZrO_2(s)$	-112
Na_2O-5 ppm O	-83	$UO_2(s)$	-113
$Al_2O_3(s)$	-113	$SiO_2(s)$	-88
$BeO(s)$	-124	$Na_2SiO_3(s)$	-105

Now, by comparing these numbers, one can see that pure Al_2O_3, BeO, ZrO_2, and UO_2 are more stable than Na_2O in sodium by 30 to 40 kcal/g atom O. Therefore, these materials will not be attacked by sodium. For example, it is observed that sapphire and single crystal beryllia are indeed not attacked by liquid sodium. However, SiO_2 at -88 kcal/g atom O, is only 5 kcal/g atom O more stable. Probably, this, in itself, would allow some attack, but the major problem with SiO_2 is the fact that it can react with Na_2O in sodium to form sodium silicate, and with a substantial driving force (56 kcal/mol of Na_2SiO_3 formed from the oxides). Therefore, SiO_2 is <u>not</u> stable in sodium. Further, ordinary ceramic materials, which contain some SiO_2, are attacked and can be un-usable as construction materials in sodium. The SiO_2 impurity, which is found at the grain boundaries, reacts and is dissolved away to loosen the basic ceramic grains. Therefore, unless a ceramic material is quite free of SiO_2, it will not survive in sodium.

3. Interactions With Organics

Sodium is used commercially as a reducing agent in the preparation of organic chemicals. Because of this, text books and summaries such as Kirk-Othmer's Encyclopedia of Chemical Technology are useful sources of information of this kind. The saturated hydrocarbons (alkanes) are inert to sodium at room temperature, except for those having an active hydrogen such as that on the second carbon atom in 2-methyl propane. At higher temperatures (above 200°C) the carbon-carbon bonds are broken and fragmentation products are formed.

The unsaturated hydrocarbons (the alkenes) polymerize at low temperatures due to the greater reactivity of the double bond. At high temperature, again, one finds major decomposition and fragmentation. The acetylene series (the alkynes) have an active hydrogen, which is replaced by the sodium, and one can form NaC_2H and Na_2C_2, for example by bubbling C_2H_2 into liquid sodium. Polymerization also occurs at low temperatures, but as one would expect, decomposition and fragmentation occur at high temperatures.

Benzene derivatives (the aryls) show no reaction at low temperatures but have a tendency at intermediate temperatures to form condensation compounds. If there are active hydrogens, sodium will replace them and lead to coupling reactions. Again, at high temperatures, the carbon-carbon bonds are broken and the compounds decompose.

4. Interactions With Oxygenated Derivatives

Sodium reacts with alcohols R-OH to form alcoholates, R-ONa, plus hydrogen gas. The reaction rate with ethyl alcohol is moderately vigorous, but it is much slower with butyl and the heavier alcohols. Because of this, butyl alcohol is frequently used to remove sodium from components, although it is a time-consuming process, especially if there are regions of small clearances or deep holes to be cleaned.

Ethers R-O-R are not reactive at low temperatures, but decompose at high temperatures. Aldehydes R-CHO and ketones R-CO-R react at various rates and undergo rearrangements and decomposition. Ketones, in addition, tend to add a sodium to the oxygen and to develop a double bond on the ketone carbon atom, to form compounds of the type $R'-CH = CONa-R''$.

Organic acids form sodium salts and liberate hydrogen, with the rates being generally proportional to the acid strength. Thus formic and acetic acids react the most vigorously, and the acids of large molecular weight react relatively slowly. At high temperatures the compounds decompose. Additional information can be found in the new Supplement to the Liquid Metals Handbook.

5. Interactions With Halogenated Derivatives

Sodium sometimes reacts quite vigorously with halogenated organics. With mono-substituted hydrocarbons RX sodium removes the halogen to form the sodium halide NaX, and the free radicals R- combine to form longer chain hydrocarbons. This is called the Würtz reaction, and is described in basic organic chemistry textbooks.

The reactions of alkali metals and of alkaline earth metals with di-, tri-, and any poly-substituted organic halide (even teflon) are potentially explosive. The very high energy of formation of the sodium halides causes a rapidly accelerating reaction to occur, once it begins. However, some people, through great good fortune, have used solvents like chloroform and carbon tetrachloride to clean sodium from samples and apparatus. Others have had explosions on their hands. The main point here is that <u>mixtures of halocarbons and alkali metals are treacherous</u>. Their reactions have variable induction periods, and possess the potential energy release of explosives like TNT. Further, these mixtures are shock-sensitive, and some have been described as having a sensitivity equivalent to that of mercury fulminate or nitroglycerine. In short, <u>DO NOT</u> mix a halogenated organic compound with any highly reactive alkali or alkaline earth metal, and <u>DO NOT</u> use halogenated hydrocarbons as cleaning agents for any alkali metal contaminated parts. Additional discussion of this danger is presented in the Supplement to the Liquid Metals Handbook.

E. SUMMARY

Stainless steel components and the refractory metals are slightly soluble in sodium, but in many cases there is some question regarding the direct applicability of reported data in corrosion process evaluations. However, these metals are all useful in that their corrosion rates are low enough to give adequate service lives in sodium, provided the oxygen content of the sodium is maintained at low levels. For stainless steels, a value of <10 wppm O is required.

Oxygen is known to be a factor in the solution behavior of metals, but a better understanding of the behavior of sodium-oxygen-metal compounds is needed to really understand solubility and corrosion data.

The inert gases have a positive temperature coefficient of solubility, which can lead to the transport of gas from a hot to a cold region in a reactor.

The reactions of sodium with ceramics are predictable from the thermodynamics of the compounds. Ceramic materials containing silica are found to be unstable in sodium, but pure alumina and pure beryllia are stable.

The reactions of sodium and organics are characterized by decompositions of the organics at temperatures above about 200°C, and by rearrangements and reorganization of the molecules at the lower temperatures for all except the straight-chain hydrocarbons.

Mixtures of sodium and halogenated organics are very dangerous, and can explode without warning.

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44. Cafasso, ANL-7403 (1968)

The following section is a collection of all the plates used in the first presentation. These are numbered in sequence as Plates, and those which are referred to in the text are also assigned figure numbers.

CHEMICAL INTERACTIONS

- "SOLUBILITIES" OF METALS
- SOLUBILITIES OF GASES
- SOLUBILITIES OF NON-METALS
- FACTORS AFFECTING SOLUBILITIES
- INTERACTIONS WITH INORGANICS
- INTERACTIONS WITH CERAMICS
- INTERACTIONS WITH ORGANICS

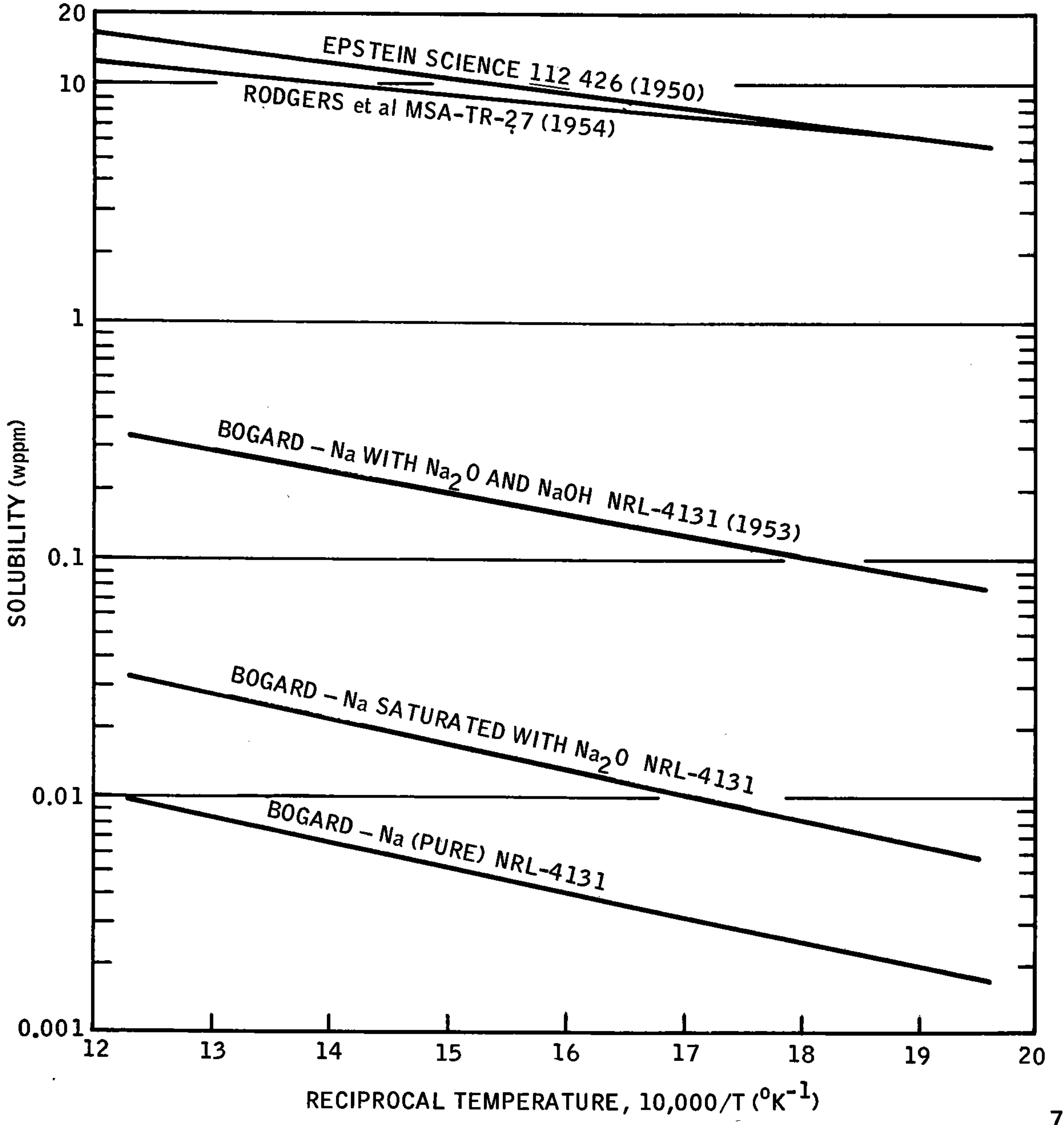
70-MA1-48-69

"SOLUBILITIES" OF METALS

- STEEL COMPONENTS
- REFRACTORY METALS
- OTHER METALS

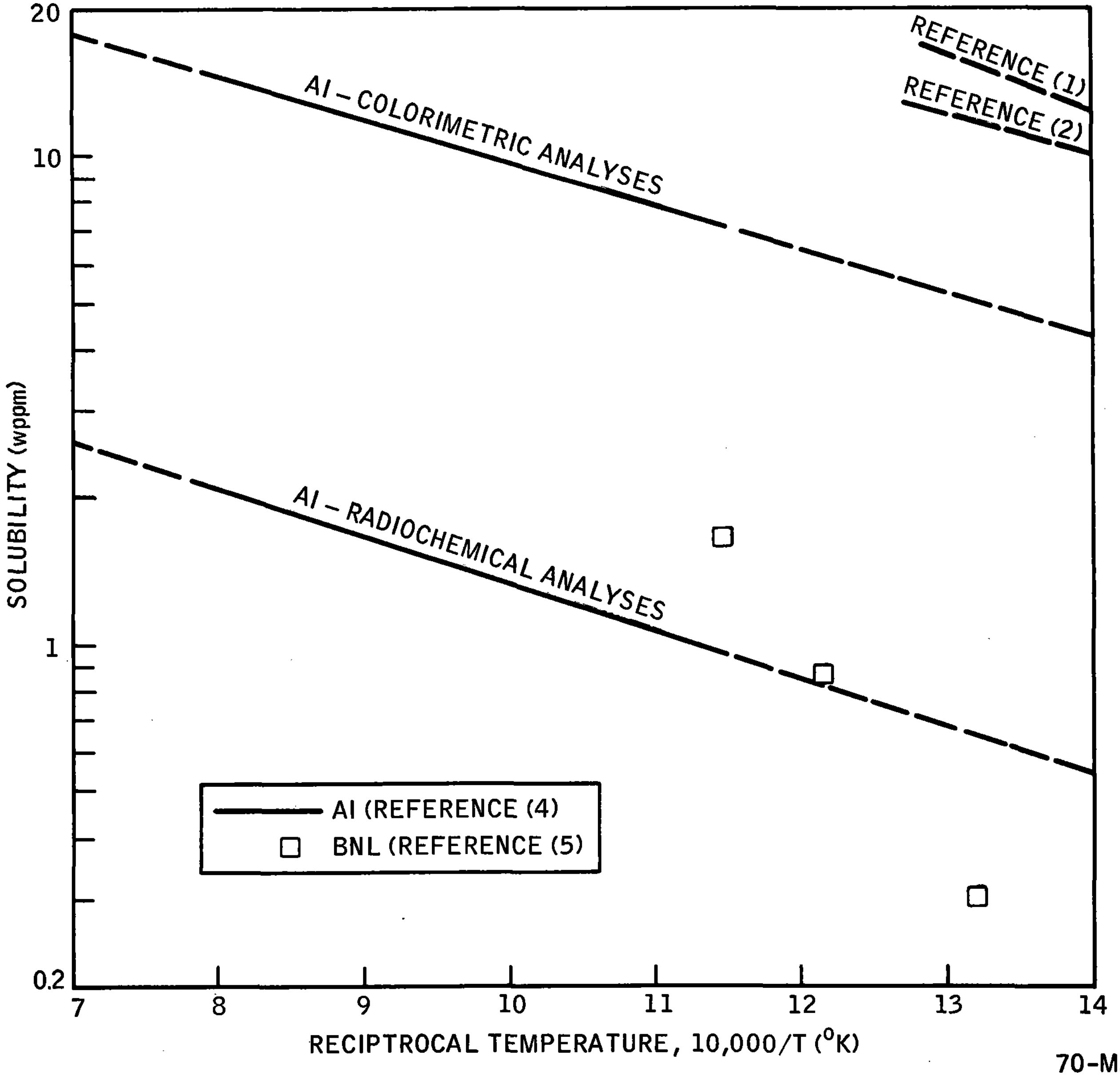
70-MA1-48-70

FIGURE 1. RESULTS OF SOLUBILITY MEASUREMENTS OF IRON IN SODIUM



70-MA1-48-55

FIGURE 2. RECENT RESULTS OF SOLUBILITY MEASUREMENTS OF IRON IN SODIUM



70-MA1048-56

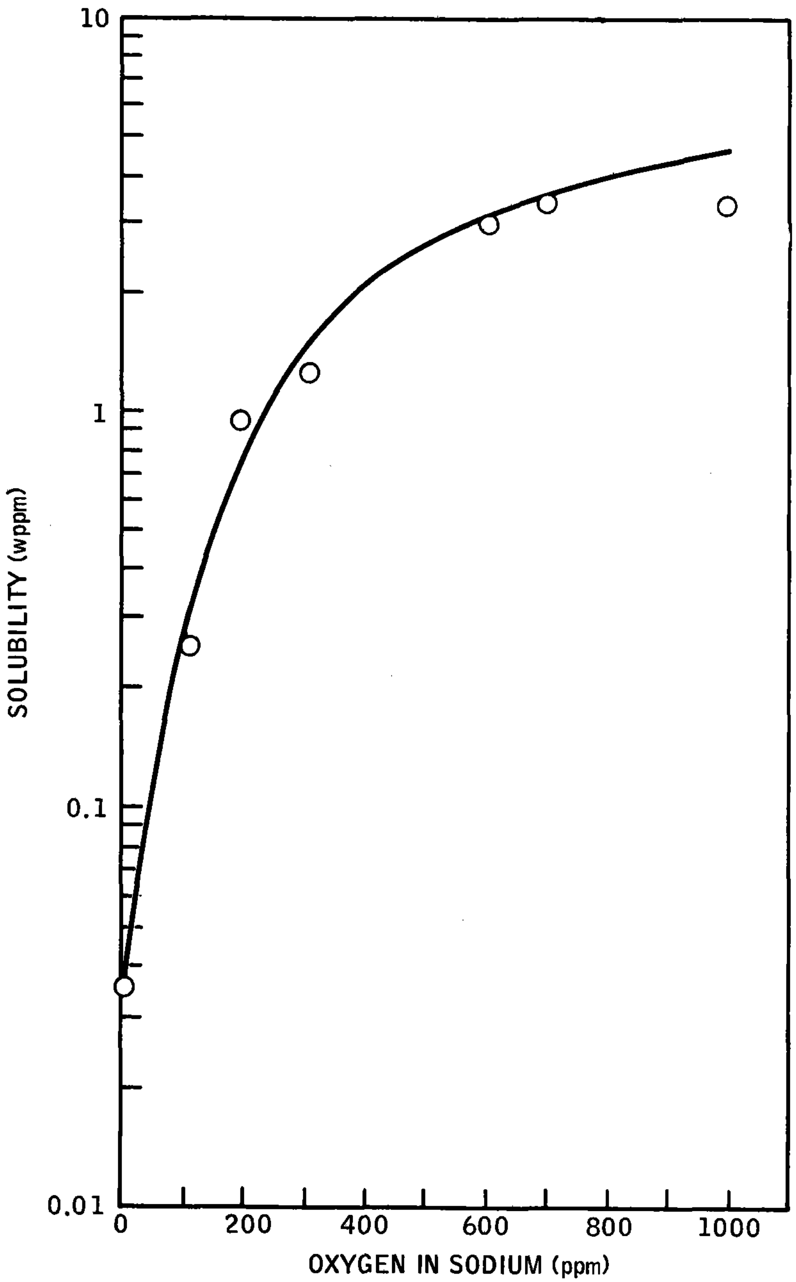
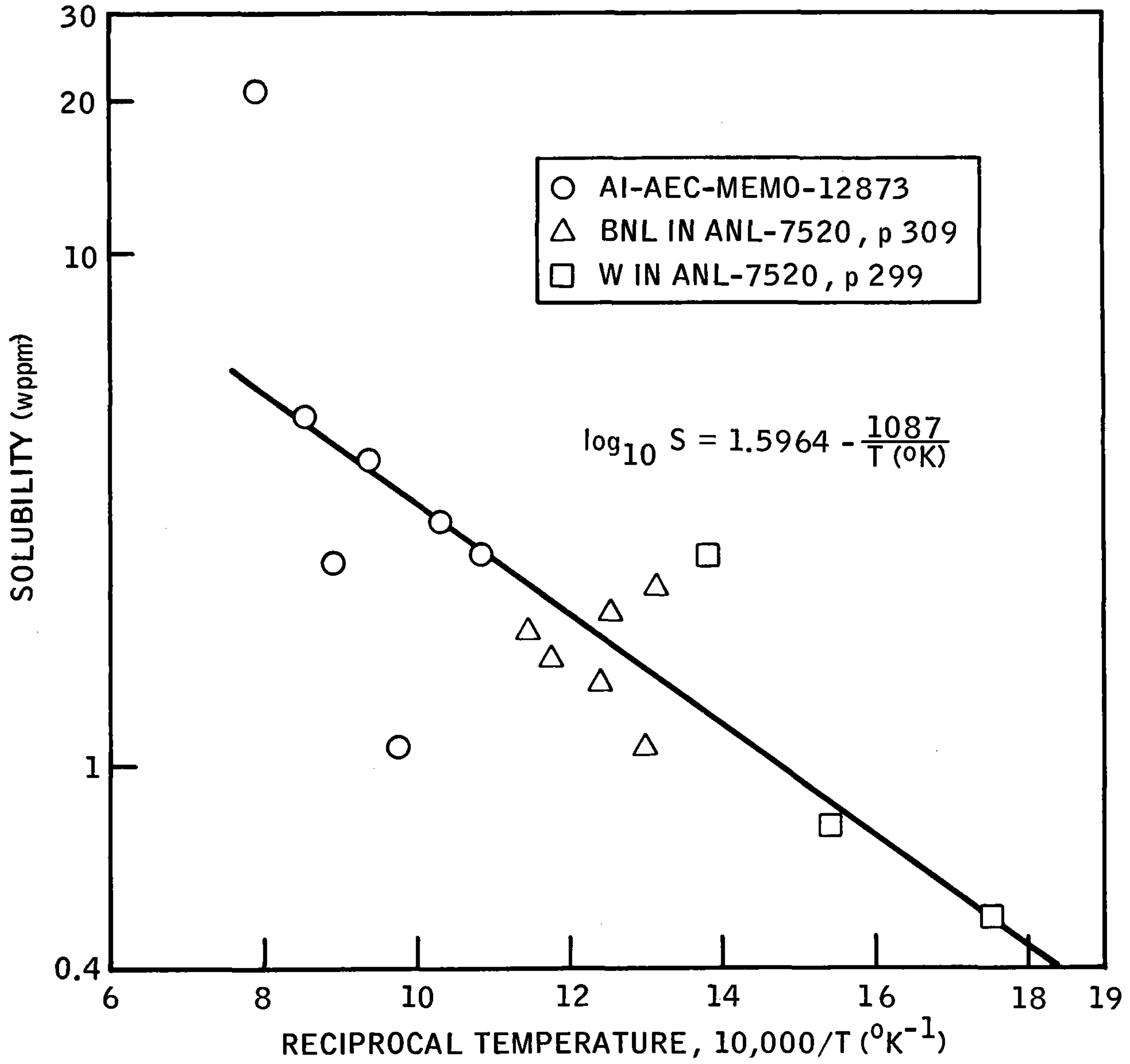


FIGURE 3.
SOLUBILITY OF IRON IN 650°C SODIUM-OXYGEN MIXTURES(6)

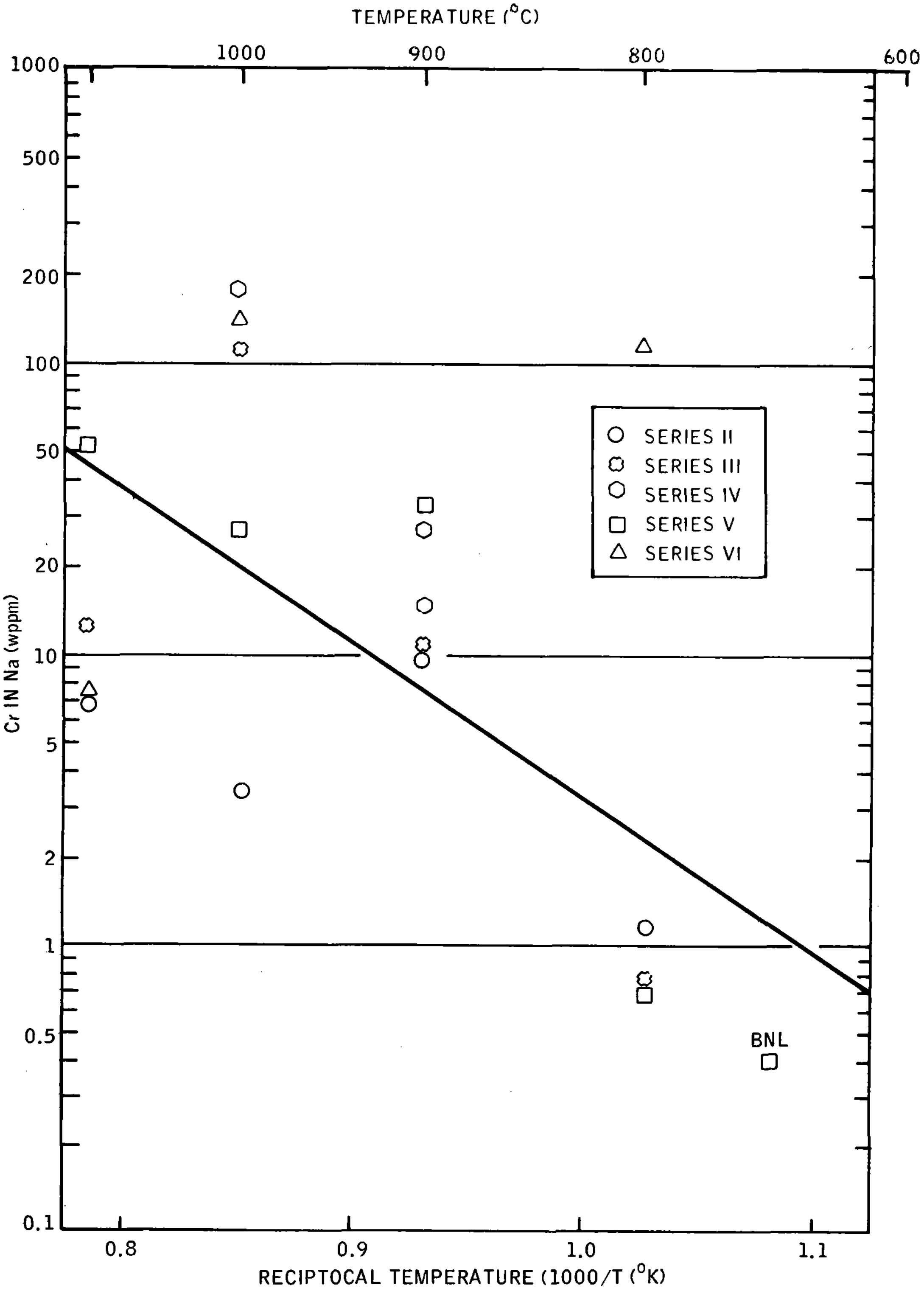
70-MA1-48-57

FIGURE 4. SOLUBILITY OF NICKEL IN SODIUM



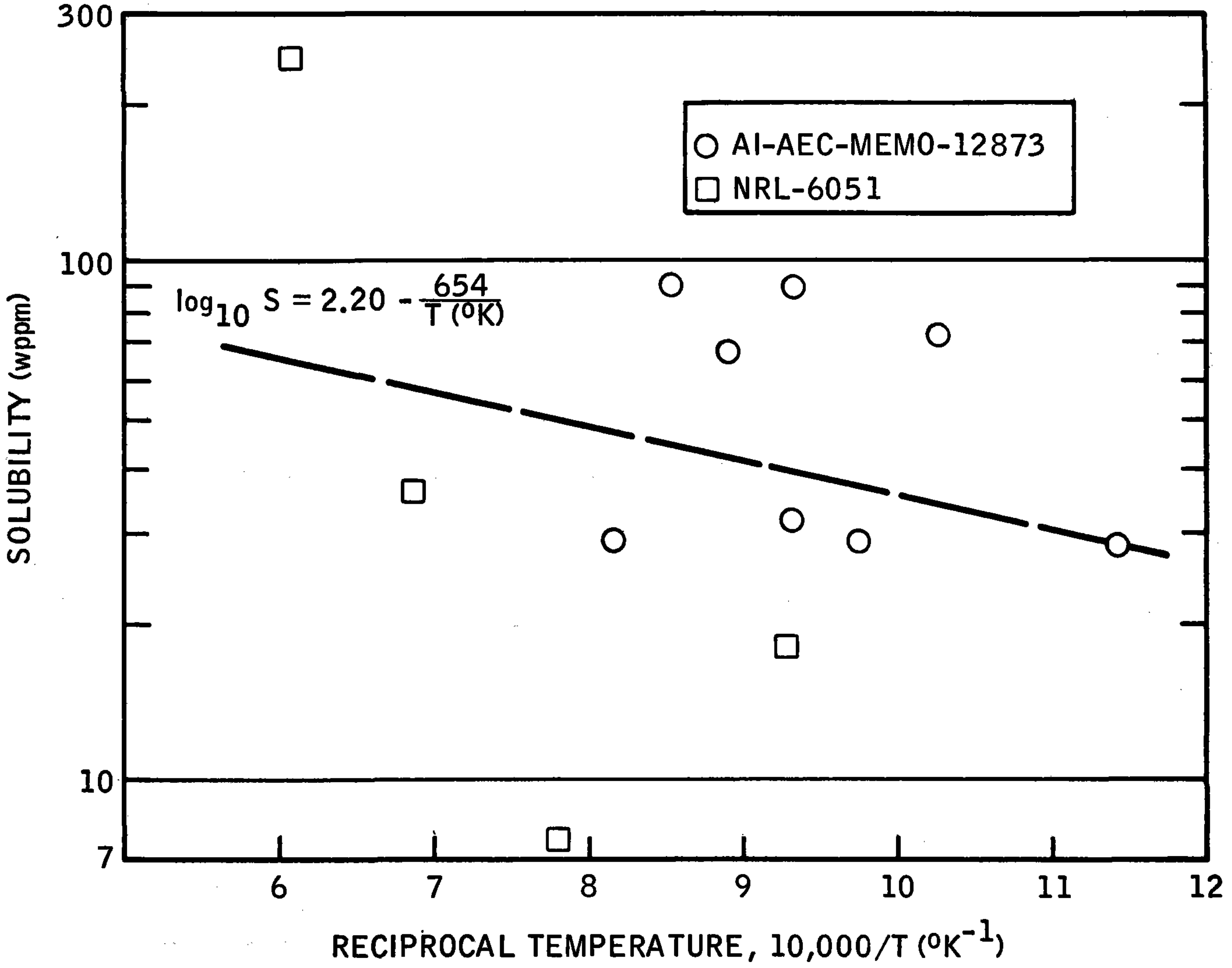
70-MA1-48-58

CHROMIUM CONCENTRATION IN SODIUM



70-MA1-48-13

FIGURE 5. SOLUBILITY OF NIOBIUM IN SODIUM



70-MA1-48-59

FIGURE 6. SOLUBILITY OF ZIRCONIUM IN SODIUM

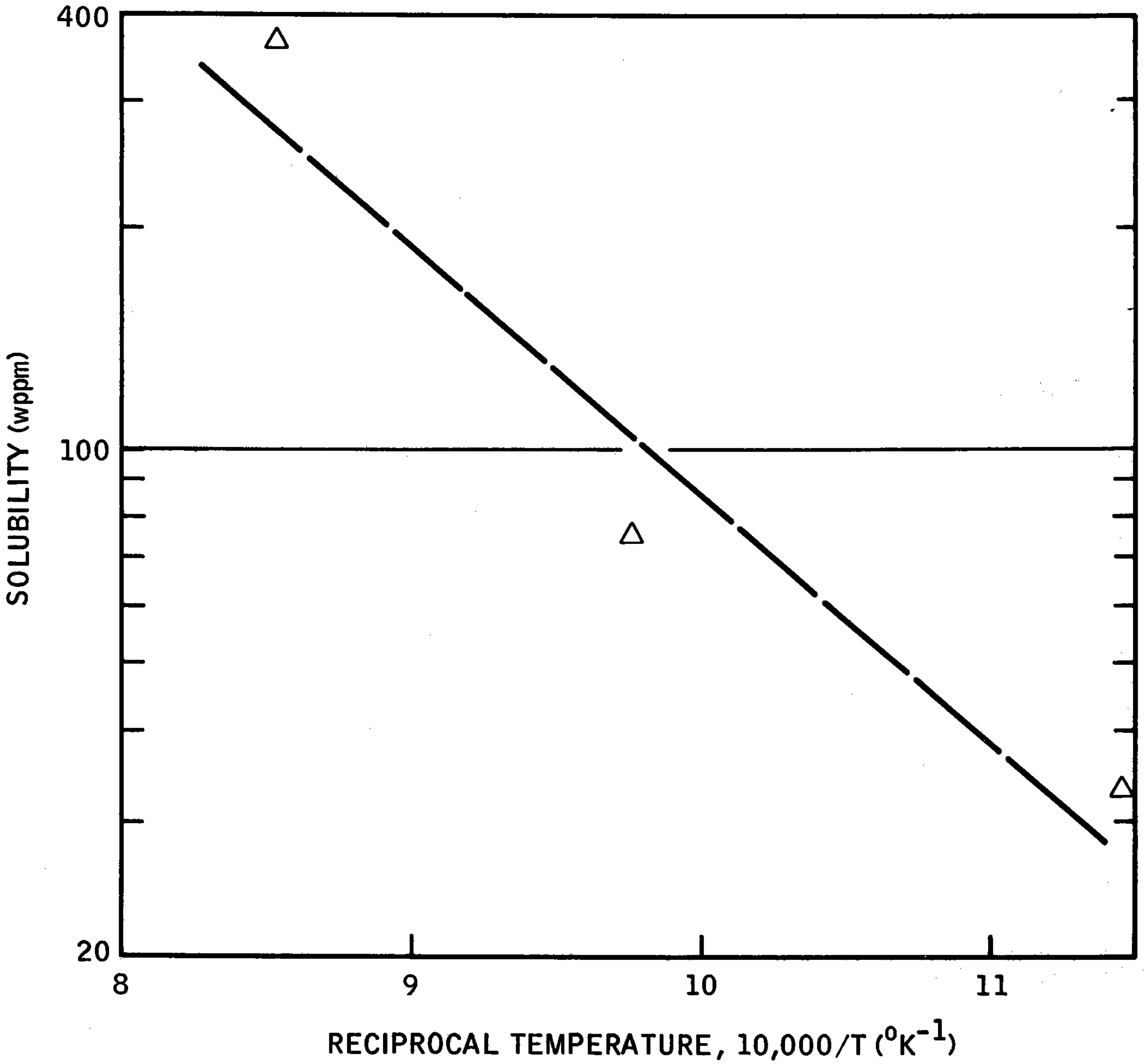


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FIGURE 7.

SOLUBILITY OF TITANIUM IN SODIUM

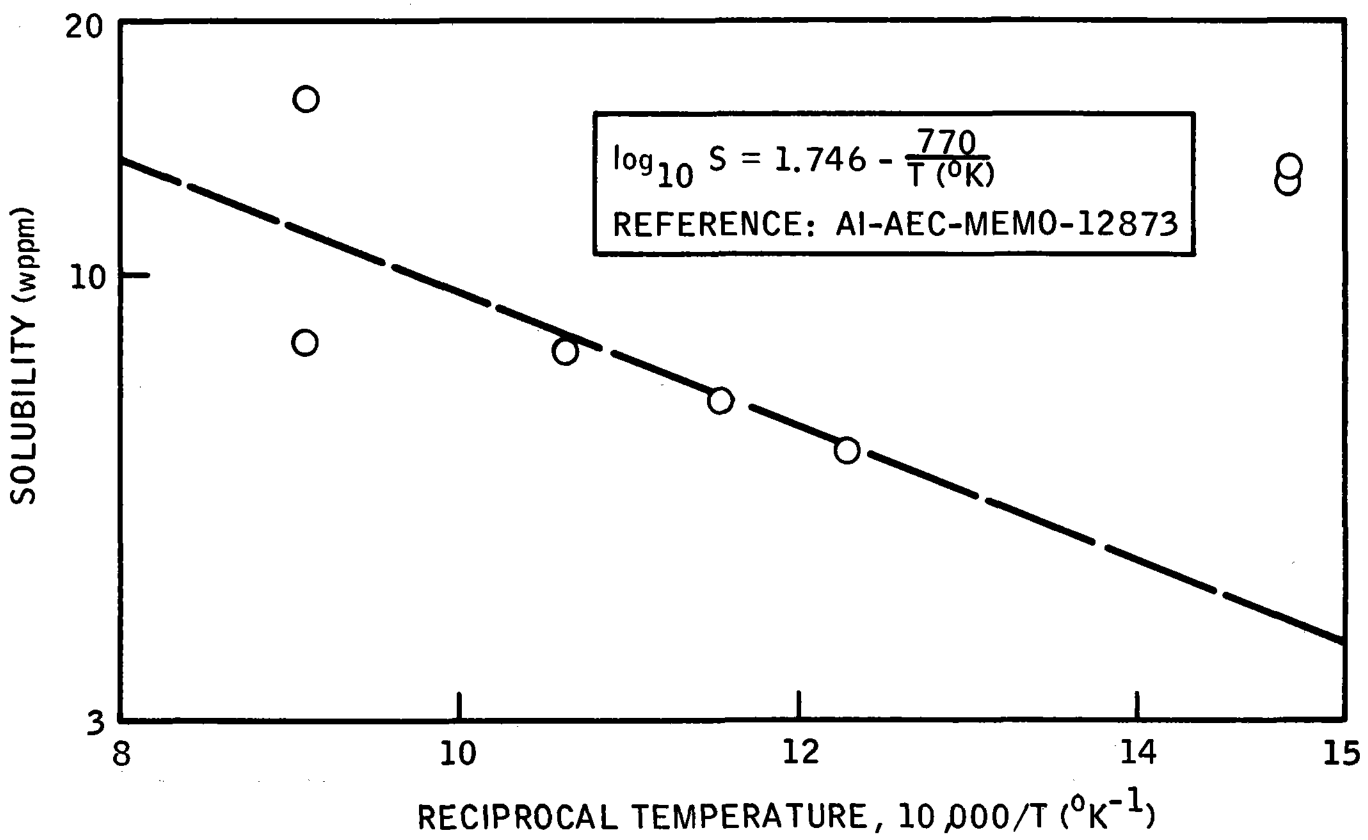
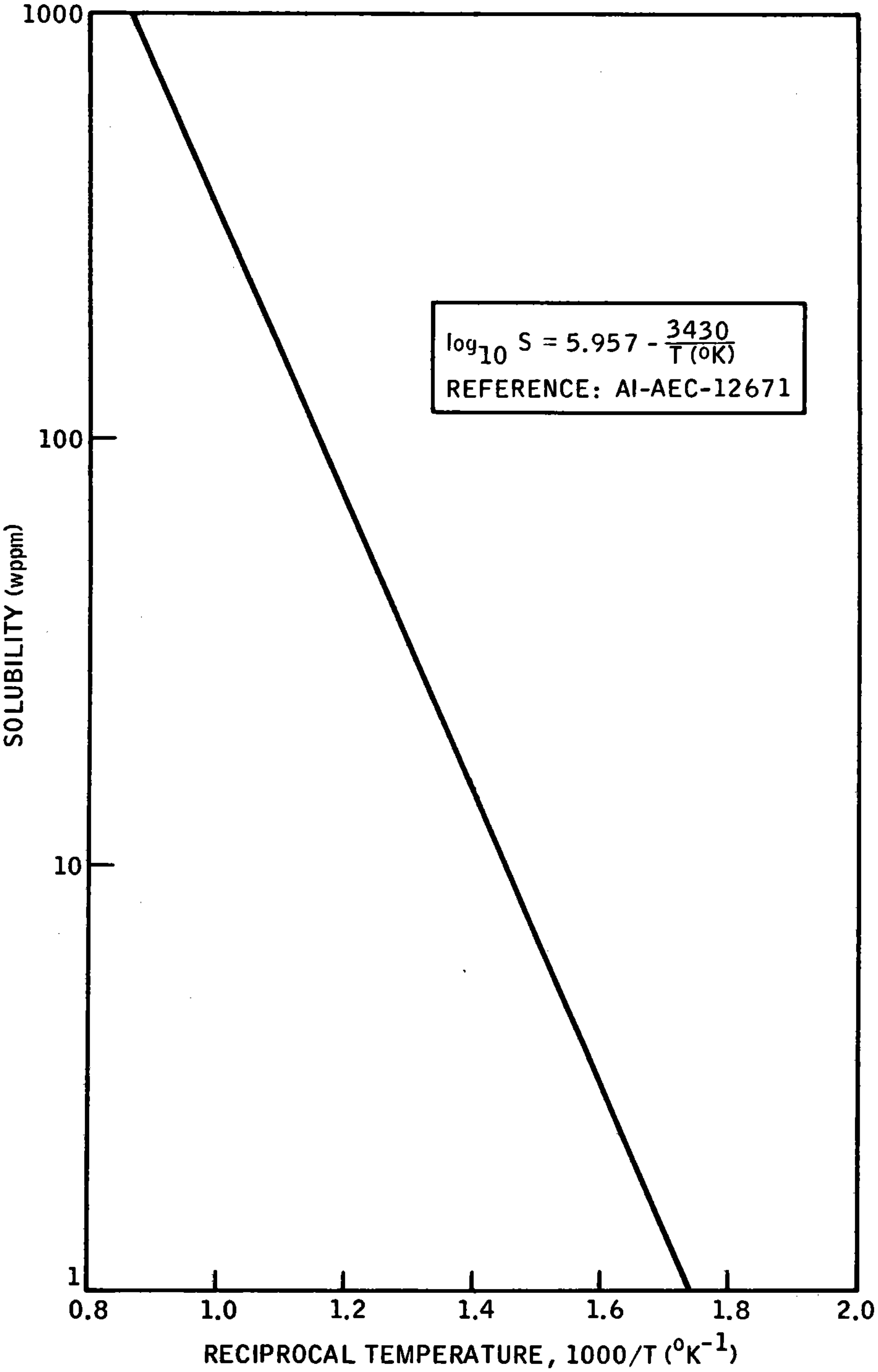


FIGURE 8.

SOLUBILITY OF COPPER IN SODIUM



$\log_{10} S = 5.957 - \frac{3430}{T\,(^\circ K)}$

REFERENCE: AI-AEC-12671

70-MA1-48-62

SOLUBILITY VALUES

Wppm AT 600°C

COPPER	110	COBALT	(<2)
NIOBIUM	28	VANADIUM	(<2)
ZIRCONIUM	27	CARBON	1.8
TITANIUM	7	IRON	1
MANGANESE	(<5)	MOLYBDENUM	(0.5)
NICKEL	2.3	CHROMIUM	(0.3)

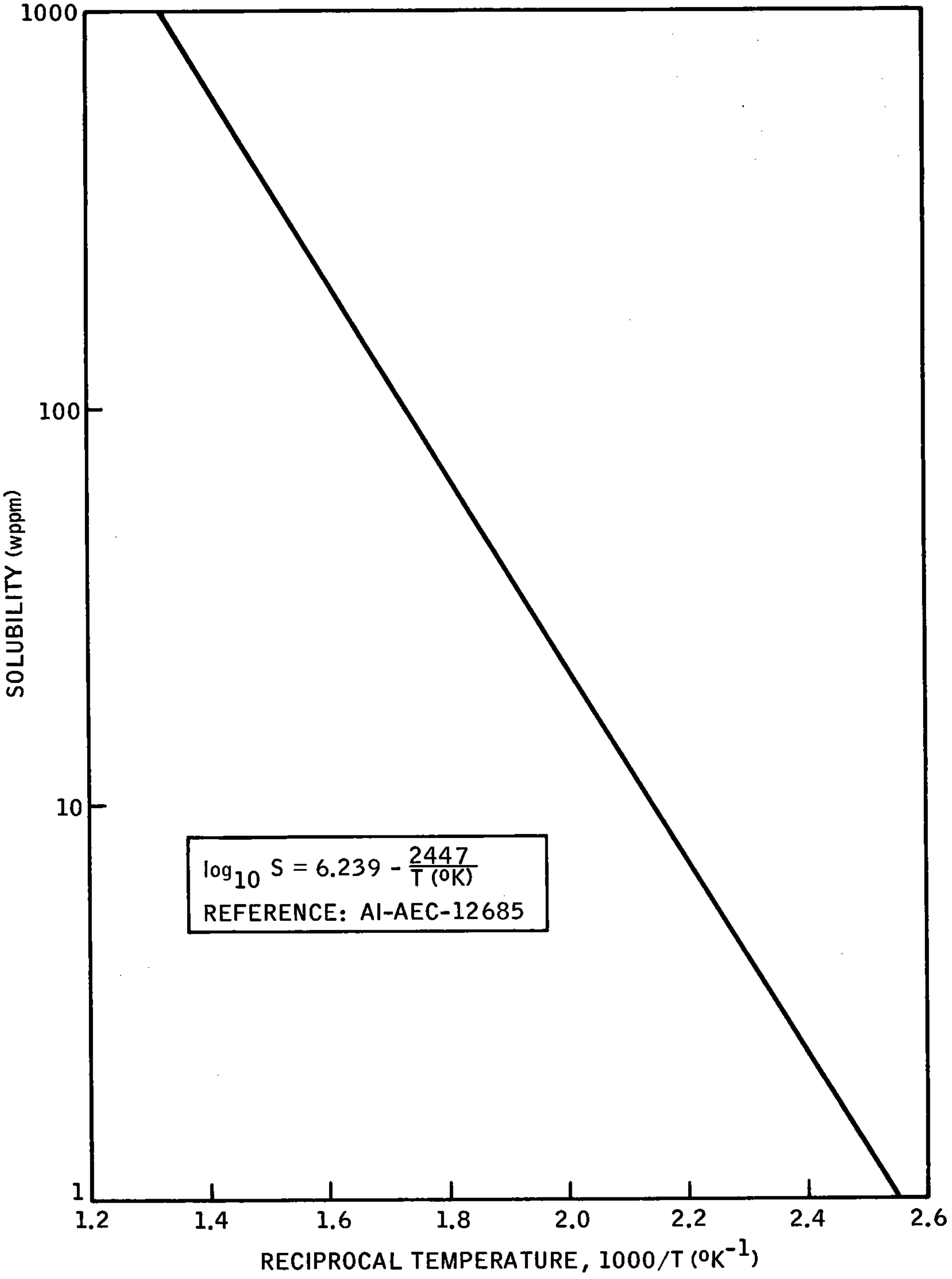
SOLUBILITIES OF GASES

- OXYGEN
- HYDROGEN
- NITROGEN
- HELIUM
- ARGON
- KRYPTON

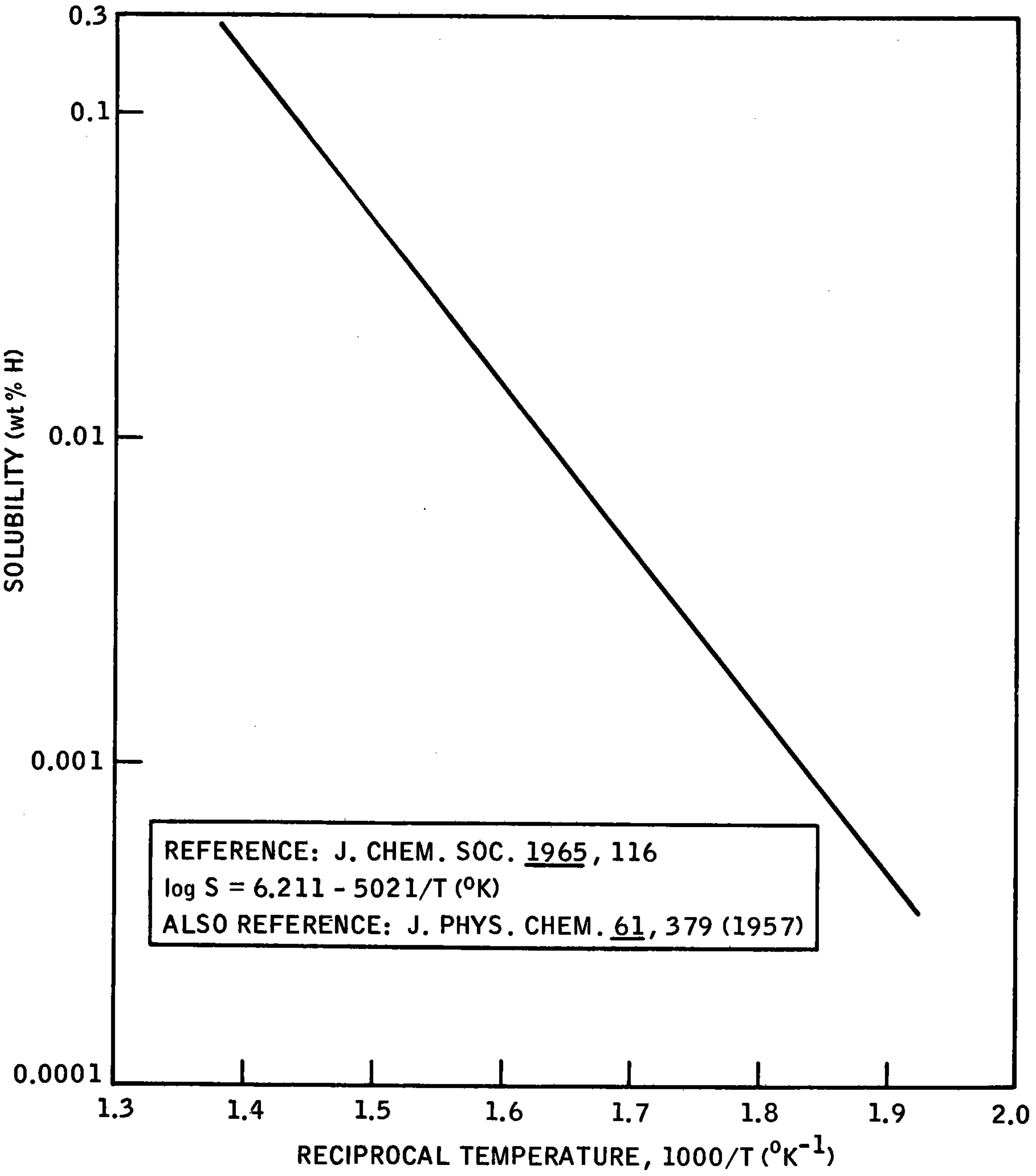
70-MA1-48-71

FIGURE 9.

SOLUBILITY OF OXYGEN IN SODIUM



70-MA1-48-63



REFERENCE: J. CHEM. SOC. 1965, 116

$\log S = 6.211 - 5021/T$ (°K)

ALSO REFERENCE: J. PHYS. CHEM. 61, 379 (1957)

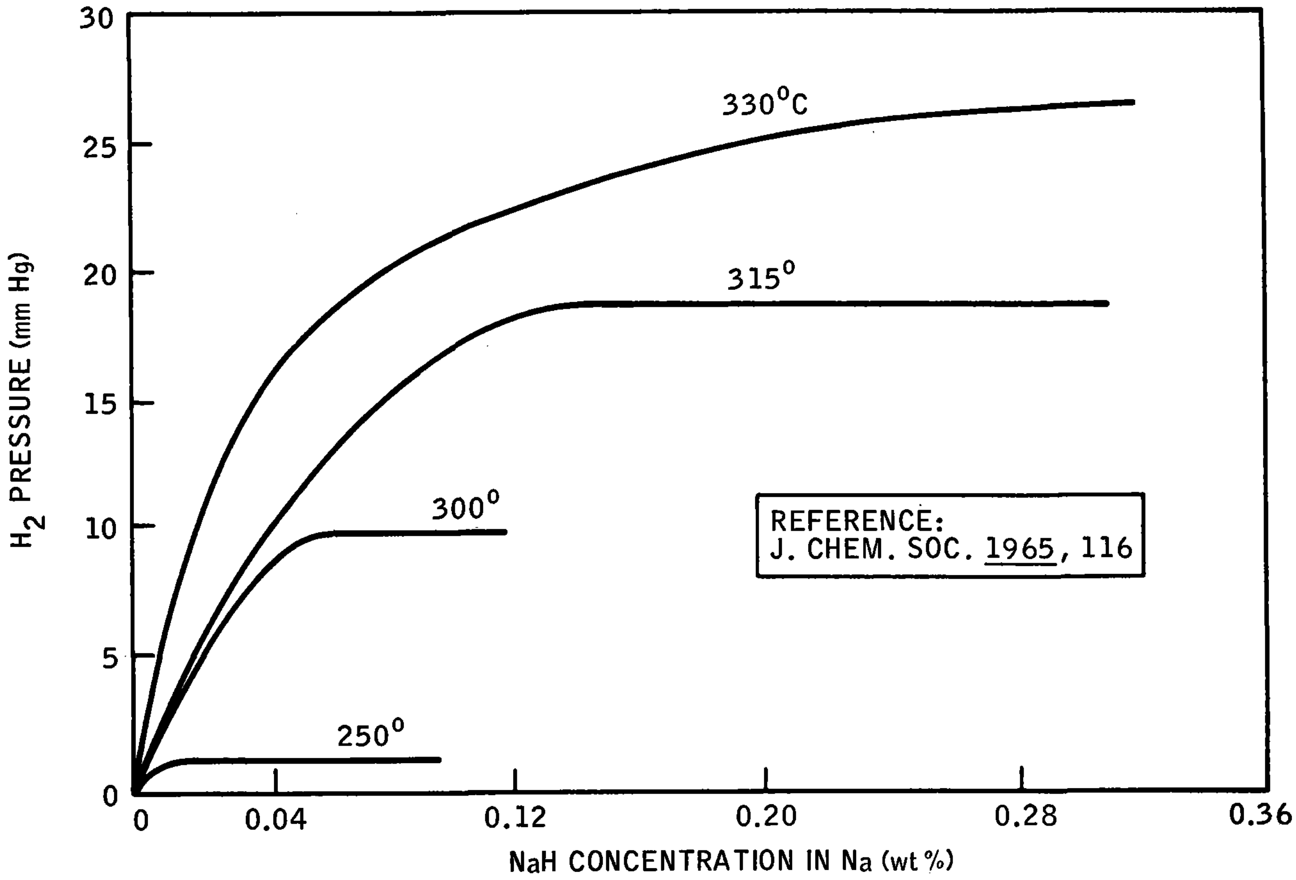
FIGURE 10.

SOLUBILITY OF HYDROGEN IN SODIUM

(SATURATED WITH NaH)

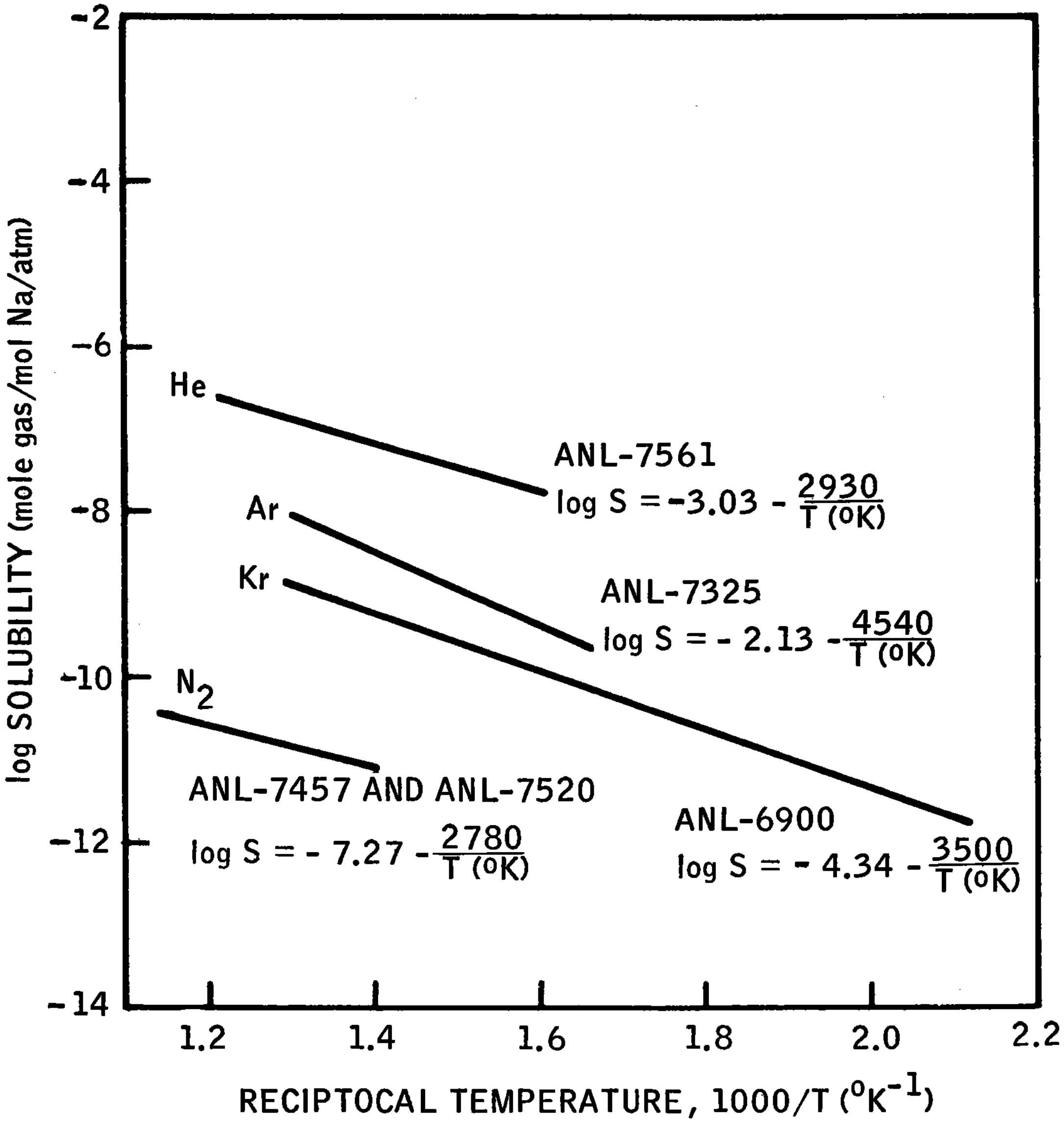
FIGURE 11.

PRESSURE-COMPOSITION ISOTHERMS FOR SOLUTIONS OF HYDROGEN IN SODIUM



70-MA1-48-65

FIGURE 12. SOLUBILITIES OF GASES IN SODIUM



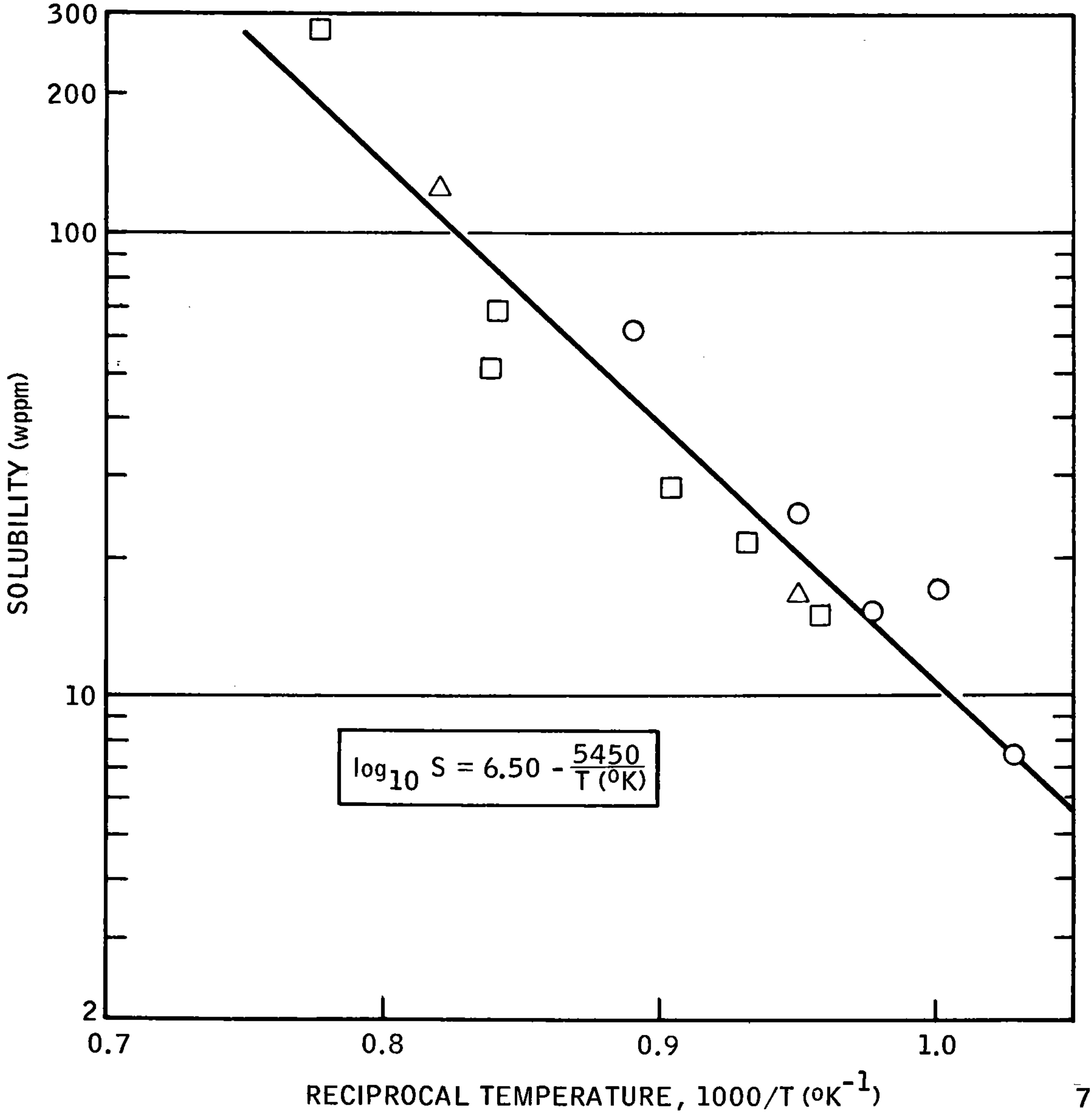
70-MA1-48-66

SOLUBILITIES OF NON-METALS

- CARBON

70-MA1-48-72

FIGURE 13.
SOLUBILITY OF CARBON IN SODIUM(31)



70-MA1-48-67

COMPLEX SOLUTION MECHANISM

- $Fe(S) + O\ (\text{SOLUTION IN Na}) + Na(\ell) = (Na_2O)_2 \cdot FeO$

- SPECIES WHICH HAVE BEEN FOUND IN ALKALI METAL SOLUTIONS
  - CHROMATES
  - NIOBATES
  - FERRATES
  - MOLYBDATES
  - TANTALATES

70-MA1-48-73

INTERACTIONS WITH INORGANICS

- WATER
- AMMONIA
- CARBON OXIDES
- CYANIDES
- CARBIDES

70-MA1-48-74

WATER REACTIONS

LOWER TEMPERATURE $\longrightarrow H_2(g) + NaOH$

HIGH TEMPERATURE $\longrightarrow H_2(g) + Na_2O$

$\longrightarrow NaH + Na_2O$

REFERENCE: LMH SUPPL. (1970)
FORD, APDA-167 (1965)
WILLIAMS, NRL-MEMO-33 (1952)

70-MA1-48-75

AMMONIA REACTIONS

$$\mathrm{Na + NH_3} \longrightarrow \text{SOLUTION}$$

$$\mathrm{Na_2O + NH_3 \longrightarrow NaOH + NaNH_2}$$

$$\mathrm{Na + NH_3} \xrightarrow[\substack{\text{CATALYST}\\ \text{Fe, Al, Cr}}]{\text{METAL}} \mathrm{NaNH_2} + \frac{1}{2}\mathrm{H_2}$$

REFERENCE: LMH SUPPL. (1970)
JOLLY, "METAL AMMONIA SOLUTIONS"
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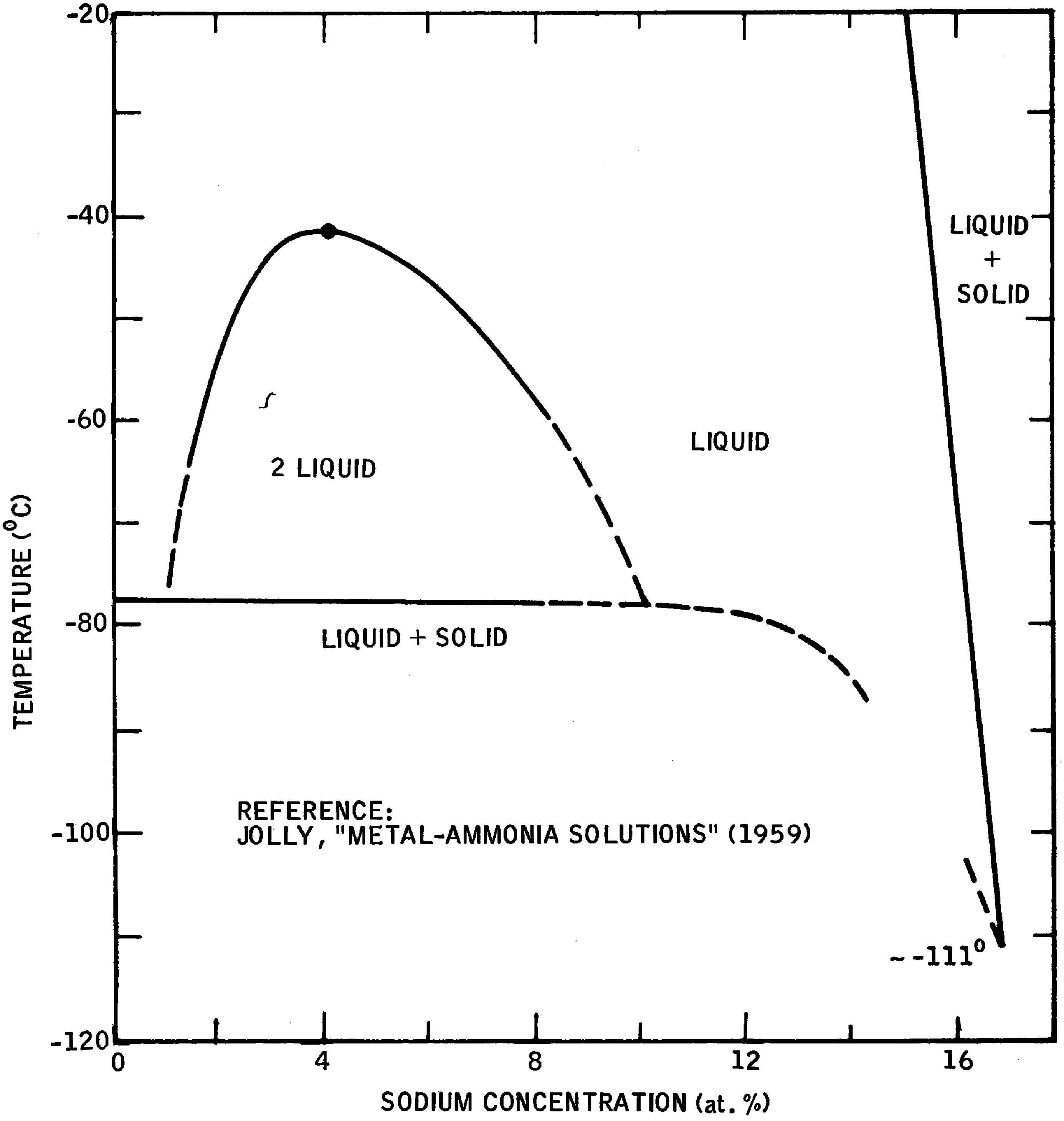
ALTER AND McMANUS GEAP-4006 (1962)

FIGURE 14.

SODIUM - AMMONIA SYSTEM



70-MA1-48-68

CARBON MONOXIDE REACTIONS

$Na + CO \longrightarrow (NaCO)_6$

$\longrightarrow Na_2C_6O_6$ (Na RHODIZONATE)

$\longrightarrow Na_2CO_3$

$\longrightarrow p(NaO)_4C_6O_2$

REFERENCE: LMH SUPPL. (1970)
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MILLER, U.S. PATENT NO. 2858194 (1968)

CARBON DIOXIDE REACTIONS

$Na + CO_2(s) \longrightarrow$ EXPLODES ON IMPACT

$Na + CO_2(g) \longrightarrow Na_2CO_3 + C$

$\longrightarrow Na_2C_2$

$\longrightarrow Na_2C_2O_4$

REFERENCE: LMH SUPPL. (1970)
LENZE AND METZ, CHEM. ZTG 56, 921 (1932)
GILBERT, CHEM. ENG. NEWS 26, 2604 (1948)
MILLER, U.S. PATENT NO. 2858194 (1958)
APDA-182 (1966)
APDA-206 (1967)

CYANIDE REACTIONS

SOLUBILITY OF NaCN IN Na AT 550°C IS 750 ± 110 wppm

REFERENCE: ANL-7403 (1968)

NaCN HAS BEEN DETECTED IN MIXTURES OF:

$Na + (NH_4)_2\ C_2O_4 \cdot H_2O$ AT 500°C

$Na + Na_2CO_3 + NaN_3$ AT 700°C

$Na + C + N_2$ AT 700°C

$Na + Na_2CO_3 + N_2$ AT 700°C

REFERENCE: HOBART AND BJORK, NUCL. APPL. 1 940 (1965)
LMH SUPPL. (1970)

CARBIDE REACTIONS

Na_2C_2 IS MARGINALLY STABLE AND DOES NOT FORM BY DISPLACEMENT FROM OTHER METALLIC CARBIDES

SOME CARBON DOES TRANSFER FROM METALLIC CARBIDES TO APPEAR IN SOLUTION IN SODIUM SO THAT SODIUM CAN ACT AS A TRANSFER MEDIUM FOR CARBON FROM ONE CARBIDE TO ANOTHER (MORE STABLE) ONE

70-MA1-48-80

INTERACTIONS WITH CERAMICS

ALUMINA

BERYLLIA

ZIRCONIA

SILICA

OXIDE STABILITIES AT 800°K

FREE ENERGIES OF FORMATION PER GRAM-ATOM OXYGEN

$Na_2O(S)$	-73		
Na_2O - 5 ppm O	-83		
$Al_2O_3(S)$	-113	$SiO_2(S)$	-88
$BeO(S)$	-124	$Na_2SiO_3(S)$	-105
$ZrO_2(S)$	-112		
$UO_2(S)$	-113		

70-MA1-48-82

INTERACTIONS WITH ORGANICS

HYDROCARBONS

OXYGENATED DERIVATIVES

HALOGENATED DERIVATIVES

HYDROCARBON REACTIONS

ALKANES	NO REACTION AT LOW T DECOMPOSITION AT HIGH T
ALKENES	POLYMERIZATION DECOMPOSITION AT HIGH T
ALKYNES	Na REPLACES ALKYNE HYDROGENS DECOMPOSITION AT HIGH T
ARYLS	NO REACTION AT LOW T POLYMERIZATION Na REPLACES ACTIVE HYDROGENS DECOMPOSITION AT HIGH T

OXYGENATED DERIVATIVES

ALCOHOL	YIELDS R-ONa
ETHER	NO Rx WITH LOW b.p. ETHERS DECOMPOSITION AT HIGH T
ALDEHYDE	REARRANGEMENT AND DECOMPOSITION
KETONE	$R \cdot CO \cdot R' \longrightarrow R \cdot CH{:}CONa \cdot R'$ CONDENSATIONS AND DECOMPOSITION
ACID	FORMS Na SALT
ESTER	FORMS COMPLEX ESTERS

REFERENCE: LMH SUPPL. (1970)

HALOGENATED DERIVATIVES

$2\ RX + Na \longrightarrow NaX + R \cdot R$ WITH VIGOR

$RX_2 \longrightarrow$ POTENTIAL EXPLOSION

$CHCl_3 \longrightarrow$ POTENTIAL EXPLOSION

$CCl_4 \longrightarrow$ POTENTIAL EXPLOSION

MIXTURES OF HALOGENATED HYDROCARBONS AND ALKALI METALS ARE STRONGLY SHOCK SENSITIVE; SOME MIXTURES HAVE AN INDUCTION PERIOD OF UNPREDICTABLE DURATION

REFERENCE: LMH SUPPL. (1970)

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SODIUM TECHNOLOGY COURSE, SESSION II
CORROSION AND MASS TRANSFER
Dr. R. L. McKisson

This session is concerned with the phenomena of corrosion and mass transfer in sodium systems. We cannot dwell very long on any particular facet, but I will try to point out literature references which do deal with the various points in detail. The subjects that will be discussed in this presentation of corrosion and mass transfer phenomena are mechanisms, rate-limiting factors, measurement techniques, the corrosion behavior of metals, carbon transport, nitrogen transport, corrosion product deposition, and fission product transport.

A. MECHANISMS

The mechanism for the transport of materials in sodium is based upon differences in chemical activity. Materials will tend to dissolve in regions in which they have a high chemical activity, and will tend to deposit from solution in regions in which that material has a low chemical activity. Thus, when sodium which is unsaturated in iron passes over a hot iron surface, solution of iron will occur, and as the partially saturated solution then moves to a colder region, and becomes saturated, iron will deposit in the cold surfaces. Thus, a solubility difference is one strong driving force for mass transfer. Further, a chemical reaction which involves the solute, either within the sodium solution or at another surface, is another driving force for the removal of material. This chemical reaction could involve some other component of the solution, such as its oxygen impurity, or it could simply be the result of the formation of a compound, perhaps an intermetallic, by the solute on a different solid surface exposed to the sodium solution. Another possibility is the formation of a solid solution, in which case the solute of interest will tend to diffuse into the surface of a susceptible material.

B. RATE DETERMINING FACTORS

The rate determining factors which are effective in mass transfer are protective layer formation, reaction at the surface, diffusion in the solid, diffusion through the liquid boundary layer, or combinations of these.

The principal characteristic of a system exhibiting protective layer formation is the time dependence of the rate of mass transfer. As the layer forms and becomes thicker the rate of solution of the solute material decreases. There is often a parabolic relation between the weight loss and time, $W = kt^{1/2}$, in such systems. If the layer is formed by the action of a component or an impurity in the sodium, then one also finds the mass transfer to be affected by the concentration of that impurity. Once the layer is formed the rate of mass transfer will usually be independent of sodium velocity, because the principal rate determining factor will be the diffusion of solute through the ever-thickening "protective" layer.

For systems in which the rate of corrosion is controlled by a surface reaction, one finds the rate to be independent of time, and of fluid velocity. It will, of course, be sensitive to the concentration of the species in the sodium which is involved in the reaction. Basically, the process is dependent upon the ease or difficulty the reactant experiences in causing the metal-metal bonds to break.

In alloy systems, one finds cases in which the rate of corrosion is dependent upon the diffusion of the corroding species from the interior of the sample to its surface. Such processes are therefore time dependent, but may be little affected by the fluid velocity or the impurity levels in the sodium. They simply depend upon the diffusion coefficient of the solute material in the matrix material.

A very common rate limiting step is the diffusion of the solute through the liquid boundary layer. This kind of phenomenon is possible because of the nature of flowing fluids, which develop a velocity gradient across the stream because they tend to adhere to the wall. In practice, at fluid flow rates of major technological interest, there is a thin layer adjacent to the wall in which layer most of the velocity gradient appears, and a "turbulent core" region which involves the major fraction of the cross sectional area of the pipe. This thin velocity gradient layer is called the boundary layer. It is presumed that the solute achieves a saturated concentration at the sample surface, so that when the bulk concentration is below saturation, there is a concentration gradient which results in the diffusion of the solute across the boundary layer. In such a case, the mass transfer rate assumes a steady-state value, and does not vary with time. If there is a reaction which maintains a low concentration in the bulk sodium, then one sees a dependence upon the impurity or reactant which participates.

The process is dependent primarily on the solubility of the dissolving species, which controls the concentration at the wall, and on the fluid velocity, which affects the thickness of the boundary layer through which this solute must diffuse.

The above situations are idealized, and one usually finds any corrosion process to be affected by two or more of them. For example, the corrosion of alloys must, by nature, be affected by the diffusion through the solid of the major dissolving species. In stainless steel corrosion, one finds this effect of difffusion in the alloy for several hundred hours in the early periods, and also finds a dependence upon the concentration of oxygen in the sodium, both coupled with a continuing major dependence upon the boundary layer diffusion. Thus, three of the above simple factors are of concern in the corrosion behavior of stainless steel in sodium.

Evidence of the velocity effect is shown in Figure 1 (Plate 9), which shows some data obtained at AI by Hopenfeld.(1) These tests were performed using sodium which was circulating in a loop at 1200°F, and flowing it past a heated region of Type 304 stainless steel for about 350 hr. The curves show a distinct velocity dependence, in a direction compatible with boundary layer theory predictions, and a temperature dependence, which produces differences in the solubilities of the dissolving species.

C. MEASUREMENT TECHNIQUES

In studies of the corrosion process it is convenient and helpful to try to analyze data in the form of the equation

$$J = h'\left(C_w^\circ - C_b\right) ,$$

in which J is the measured corrosion rate, h' is the mass transfer coefficient which includes the variables of system geometry and flow rate, C_w° is the solubility of the diffusing species at the temperature of the corroding surface, and

C_b is the concentration of the corroding species in the bulk fluid. The units of J are usually mgm/cm^2/hr or mil/yr. This expression can be evaluated in at least two different ways. One can attempt to use separately measured solubility data of C_w° and C_b, measure J, and evaluate the values of h' as a function of system parameters. Alternately, one can measure J, and knowing that there is a demonstrated correspondence between heat and mass transfer, one can then use this Chilton-Colburn j-factor analogy and compute a value of h' on this basis. This can be done with some confidence because we do know a good deal about heat transfer in liquid metal systems, and because there is no reason to believe that this analogy should be any poorer in liquid metals than in other fluids. With J and h', then, one can evaluate the term, $C_w^\circ - C_b$.

When the first approach is attempted, one finds that the evaluated mass transfer coefficient is very low compared with the value predicted by the analogy. In the second calculation, one finds that the necessary values of $C_w^\circ - C_b$ are very much smaller than the usually measured solubility values for iron. Which is correct? We will explore this further as we examine more information.

Figure 2 (Plate 11) shows a diagram of a test loop used at the General Electric Co. to measure corrosion rates of stainless steel in sodium.(2) It consists of a sequence of heaters and test sections beginning at the EM pump. The first heater increases the temperature of the sodium to 1000°F and then it flows through the H-1 test section. The second and third heaters bring the temperature up stepwise to 1200°F. After passing through the second 1200°F sample station, the sodium is cooled to 1100, then to 1000, and finally to 700°F. At this temperature the sodium finally passes through a last test station and is returned through the surge tank to the pump. The loop is also fitted with a cold trap for oxygen-concentration control, a plugging meter, and EM flow meters to monitor the system. One problem with this system is that it is difficult to define the value of C_b that should be used in the mass transfer equation. However, the loop has been used extensively and has generated a great deal of very useful data. They find the expected dependence of mass transfer on fluid velocity, and an oxygen concentration effect, and a downstream effect. From the results of measurements made on a system similar to that shown in Figure 2 (Plate 11), Young and Zebroski(3) offer an empirical corrosion rate expression to which the measured data can be fitted. Several evaluations of the empirical constants in the expression have been published, but each of them refers to the best fit of the data for a particular series of tests, and for a particular test unit. A recent evaluation is given by Wozaldo and Spalaris.(4)

$$\ln CR = 14.55 + 0.435 \ln V - 0.000958(L/D)_1 - 0.122 \ln (L/D)_2$$

$$+ 1.445 [1/(t + 1)] + 1.156 \ln O_2 - [23827/(T + 460)]$$

where

CR = corrosion rate (mg/dm^2 - mo)

V = sodium velocity (ft/sec)

$(L/D)_1$ = downstream factor of an isothermal region, the number of hydraulic diameters downstream in an isothermal region

$(L/D)_2$ = downstream factor of an iso-velocity region, the number of hydraulic diameters downstream in an iso-velocity region

t = exposure time (mo)

T = the sample temperature (°F).

The test unit shown in Figure 3 (Plate 12) has been designed by Hopenfeld and Darley(5) at AI with the goal of being able to control C_b, and of measuring J. The unit shown is used in a large 2-in.-diam pipe loop which is maintained at a constant temperature, say 1200°F. The 1200°F sodium approaches the end of the heater as shown. The heater consists of a graphite rod through which a high current is passed. The heat is conducted to the outer sample sheath, whose surface temperature is 20 to 50°F higher than that of the sodium. Thus, the value of C_w° is characteristic of, say 1250°F, and that of C_b is characteristic of 1200°F. The large isothermal loop serves to hold C_b constant during a test run of several hundred hours. I believe this is the only loop presently in service that has this rather unique feature of being able to control C_b, and to thereby get a better evaluation of mass transfer. A report on the test results from this system has been prepared by Hopenfeld.(6)

However, as was noted above, mass transfer measurements, both at GE and at AI, show that the measured values of J, the estimated values of h', and the gross solubility measurement values of $C_w^\circ - C_b$ are not compatible. Some insight into this is perhaps gained by an examination of Figure 4 (Plate 13) — the solubility data for iron, as they now appear. The early data of Epstein(7) and of Rodgers et al(8) appear in the 10-wppm Fe regime. The Bogard(9) data appear in the 0.01 to 0.001-wppm Fe regime. The most recent data fall in between these extremes. Eichelberger and McKisson(10) show results which extrapolate to 0.2 to 1.0-wppm Fe in the same temperature range, 300 to 560°C and 570 to 1040°F. The data of Singer and Weeks(11) show a much steeper temperature dependence, and their extrapolation values are from ~0.003 to 1.0-wppm Fe in that temperature range. Epstein's measurements involved the use of a crucible from which dip samples were taken; Rodgers used small pumped loops; Bogard used a crucible, but removed his samples through a nickel screen assembly. Eichelberger used an invertible sealed capsule technique, and Singer used a dip sample in a closed crucible. Singer had one additional difference, however, in that he made an attempt to extrapolate data measured at various oxygen concentrations in the sodium to give a zero-oxygen value. To date, however, the BNL line is defined by only three points, so that it must be considered tentative. Further, it is now suspected that the filtering action involved in the Bogard samples is potentially capable of removing material from the sample, so that his results may be low. It is evident in these wide variations in the "solubility" of iron, that there is something going on in the iron-sodium-oxygen system that is not yet understood. One suggestion that has been made is that the iron measured in the usual solubility measurement represents a form which is not active in the corrosion process. It does seem likely on the basis of the present beliefs about iron-oxygen-sodium compounds — the ferrates or ferrites — that this is the case.

However, it turns out, perhaps fortuitously, that the data given by Bogard are in the concentration range which does fit the measured J values. Because of this, these values have been used in making corrosion estimates. But, the solubility of iron in sodium does not yet seem to be satisfactorily resolved, and until it is, we are better advised to turn to a more empirical approach in the prediction of corrosion rates.

D. CORROSION BEHAVIOR OF METALS

Typical observed corrosion rates of 300 series stainless steels are shown in Figure 5 (Plate 15). Data from four laboratories are shown. They are nicely separated into the two groups at different oxygen contents, and the temperature dependence is also quite clearly defined. At temperatures of interest to the LMFBR, the rates for the lower oxygen concentrations range up to about 1 mil/yr at the highest temperature.

It is of interest to note here that Hopenfeld's test results predict the rates to be higher than these by about a factor of two or three. Hopenfeld attributes his higher results to his better knowledge of the value of C_b, while in the other test results, he believes the effective value of C_b to be higher than is assumed, due to dissolution in the heaters. However, Hopenfeld's tests ran only for a few hundred hours, so that there may be unsteady state effects which affect his results. In any event, these are significant corrosion rates, but they are not disastrously high.

It was mentioned above that the corrosion of stainless steel was dependent upon diffusion through the metal. An examination of a stainless steel surface which is undergoing a corrosion attack shows the preferential loss of chromium and nickel. As time passes, a concentration gradient of chromium and nickel appears in the metal adjacent to the surface. Thus, one would expect the corrosion rate to be time dependent. Figure 6 (Plate 16) shows the weight loss rate to start out at a very high value, for a 1100°F exposure to flowing sodium, but that after 1200 to 1300 hr, the rate has assumed a steady-state value. This steady-state value turns out to be 0.65 mil/yr, which is in reasonable agreement with the values in Figure 5.

A further explanation of the corrosion behavior of stainless steel is shown in Figure 7 (Plate 17), which shows an electron microprobe trace of the iron, chromium, and nickel concentrations in the surface layer of a corroded sample. The more rapidly dissolving chromium and nickel are depleted at the surface, leaving the original iron, which has therefore become more concentrated at the surface. The reduced chromium and nickel concentrations at the surface have reduced their relative rates of loss, and theoretically at least, one should find the three elements each reach concentration levels for which their loss rates are in the same proportion as the starting material composition. Then the surface will recede at just the necessary rate to keep the surface concentrations in a steady-state balance.

One other consequence of this surface depletion of the chromium and the nickel in the surface layer is the fact that the metal changes from the original austenitic structure to a ferritic structure. Because of this, one finds that all 300 series stainless steels ultimately show essentially the same corrosion rates which rate is also close to that exhibited by a ferritic steel.

The development of the ferritic layer thickness, and its dependence upon the corrosion behavior is shown in Figure 8 (Plate 18), which shows some results from Hopenfeld's system.(12) He examined the ferrite layer thickness along the two-inch length of his heated surface after a 350-hr test. The upper curve shows the variation in thickness. The center curve shows the corresponding sodium temperatures as it is heated in flowing along the flow channel. The lower curve shows the heated surface temperature as it rises from 1200 to 1250°F. Thus, the ferrite layer thickness does follow the expected corrosion rate pattern in this test. The value of C_b is changed only slightly as a large volume of sodium corrodes the rather small sample area, but the value of C_w° does change with increasing surface temperature. Therefore, $C_w^\circ - C_b$ increases along the length of the heater, as does the ferritic layer thickness. Then as the surface temperature falls sharply beyond the end of the heated section, so does the ferrite layer thickness.

This is the present circumstance. We have empirical data on corrosion; we have a good basic theory but imperfect basic data to use in it. What can one then do to supply the designer with the data he needs, except to prepare charts of corrosion rates or corrosion allowances based upon the most reliable and consistent observations. Figure 9 (Plate 19) is such a corrosion allowance chart for 300 series stainless steels and low-alloy ferritic steels. As noted above, all of these metals form a ferritic surface layer, and, within the accuracy of the measurements, have the same steady-state corrosion rates. The chart includes the effects of velocity and temperature for a "reactor quality" sodium containing 10 to 15-wppm O. As one can see, the corrosion allowances range up to several mils per year under the most severe conditions, and down to much <1 mil/year in low velocity regions. Similar curves could be drawn for a system having a lower oxygen content, and they would all be displaced downward by a suitable factor. The GE data suggest an oxygen dependence of (wppm O)$^{1.156}$, but, the lower oxygen level limitation of the exponent is not known.

The corrosion of nickel alloys, which are possible alternate materials for cladding or structural materials, is summarized in Figure 10 (Plate 20). There is far less information on nickel alloy corrosion than on stainless steel. The chart shows a band of the observed range of overall corrosion rates of nickel alloys as a function of their nickel content. The temperature is 1200°F, and the oxygen content of the sodium is about 25 ppm. Alloy A is an austenitic stainless steel with 8 to 10% nickel. Alloy B is Incoloy 800, with about 30% nickel. Alloy C is Inconel 600, which has about 80% nickel. As one sees, the corrosion rate increases with the nickel content of the alloy, but falls again for pure nickel. Thus, one must have some compelling need to avoid stainless steel in order to favor high nickel alloys, and must be prepared to accept the rather high corrosion rates they exhibit.

The corrosion of zirconium in sodium was studied several years ago. The results shown in Figure 11 (Plate 21) are AI data and show the time and temperature dependence of the corrosion rate. The corrosion of zirconium in cold-trapped sodium containing perhaps 10-ppm O, takes the form of a protective film formation on the zirconium. As the data shows, parabolic rate dependence is approached in the system. On the chart, 3.16 on the log time scale represents one day, and at that time at 500°C one finds a layer of about 10 mgm/dm^2, but at 650°C the layer is nearly 100 mgm/dm^2. A month is at 4.64 and a year is at 5.72 on the log time scale, so one sees that these rates are rather high, although a year's exposure at 500°C might be tolerated.

The behavior of beryllium in sodium or in NaK, which data are shown in Figure 12 (Plate 22), is rather catastrophic since, even in well cold-trapped sodium, a thick layer of BeO forms on the surface. Because this oxide material's density is quite different from that of the metal, the oxide layer grows and then spalls off, to expose a new surface of metal. The figure shows the very high corrosion rate of 5 mil/mo at 977°F in a NaK stream flowing at only 6 ft/sec. Therefore, if beryllium is to be used in sodium, the oxygen content must be extremely low to prevent catastrophic corrosion.

The behavior of pure tantalum and of pure niobium in sodium is similar to that of beryllium, except that the rates are much lower. However, another phenomenon, related to the oxygen content of the metal, appears in these metals. Klueh(13) reports on a study he made of the penetration of tantalum and niobium walls by alkali metals at 600°C. His data are shown in Figure 13 (Plate 23), in which he lists the maximum oxygen content of the metal if intergranular attack by the alkali metal is to be avoided, followed by the ultimate penetration of the wall and the bleeding through of the alkali. Note the trends among the alkali metals. This is in accord with the greater expected stability of the lithium niobates and tantalates over the corresponding sodium and potassium compounds.

Unfortunately, "pure" tantalum and niobium stock metals are usually found to have oxygen contents of 500 to 1000-wppm O so that they cannot be used reliably in liquid metal systems. However, the gettered alloys of niobium and tantalum, Cb - 1 Zr and T-111, which contain 1 or 2% of a Group IV element (Zr and Hf) behave significantly better in alkali metals. The zirconium or the hafnium in the alloy acts as a getter for the oxygen and chemically combines with it so that it is essentially unavailable to react with the alkali metal and the Cb or Ta to form the compounds. However, one must still maintain a low oxygen content in the sodium to prevent excessive direct corrosion.

Vanadium is very sensitive to the oxygen content in sodium, and is in addition, a strong getter for carbon and nitrogen. If vanadium is placed in a stainless steel system, it will getter carbon and nitrogen from the steels. In addition, vanadium absorbs oxygen very actively. Whitlow et al(14) and Smith and Kassner(15) reported on this absorption of oxygen in vanadium at 600°C from sodium containing only 1-wppm O. Under these conditions, pure vanadium will become saturated with oxygen at 1.3 wt % O.

1. Carbon Transport

In the preceding discussion, the gettering propensity of vanadium for carbon was mentioned. In addition, the transport of carbon around a sodium system is a well known phenomenon. Stainless steel will getter carbon from the sodium solution, and the depleted solution will absorb carbon from any source of high carbon activity, such as a low chrome or a ferritic steel. Therefore, one must be careful in the design of bi-metallic systems to account for the carbon transport which will occur, or to regulate it in some way. Figure 14 (Plate 25) shows the effect of exposure time on the carbon content of a 316 stainless steel hot leg specimen in a system containing 2-1/4% Cr cold leg specimens.(2) The as-received carbon level in the 316 stainless steel was 0.045 wt % C, as shown, and it rose to 0.13 wt % C in 14,000 hr (20 mo) at a 1100°F region, and to nearly 0.11 wt % in a 1000°F region.

The behavior of a 1-1/4% Cr steel in a similar loop is shown in Figure 15 (Plate 26). Here, the initial carbon content of 0.105 wt % C dropped rather rapidly to 0.075 wt % C under 1000°F exposure and continued to fall as the exposure time continues. For a 1100°F exposure, the initial 3000-hr drop was to a level of about 0.025 wt % C, but it remained there for the duration of an 18,000-hr test.

Further evidence of carbon movement is given by Figure 16 (Plate 27), a chart showing the carbon content of an 18-10 SS heat exchanger tube operating at 500 to 700°C for 30,000 hr.(16) This shows the combination of effects of reduced temperature, and some carbon removal as the sodium moves along the tube. I suspect that the temperature effect is the major one, but the system does show the pickup of carbon from an initial value in the tube material of ~0.085 to ~0.27 wt % at the maximum point.

The problem with carbon transport becomes a metallurgical one, and knowledge of the consequences of altered carbon contents of the various steels must be obtained and evaluated in the design of bi-metallic systems.

2. Nitrogen Transport

The transport of nitrogen in a sodium system has been studied by Gill and Bokros,(17) whose data are shown in Figure 17 (Plate 28). They used flowing sodium at 1000°F and a 304 stainless steel test chamber in which there was a free surface of sodium covered by nitrogen gas. Samples of 304 stainless steel were removed at 660, 1140, and 1400 hr, and examined for the nitride case thickness. The data show that nitrogen reacts with the steel beneath the sodium surface to a much greater degree than it does in the gas phase. Therefore, nitrogen will transfer through sodium to a stainless steel surface, provided there is a source of nitrogen present. However, the amount of transfer and the effects of such transfer in a system which does not have a nitrogen gas source is expected to be negligibly small.

3. Corrosion Product Transport

Figure 9 shows the corrosion allowances for stainless steel systems. A representative value is 1 mil/yr. In the past, the goal of mass transfer studies has been the determination of the rate of removal of material from a hot region, and very little attention has been paid to the question of what happens to the material that is removed. However, in an LMFBR system, an average corrosion rate of one mil per year in the core can produce 500 to 1000 lb of corrosion products. Because of this, studies of the fate of this material have been initiated. Studies of the examination of the chemical species deposited downstream of a corroding region have been reported by Roy et al.(18) Figure 18 (Plate 29) shows a summary of their results. Deposits found in a high temperature (1100°F) region in a stainless steel system in sodium containing about 5 ppm O were found to be high in chromium and nickel, but relatively low in iron. Those in the lower temperature regions (800°F) were high in iron. The deposits rich in chromium were found to have a number of identifiable chromium compounds in them, such as the complex carbide $M_{23}C_6$, the carbides Cr_7C_3 and Cr_3C_2, and sodium chromite $NaCrO_2$. Nickel was found in these studies only as elemental nickel, and iron as α-Fe.

Roy examined the deposits on the 1100°F and the 800°F surfaces and found that there were particles on the 1100°F surface but they were rather sparse. They gave the appearance of having been nucleated in the liquid and then they became attached to the surface as particles. In the 800°F region the particle density was much higher, and in some places a sort of jumble of particles was found. Roy believes that nucleation of these particles occurred on the surface and they had therefore primarily grown in place. This is supported by the observation that there were many crystal facets in evidence, as compared to seeing none in the 1100°F deposits. Much more work needs to be done here, and it does seem like a fruitful thing to be doing at this time, not only because of the question of the deposits themselves, but also because of the additional insight these results will give into the chemistry of the corrosion process and of the chemistry which occurs within the sodium itself.

4. Fission Product Transport

A transport and deposition problem similar to that of the corrosion products is that of the fission products. In a reactor system, both types of materials are radioactive and their ultimate disposition and fate in a reactor system is of considerable concern in the development of maintenance techniques for reactors. Brehm(19) reported on a study of the transport behavior of the components of an irradiated stainless steel specimen in 1300°F sodium containing 10-wppm O. He finds that the rate of release of the elements, Mn, Cr, and Co is in the order,

$$^{54}\mathrm{Mn} > {}^{51}\mathrm{Cr} > {}^{60}\mathrm{Co} \quad .$$

Manganese was found to migrate rather rapidly to the cold trap. Chromium moved more slowly, and as of the end of his experiment, was found in the cold leg. The cobalt, however, exhibited a rather slow rate of movement along the hot leg. Brehm also found that there was an enhancement of deposition in regions of high sodium velocity.

Guon(20) has reported a study made on the transport characteristics of radioactive cesium and barium in a circulating sodium system. He finds that these materials move around a system by a sort of chromatographic mechanism. The rate of movement is apparently dependent upon the solubility of the moving species. Cesium, for example, moves rapidly and will re-distribute itself rather quickly if the system temperature pattern is changed. Barium, which is thought to be present as the oxide, is very sluggish.

For both materials, an equilibrium is set up between the concentration of material on the wall and the concentration in the liquid. For cesium, it is found that the temperature history of the surfaces plays an important role in the surface's ability to adsorb the cesium. Tests made with a new stainless steel surface which has not been heated to high temperatures in sodium show larger surface concentrations than are found on surfaces that have been heated above, say, 800°F. Guon has developed an equilibrium constant for cesium deposition for high-temperature treated surfaces,

$$\frac{\text{Gm Cs/cm}^2\text{ on wall}}{\text{Gm Cs/cm}^3\text{ in sodium}} \cong 0.01$$

The behavior of barium in Guon's test system was similar to that of cesium, but the high solubility of cesium appears to make it more mobile. Further, the low solubility of the moving barium species (BaO) tends to make the K-value for barium much higher than that for cesium. However, further testing is needed to ensure that the observed K-values are representative of adsorption of the surface, and are not distorted because of the presence of a precipitated barium compound.

E. SUMMARY

The maximum corrosion rate of stainless steels in reactor systems is expected to be of the order of 1 mil/yr.

The corrosion rate of stainless steels is dependent upon (1) diffusion through the liquid boundary layer, (2) diffusion through the metal, at least in the first 1000 hr, and (3) oxygen concentration in the sodium.

The corrosion rate of all austenitic stainless steels will ultimately reach the same value in any given system, because a ferrite surface layer forms.

The corrosion of vanadium, niobium (columbium) and tantalum is very sensitive to the oxygen concentration in the sodium.

The corrosion rate of these metals is probably less than that of steel if the oxygen levels are maintained <1 wppm O.

Zirconium forms a protective film, whose rate of growth is sensitive to the oxygen concentration in sodium.

Beryllium corrodes at a very high rate, even in cold-trapped sodium, because of the formation of an oxide layer which spalls off.

Carbon will move from regions of high chemical activity to those of low chemical activity.

Carbon is gettered by refractory metals and can be strongly depleted from steel by such metals.

Corrosion and fission products move toward the colder regions in a system. The rates appear to be related to the solubilities of the species involved in the transport process. For cesium, an equilibrium constant relating the amount of material on the wall to the amount in the liquid is found.

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11. Singer and Weeks, ANL-7520, Pt I, p 309 (1968)
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13. Klueh, Corrosion by Liquid Metals, AIME Symposium (October 13-15, 1969), Philadelphia, Pa.
14. Whitlow et al, Corrosion by Liquid Metals, AIME Symposium (October 13-15, 1969), Philadelphia, Pa.
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16. Bykov, et al, JPRS 48330, p 426 (July 1, 1969)
17. Gill and Bokros, NAA-SR-6162 (1961)
18. Roy et al, Corrosion by Liquid Metals, AIME Symposium (October 13-15, 1969), Philadelphia, Pa.
19. Brehm, Corrosion by Liquid Metals, AIME Symposium (October 13-16, 1969), Philadelphia, Pa.
20. Guon, AI-AEC-12952 (1970)

The following section is a collection of all the plates used in the second presentation. These are numbered in sequence as Plates, and those which are referred to in the text are also assigned figure numbers.

CORROSION AND MASS TRANSFER

- MECHANISMS
- RATE – LIMITING FACTORS
- MEASUREMENT TECHNIQUES
- CORROSION BEHAVIOR – METALS
- CARBON TRANSPORT
- NITROGEN TRANSPORT
- CORROSION PRODUCT DEPOSITION
- FISSION PRODUCT TRANSPORT

70-MA1-48-87

MECHANISMS

CHEMICAL ACTIVITY DIFFERENCES

- SOLUBILITY
- COMPOUND FORMATION
- SOLID SOLUTION FORMATION

70-MA1-48-88

RATE DETERMINING FACTORS

- PROTECTIVE LAYER FORMATION
- REACTION AT SURFACE
- DIFFUSION IN SOLID
- DIFFUSION THROUGH LIQUID BOUNDARY LAYER
- COMBINATIONS OF ABOVE

70-MA1-48-89

PROTECTIVE LAYER

RATE IS

- TIME DEPENDENT
- IMPURITY LEVEL DEPENDENT
- VELOCITY INDEPENDENT
- DEPENDENT ON DIFFUSION THROUGH LAYER

70-MA1-48-90

REACTION AT SURFACE

RATE IS

- TIME INDEPENDENT
- IMPURITY LEVEL DEPENDENT OR INDEPENDENT
- VELOCITY INDEPENDENT
- DEPENDENT ON EASE OR DIFFICULTY OF BREAKING METAL – METAL BOND

70-MA1-48-91

DIFFUSION IN SOLID

RATE IS

- TIME DEPENDENT
- IMPURITY LEVEL INDEPENDENT
- VELOCITY INDEPENDENT
- DEPENDS ON DIFFUSION COEFFICIENT

70-MA1-48-92

DIFFUSION THROUGH LIQUID BOUNDARY LAYER

RATE IS

- TIME INDEPENDENT
- IMPURITY LEVEL DEPENDENT OR INDEPENDENT
- SOLUBILITY DEPENDENT
- VELOCITY DEPENDENT

70-MA1-48-93

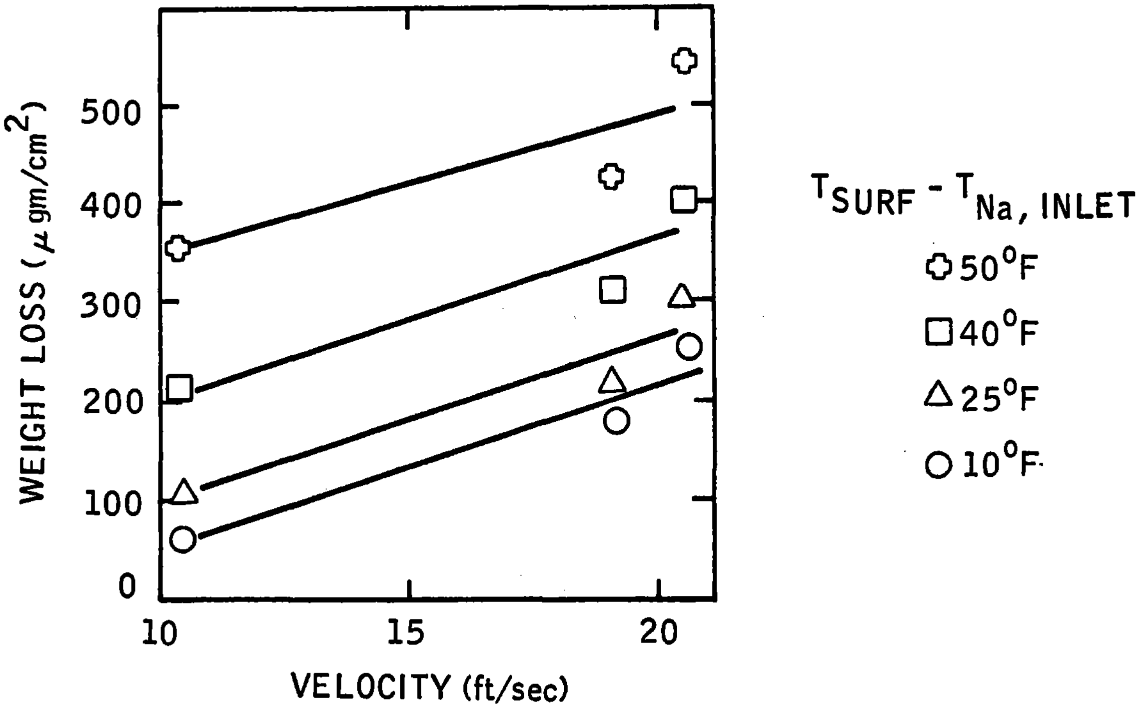
COMBINATIONS FOR STAINLESS STEEL

- DIFFUSION THROUGH LIQUID BOUNDARY LAYER
- DIFFUSION IN SOLID
- REACTION

70-MA1-48-94

FIGURE 1.

EFFECT OF VELOCITY ON WEIGHT LOSS



REFERENCE: HOPENFELD, PAPER 3, CORROSION BY LIQUID METALS I, AIME SYMP. ON LIQ MET, OCT 13-15, 1969, PHILADELPHIA, PA.

MEASUREMENT CONSIDERATIONS

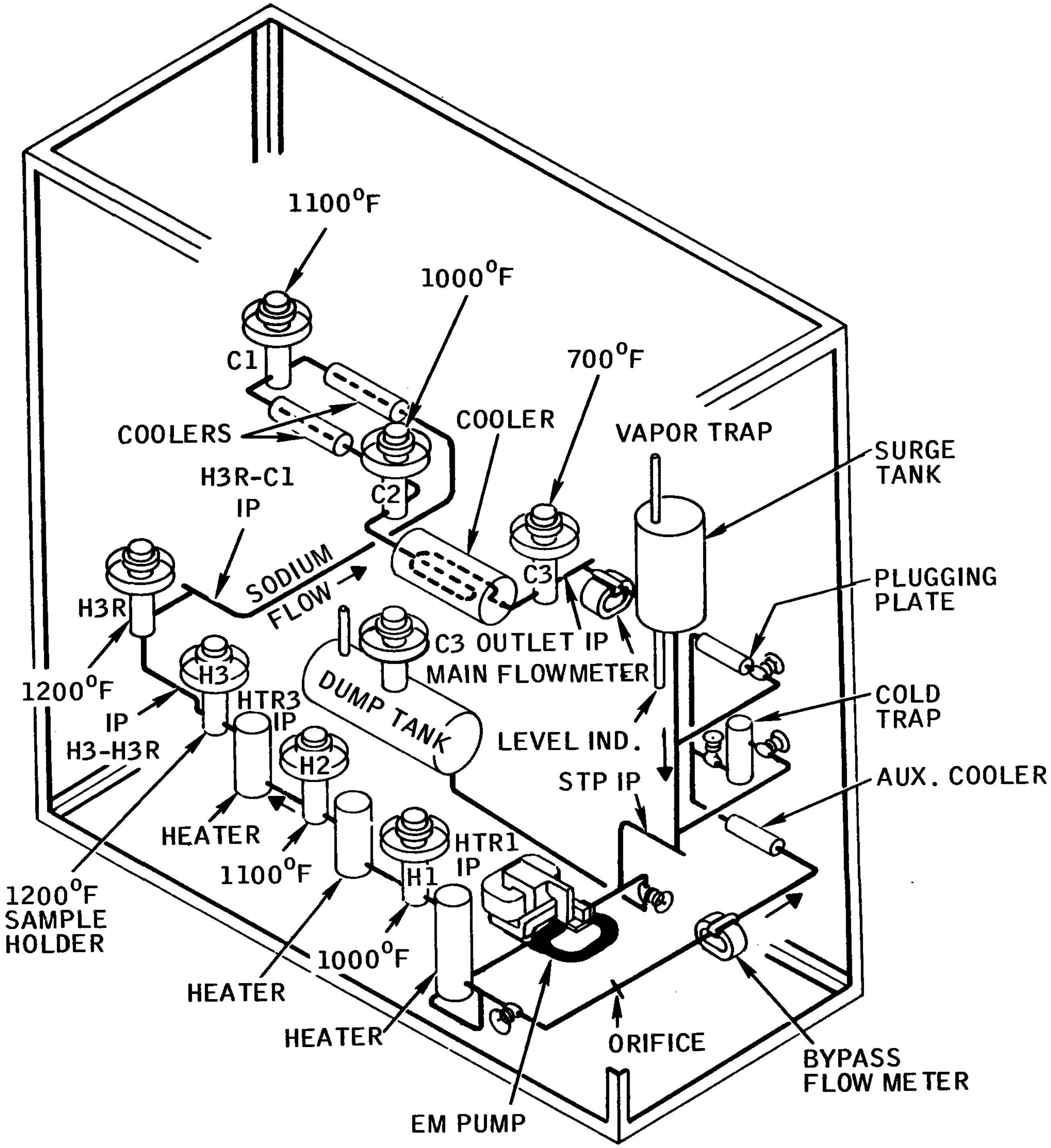
$$J = h'(C_w^o - C_b)$$

70-MA1-48-96

FIGURE 2.

TEST LOOP ARRANGEMENT

(GEAP-4831)

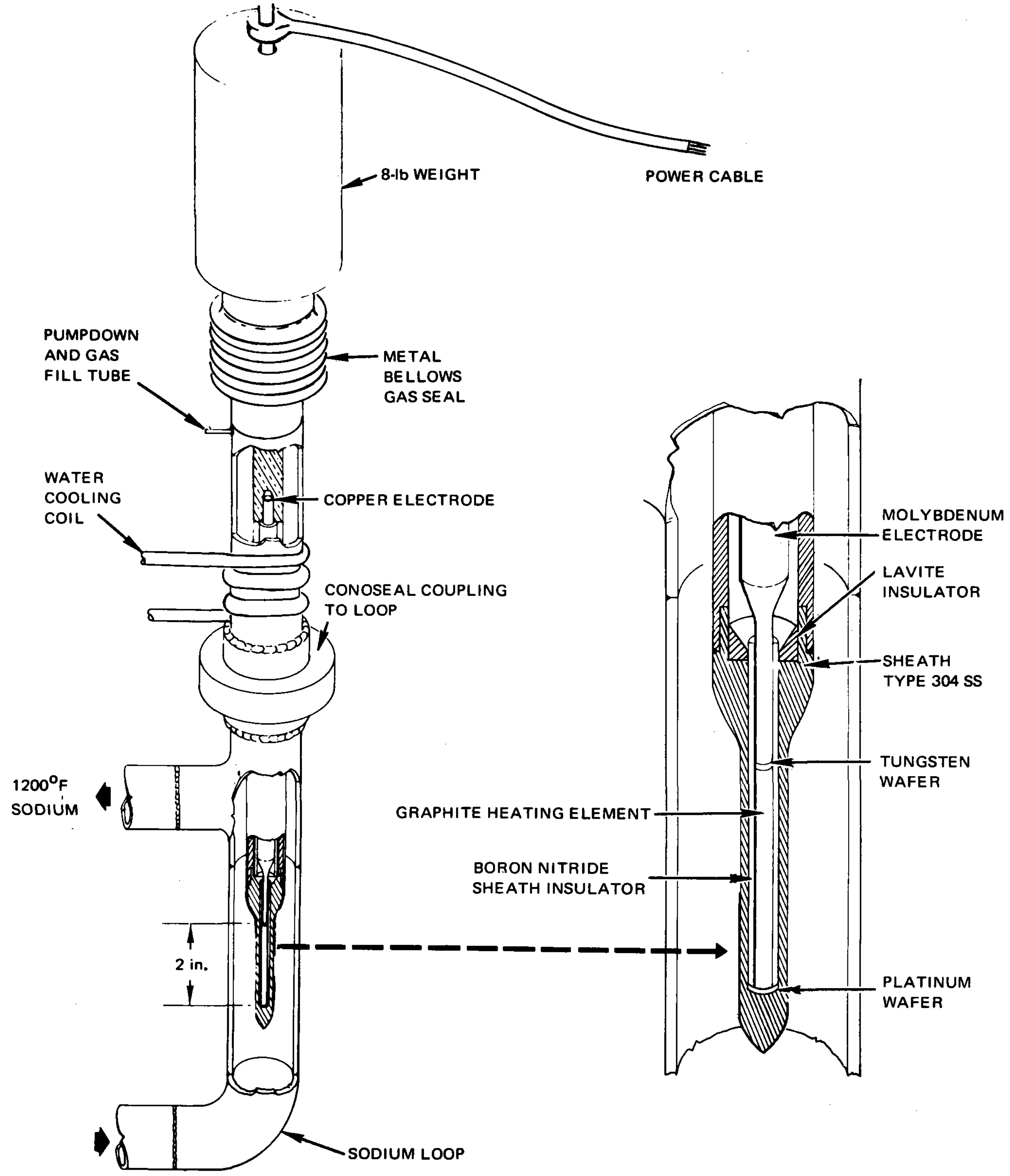


IP = IN-PIPE SAMPLE LOCATIONS
TEMPERATURES FOR RUN TYPE 1 OR 2 CONDITIONS

9-MA19-051-20

FIGURE 3.

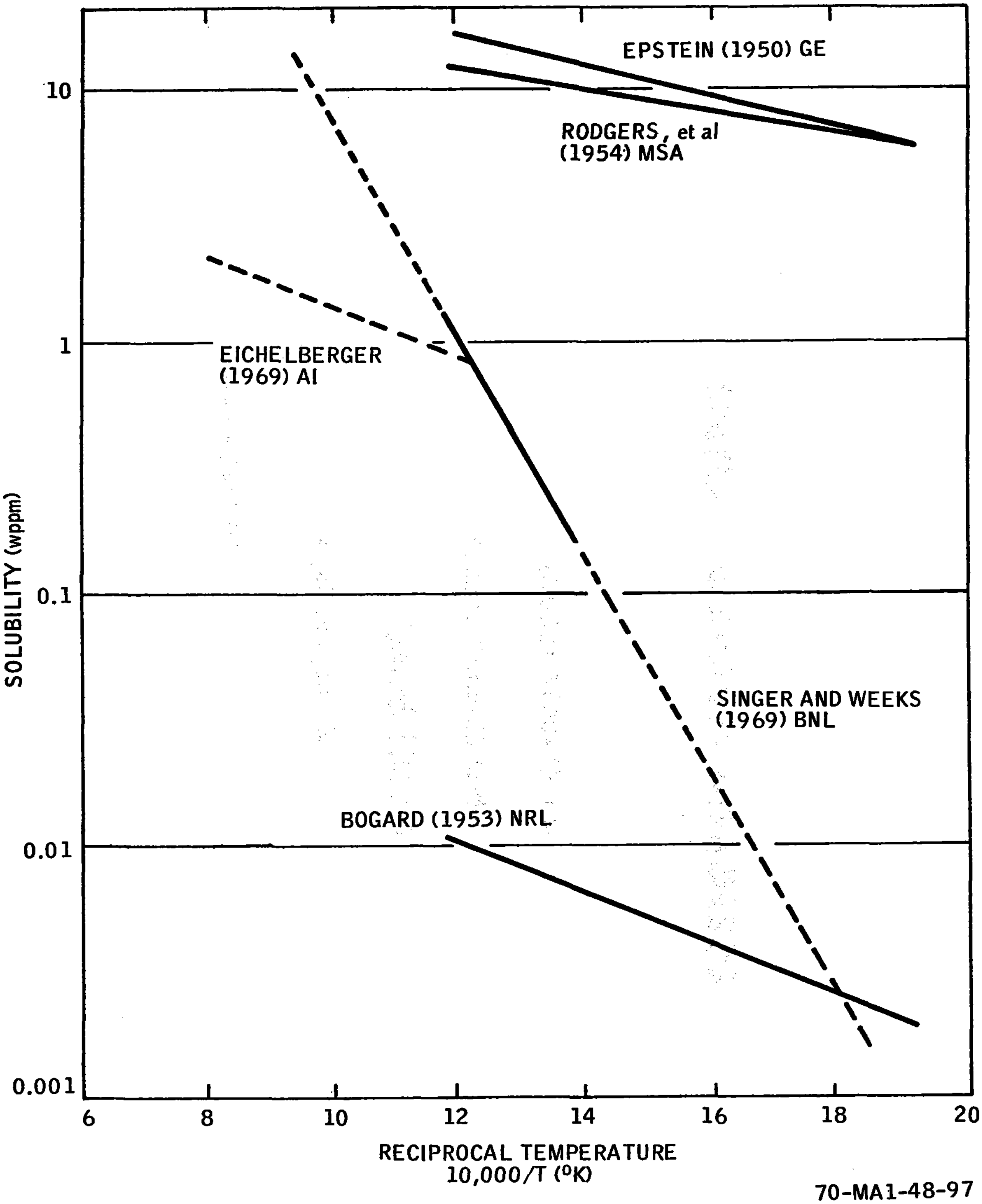
UNIT DESIGNED FOR TESTING TO OBTAIN MASS TRANSFER MEASUREMENTS



6-13-69 UNCL

7706-2501 C

FIGURE 4. RESULTS OF SOLUBILITY MEASUREMENTS OF IRON IN SODIUM



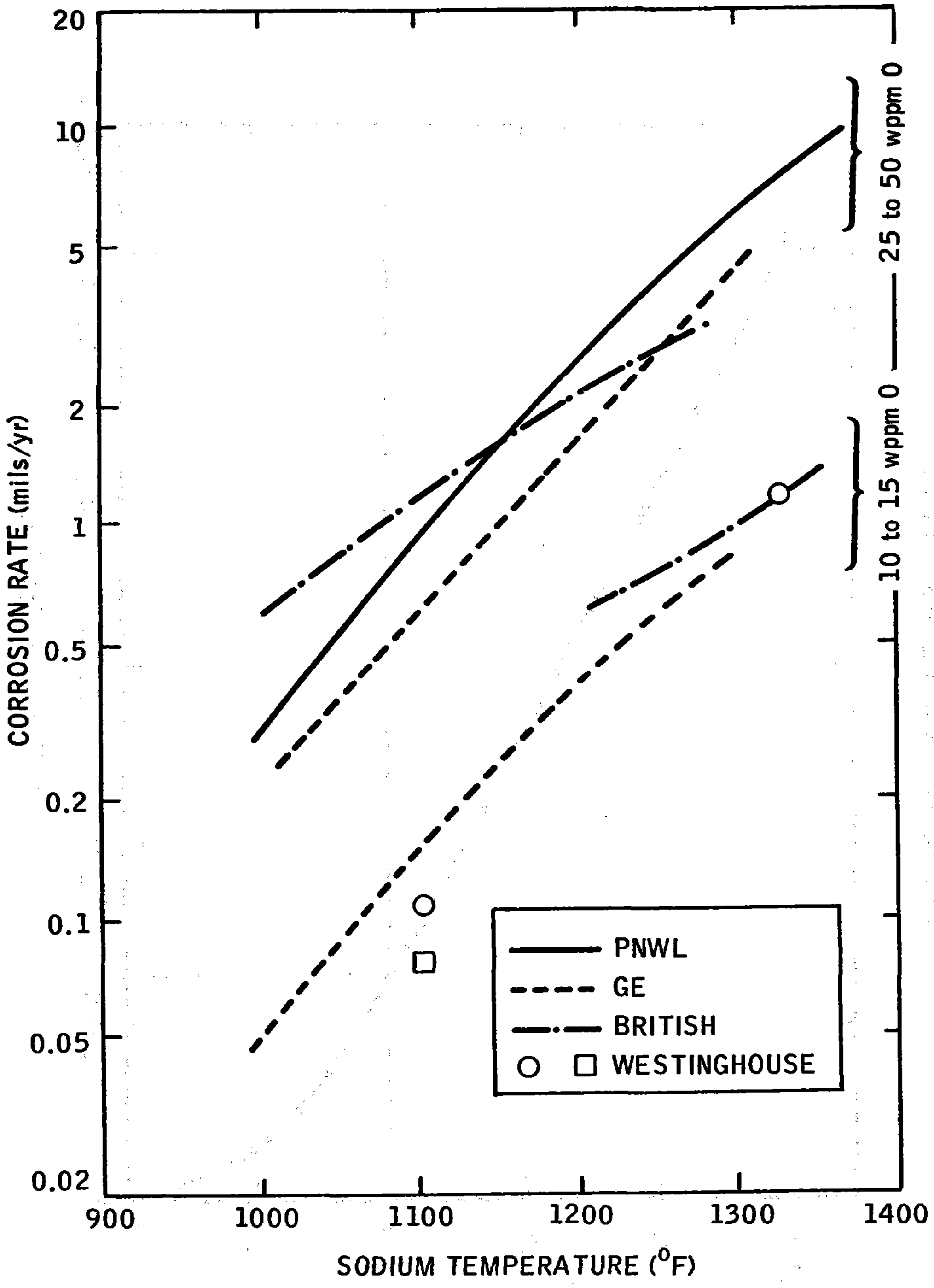
70-MA1-48-97

CORROSION BEHAVIOR - METALS

- IRON-BASE ALLOYS
- NICKEL-BASE ALLOYS
- OTHER METALS

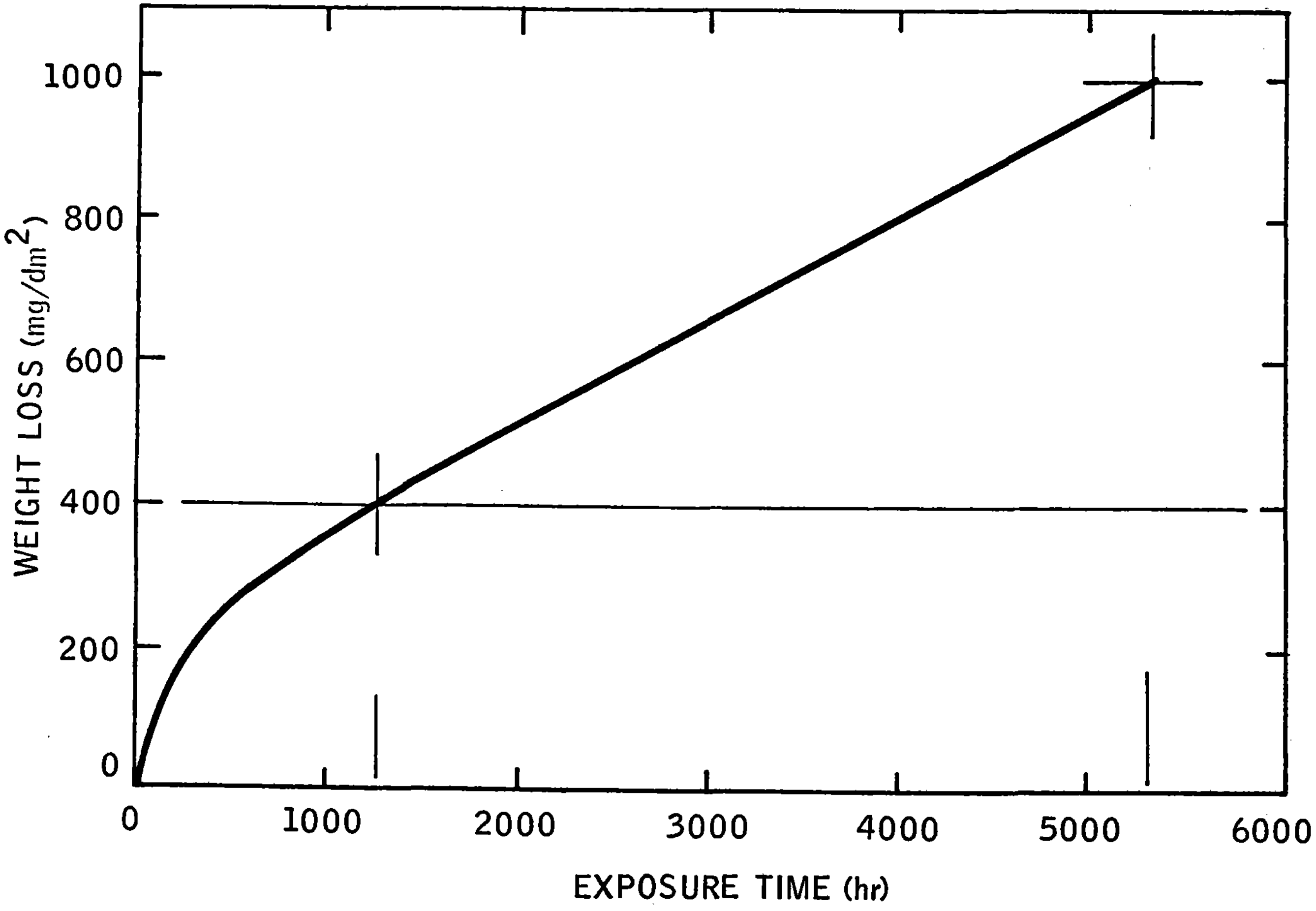
  Zr, Be, Nb, Ta, V

FIGURE 5.
SODIUM CORROSION DATA 300 SERIES SSTL



70-MA1-48-99

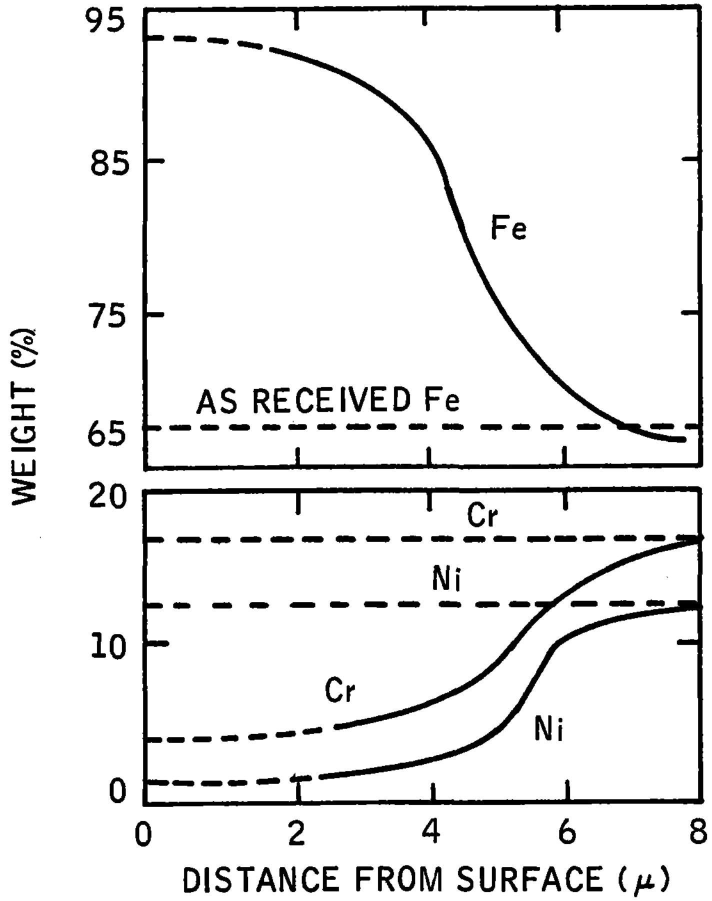
FIGURE 6.
WEIGHT LOSS vs TIME



70-MA1-48-100

FIGURE 7.

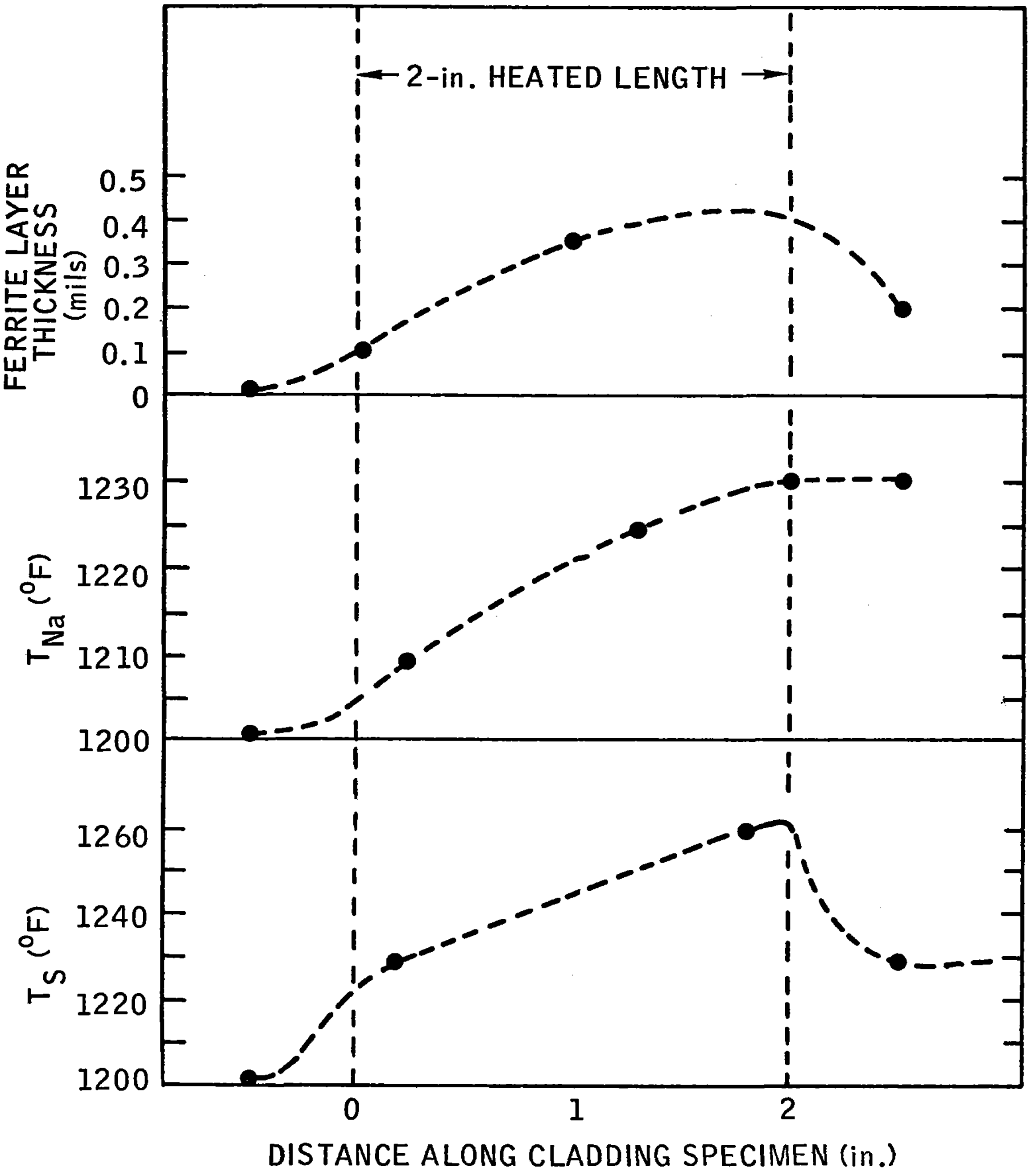
COMPOSITIONAL CHANGE IN SS ASSOCIATED WITH ELEMENTAL LEACHING IN Na



9-010-116-23

FIGURE 8.

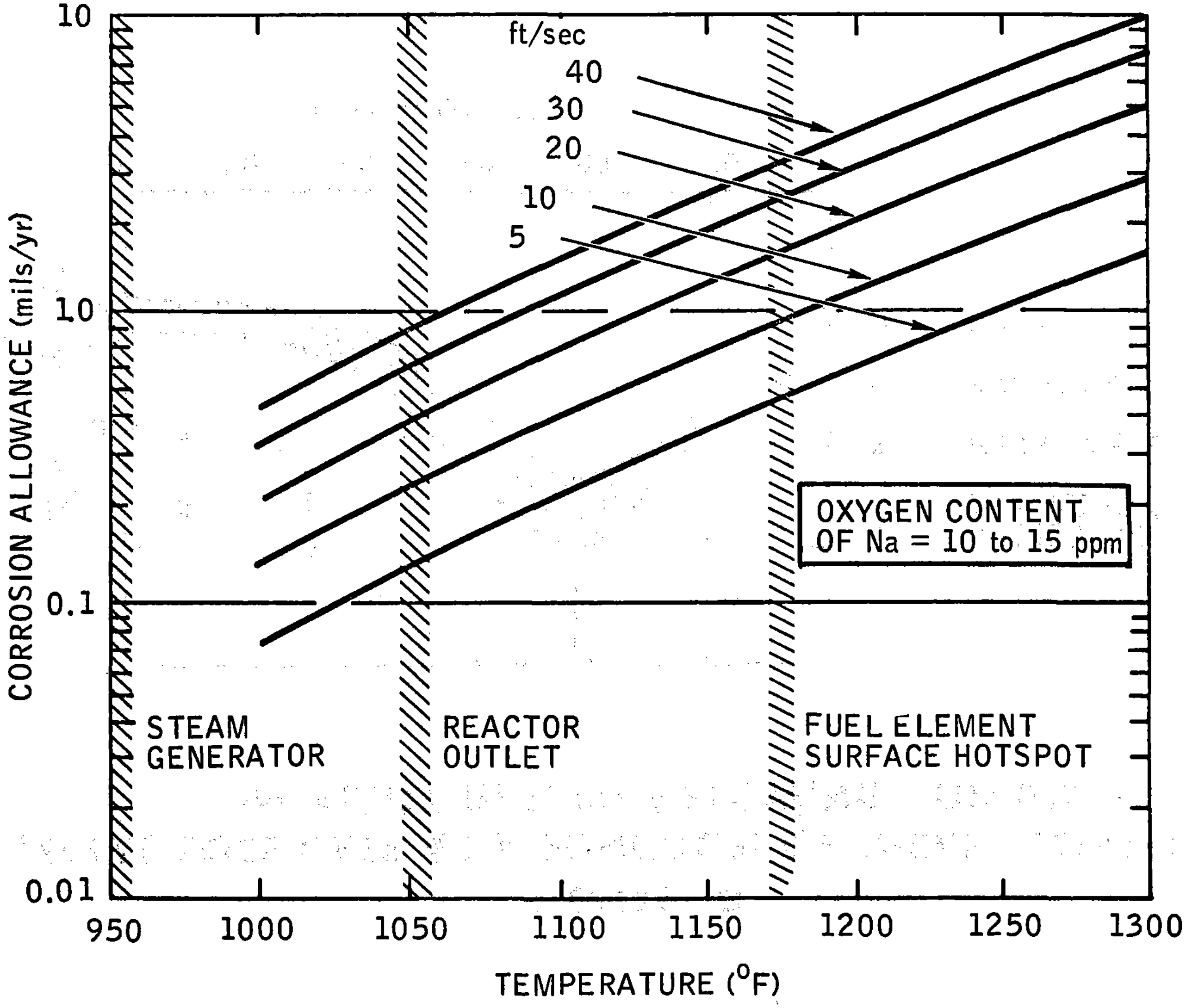
FERRITE LAYER FORMATION



7-016-251-10

FIGURE 9.

FBR SODIUM CORROSION ALLOWANCE FOR 300 SERIES STAINLESS STEEL AND LOW ALLOY FERRITIC STEELS



70-MA1-48-101

FIGURE 10.
METAL LOSS RATE AS A FUNCTION OF NICKEL CONTENT IN ALLOY IN 1200°F FLOWING SODIUM

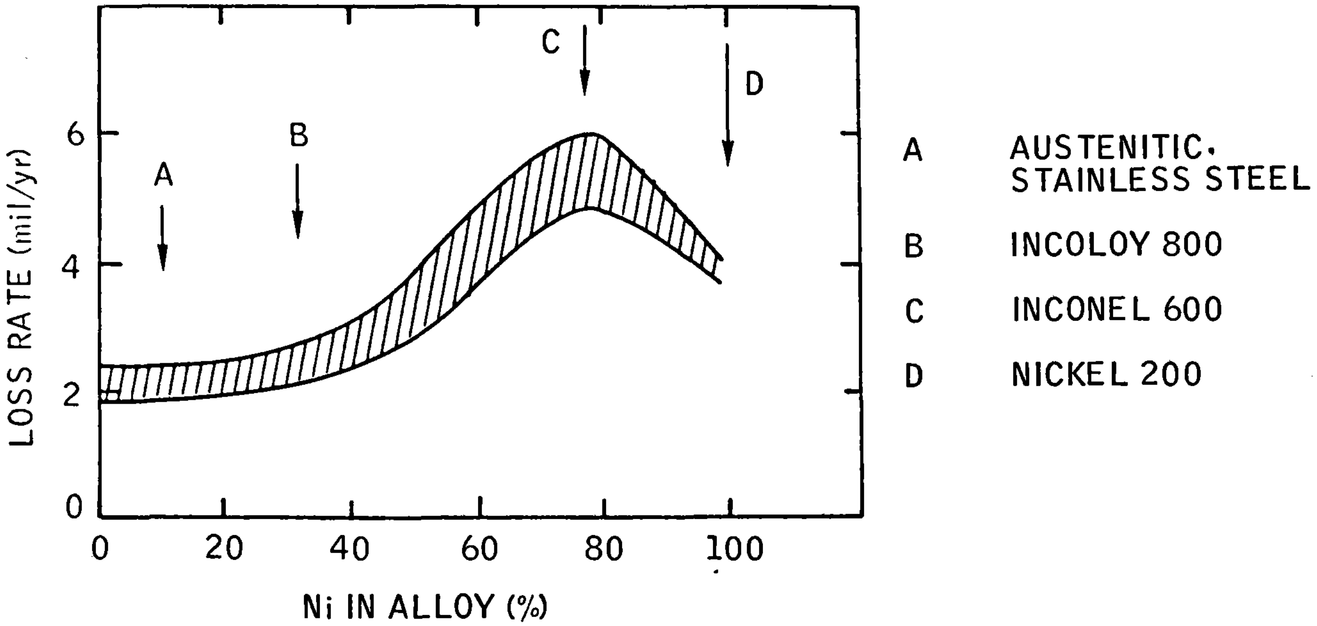
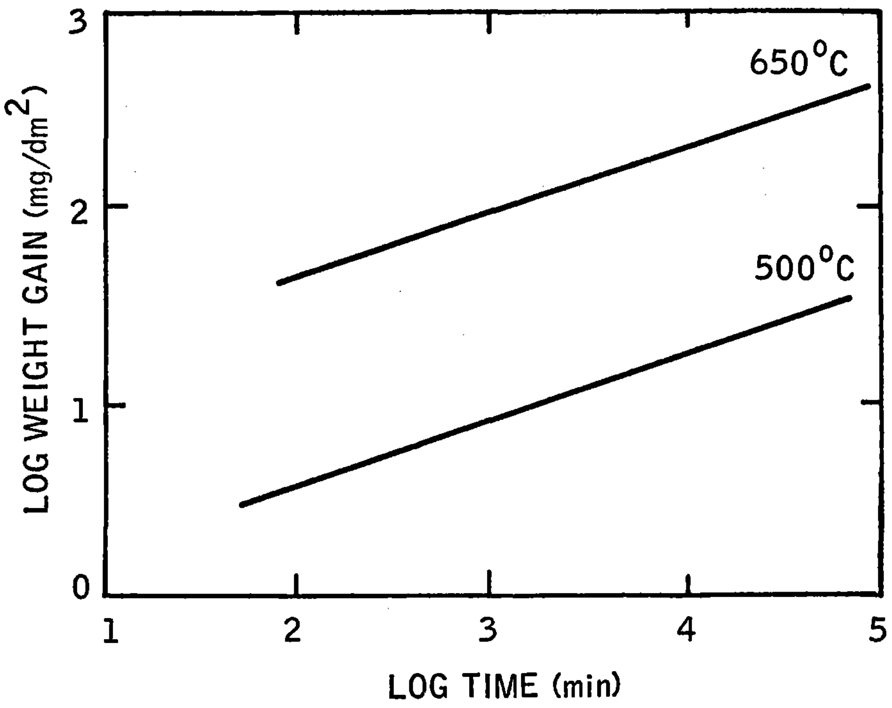
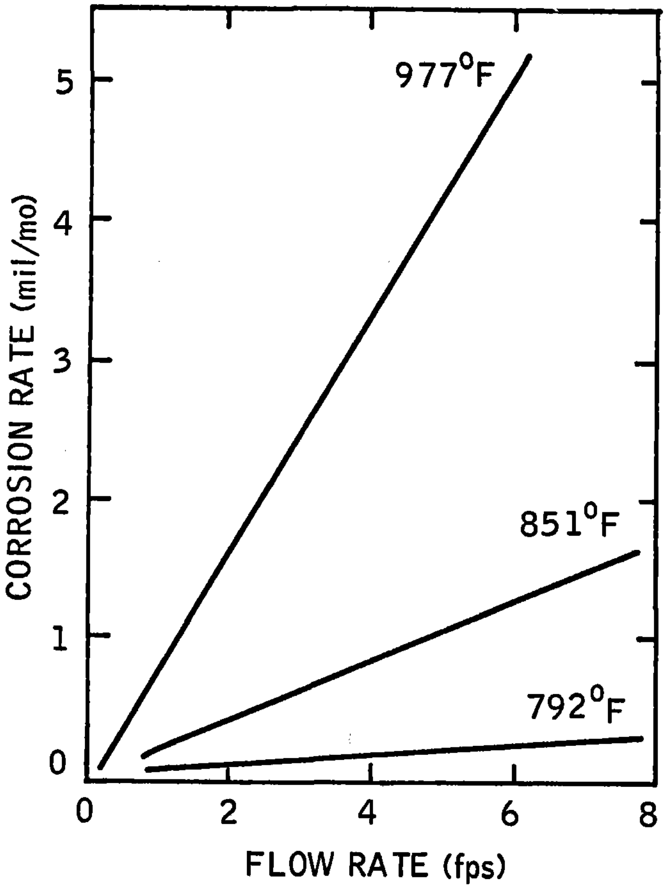


FIGURE 11.
CORROSION OF ARC-MELTED ZIRCONIUM IN COLD-TRAPPED SODIUM



70-MA1-48-103

FIGURE 12
BERYLLIUM CORROSION RATE vs NaK VELOCITY AND TEMPERATURE



70-MA1-48-104

FIGURE 13.

MAXIMUM PERMISSIBLE OXYGEN CONCENTRATIONS IN Ta AND Nb TO PREVENT PENETRATION BY ALKALI METALS AT 600°C

REFERENCE METAL	ALKALI METAL	O LIMIT (wppm)
Ta	Li	150
	Na	300
	K	500
Nb	Li	400
	Na	800
	K	1000

REFERENCE: KLUEH, PAPER 4, CORROSION BY LIQUID METALS II, AIME SYMP. ON LIQ. MET., PHILADELPHIA, PA. (OCT 13-15, 1969)

CORROSION OF VANADIUM ALLOYS

VERY SENSITIVE TO O_2 CONTENT

ABSORB CARBON FROM STAINLESS STEEL

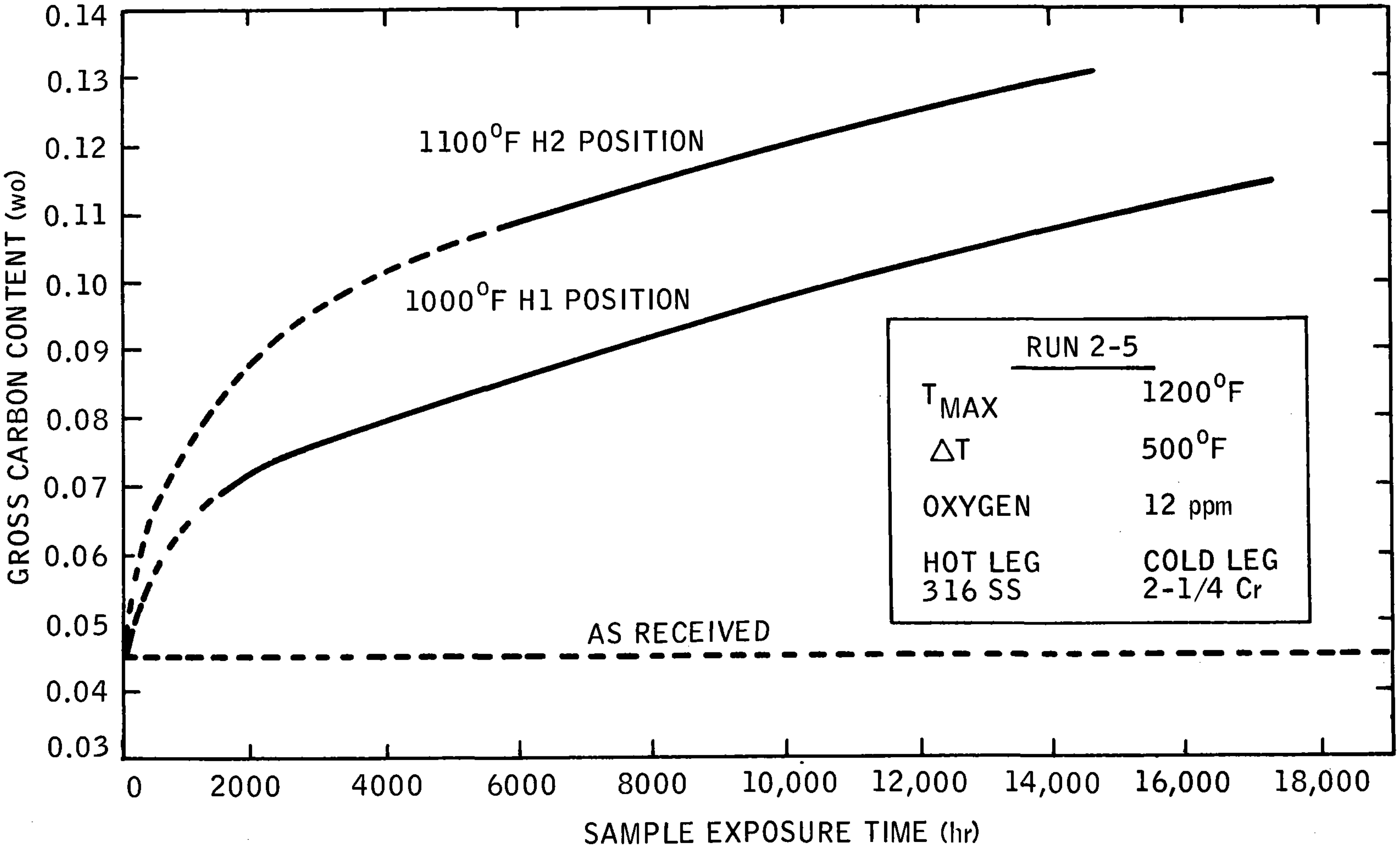
ABSORB NITROGEN FROM STAINLESS STEEL

PURE V SATURATES WITH O_2 AT 1.3% O_2 IN SODIUM CONTAINING > 1 ppm O_2

REFERENCE: WHITLOW et al, PAPER 1 AND SMITH AND KASSNER, PAPER 2, CORROSION BY LIQUID METALS II, AIME SYMP. ON LIQ. MET., PHILADELPHIA, PA. (OCT 13-16, 1969)

FIGURE 14.

EFFECT OF EXPOSURE TIME ON CARBURIZATION OF 316 SS HOT LEG SAMPLES*

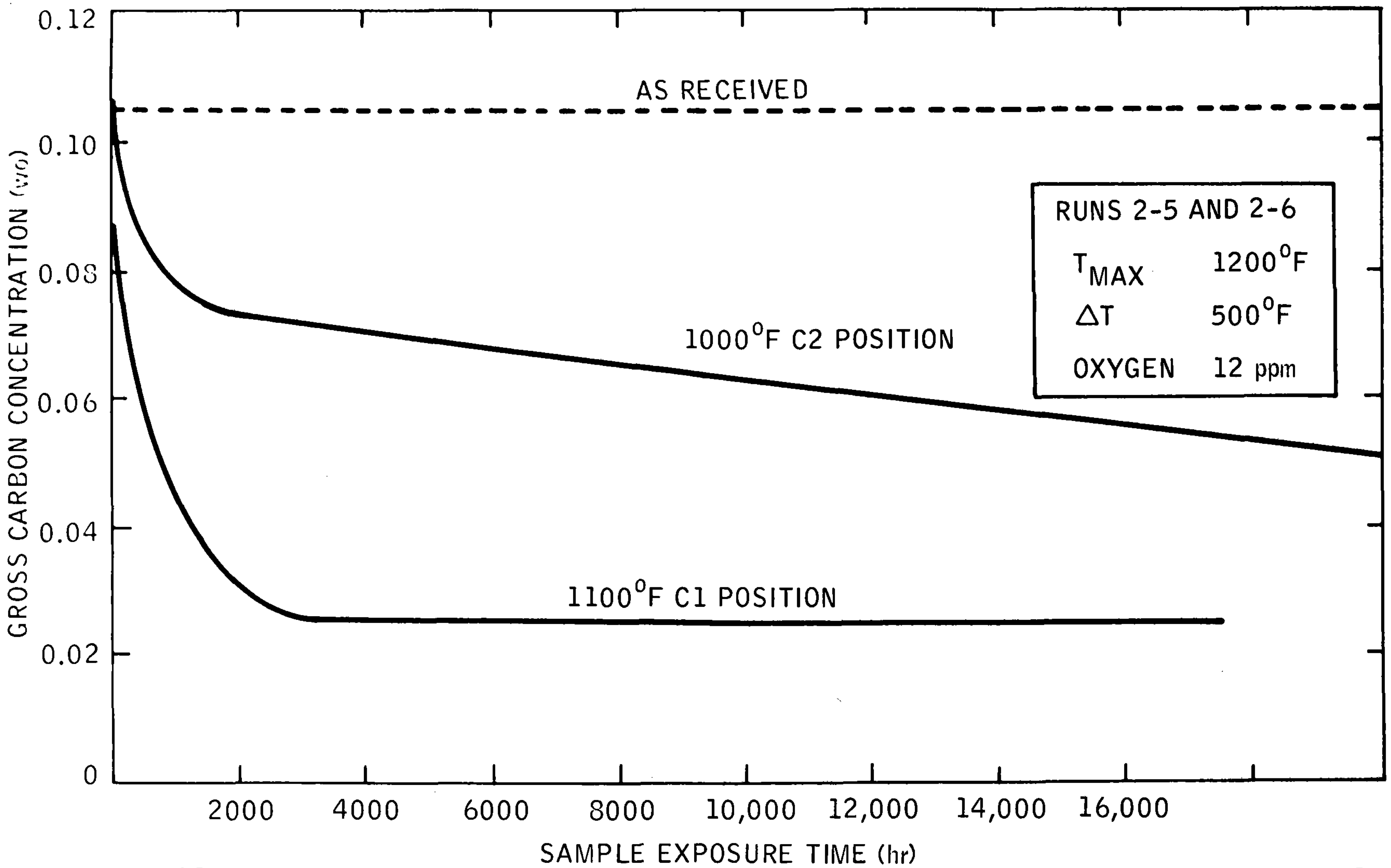


*GEAP-4831

8-J10-087-20

FIGURE 15.

EFFECT OF EXPOSURE TIME ON DECARBURIZATION OF 1¼ Cr*

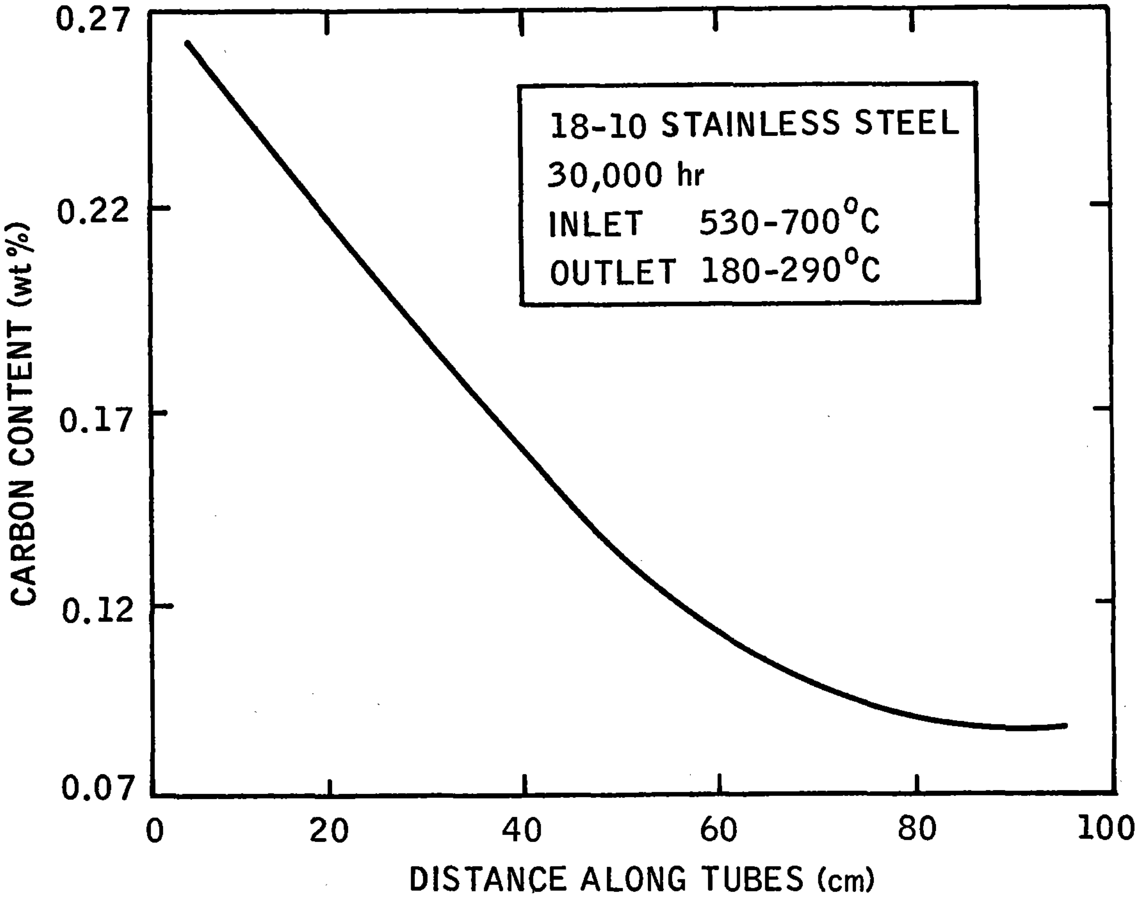


*GEAP-4831

8-J10-087-19

FIGURE 16.

CARBON DEPOSITION ALONG HEAT EXCHANGER TUBES



REFERENCE: BYKOV et al, JPRS 48330, p 426 (JULY 1, 1969)

FIGURE 17. NITRIDE CASE FORMATION WITH 304 STAINLESS STEEL IN 1000°F FLOWING SODUIM

TIME (hr)	CASE THICKNESS			
	IN Na AT SURFACE (mil)	IN Na 3 in. UNDER SURFACE (mil)	IN Na AT SURFACE (mil)	IN Na 3 in. ABOVE SURFACE (mil)
660	0.9	0.1	NONE	NONE
1140	1.5	0.1	0.1	0.1
1400	2.0	0.3	-	0.4

REFERENCE: GILL AND BOKROS, NAA-SR-6162 (1961)

70-MA1-40-108

FIGURE 18.
CORROSION PRODUCT TRANSPORT

● Cr	$M_{23}C_6$ $NaCrO_2$	M_7C_6	M_3C_2
● Ni	Ni		
● Fe	α Fe		

■ HIGH T DEP 1100°F	HIGH Cr, Ni LOW Fe
■ LOW T DEP 800°F	HIGH Fe

REFERENCE: ROY et al, PAPER 1, CORROSION BY LIQUID METALS I, AIME SYMP. ON LIQ. MET., PHILADELPHIA, PA. (OCT 13-16, 1969)

FISSION PRODUCT TRANSPORT
(1300°F, 35 ft/sec FLOW RATE, 10 ppm 0)

- RELEASE RATE
    - $^{54}\mathrm{Mn} > {}^{51}\mathrm{Cr} > {}^{60}\mathrm{Co}$
    - Mn   RAPID MIGRATION TO COLD TRAP
    - Cr   MIGRATION TO COLD LEG
    - Co   SLOW MIGRATION FROM HOT LEG
- DEPOSITION ENHANCED IN HIGH VELOCITY REGIONS

REFERENCE: BREHM et al, PAPER 7, CORROSION BY LIQ. MET. I, AIME SYMP. ON LIQ. MET., PHILDALPHIA, PA. (OCT 13-16, 1969)

FISSION PRODUCT TRANSPORT

- Cs DEPOSITION AND MOVEMENT
  - SENSITIVE TO SURFACE TEMPERATURE HISTORY
  - RAPID MOVEMENT
  - EQUILIBRIUM PROCESS
  - $K = \frac{\text{Gm Cs/cm}^2 \text{ ON WALL}}{\text{Gm Cs/cm}^3 \text{ IN SODIUM}} \cong 0.01$
- Ba DEPOSITION AND MOVEMENT
  - RAPID DEPOSITION
  - SLOW MOVEMENT

70-MA1-48-111

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SODIUM TECHNOLOGY COURSE, SESSION II
PURIFICATION AND INSTRUMENTATION
Dr. E. W. Murbach

A. INTRODUCTION

In this section, the purification, sampling and analysis of sodium will be discussed. Also, some of the analytical instrumentation used on sodium systems will be reviewed. In the previous section of this series, some of the chemical properties and reactions of sodium were presented. Some of these principles will be applied to the purification of sodium.

B. PURITY

On the subject of sodium purity, it is now possible to obtain sodium of 99.95% purity which means that there are 500 ppm total impurities. Of these 500 parts, the principal impurity is potassium, nominally about 200 ppm. However, potassium is chemically similar to sodium and in the application as a reactor coolant, the potassium presents no problems.

The impurities oxygen and carbon, are of particular interest in reactor coolant application. Oxygen is of imprtance because of its probable role in the corrosion and mass transfer of reactor material. Carbon is of particular importance because of its effect on the mechanical properties of materials. In any sodium system in which a carbon source and a carbon sink are present, carbon will transfer from the source to the sink. In particular, carbon can be added to or removed from the stainless steel used as fuel cladding which will embrittle or weaken the cladding, either of which is undesirable.

At one time nitrogen was considered to be a problem in sodium systems as the calcium impurity acted as a transfer agent to move nitrogen around the system. The addition of nitrogen to cladding materials is deleterious to their mechanical properties. Reactor grade sodium which is commercially available has a much lower calcium content that previously available, less than 10 ppm compared to 100 ppm or more. Hence, nitrogen is of little concern in reactor sodium systems.

After a system has been assembled, it is necessary to add the sodium inventory. Whether the system is a loop or a reactor, molten sodium should be loaded through a sintered metal filter of 5- to 10-μ pore size. For example, the sodium-graphite reactor at Hallam, Nebraska was loaded through such a filter. (Ten tank cars of sodium were used.) Very little extraneous material was found on the filter. However, the filter serves to remove any scale or particulate materials which might be in the drums or tank cars, or whatever containers were used in the transportation.

After the system is loaded, the sodium will pick up both particulate and chemical impurities. Oxide-bearing materials will react with the sodium to increase the oxygen content. Carbonaceous material such as residual pipe cutting oil will add carbon to the sodium. Scale particles and loose bits of welding material and metal turnings which might be inadvertently left in the system will add particulates. Whatever the source, it is desirable to remove these impurities prior to system operation.

Cleanup of sodium is accomplished by means of traps. Probably the most important trap is the cold trap. The first figure shows a small loop of about 200-gal capacity. The cold trap is equipped with external fins over which air is circulated to aid in cooling. Figure 2 illustrates the internal construction of a trap. The sodium enters the top, flows over the economizer section which partially cools the stream and then down the outer annulus which completes the cooling process. The cooled sodium now enters the central part of the trap which is usually packed with a high surface area material such as stainless steel mesh. Any oxide which precipitates as a result of the cooling process deposits in this packed section. Also, any particulates swept up by the flowing sodium will be removed by the trap.

Obviously it is not practical to circulate the entire flow of the primary pump circuit through such a trap. On a particularly large system, perhaps only 1% of the flow would be bypassed through the trap system so that many hours would be required to complete the primary impurity removal. However in 24 to 48 hr the bulk of the impurities will have been collected on the trap.

At a trapping temperature of 250°F, the solubility of oxygen in sodium is ~ 1 ppm. Thus, operating a cold trap at this temperature will lower the oxygen content of the sodium to <5 ppm. Obviously, if an in-leakage of air or oxygen should occur, the equilibrium concentration of oxygen in the system will be higher.

Other impurities besides oxygen can be removed by a cold trap. Hydrogen which could result from in-leakage and reaction of water can be effectively cold trapped. Carbonaceous material, cyanide and carbonate for example, have been identified in cold trap deposits.

Carbon content of a sodium system is generally controlled by means of a hot trap. In general, the hot trap is constructed quite like a cold trap except that the packed section contains metal foil. The principle of the carbon hot trap is that the carbon in the sodium is removed by chemical reaction with the metal foil. In practice, the trap is heated to 1200 to 1400°F. The most common foil used is Type 304 stainless steel. Reactor grade sodium contains ~30 ppm of carbon. A trap of this type will lower the carbon content to ~5 ppm, which is near the limits of the analytical procedures currently in use for determining carbon in sodium.

Hot traps have also been utilized for oxygen removal from sodium systems. In this case, the trap is packed with a reactive metal such as zirconium, titanium, uranium, etc. All these metals form oxides with a more negative free energy of formation than sodium oxide so are capable of removing oxygen from sodium down to a level of <1 ppm. In practice, it may prove difficult to maintain such a low level of oxygen.

Zirconium and zirconium-titanium alloy have been the principal metals used in oxygen hot traps. Uranium has been utilized in an analytical technique where it is allowed to react with oxygen in sodium and the amount of oxygen picked up determined by weighing. One of the advantages of zirconium is that the oxygen which reacts on the surface diffuses into the metal so that a protective oxide layer is not formed on the metal.

A potential problem with hot traps of this type is that the metals are strong carbide formers. If the trap is operated for extensive periods of time the level of carbon in the sodium could be lowered to the point where carbon in the stainless steel components would dissolve in the sodium and transfer to the hot trap. Thus, some of the reactor compoentns could become weakened.

Another purification technique which has never been investigated intensively is the use of "soluble getters." The theory is that an active metal which is soluble (or slightly so) in sodium would be added to the system, react with oxygen and be collected as metal oxide in the cold trap. Potential additives are lithium, calcium, barium, strontium, and perhaps magnesium. Again the free energy of formation of the oxides of these metals are more negative than that of sodium. One of the earlier sodium systems to be operated was the submarine intermediate reactor (SIR) coolant system. At that time, the commercial sodium which was available contained calcium impurity at about 100 parts per million. However, after operation of the coolant system for a short time, the calcium content decreased to less than 10 parts per million. It can be surmised that the calcium reacted with oxygen in the sodium and the resulting calcium oxide was collected in the cold trap.

Another purification method which has been investigated briefly is centrifugation. The idea is to pass sodium through a centrifuge in order to remove any particulate or suspended materials. Atomic Power Development Associates (APDA) in Detroit have tested a small centrifuge in their sodium technology loop. Some information has been published in their quarterly progress reports. After one 100-hour run, increased concentrations of carbon, iron, chromium and nickel were found in the centrifuge bowl. APDA will publish a topical report summarizing the results of their studies with the centrifuge.

Sodium can also be purified by the simple technique of holding it just above the melting point. The oxide content of the liquid can be lowered to about one part per million by this method.

If sodium of even higher purity is desired than that obtainable by methods mentioned previously, the sodium can be distilled. Atomics International investigators distilled sodium in a packed column yielding a product which was of higher purity than the sodium chloride standard used in the spectrographic laboratory. Obviously this would not be practical for reactor coolant sodium.

C. SAMPLING

Following the loading and preliminary cleanup of a sodium system, it is necessary to sample the sodium in order to determine the effectiveness of the cleanup process. Sampling is a crucial phase of the sodium business. The problem in taking a sodium sample is to sample without introducing impurities. All the analyst can report is his findings. If the sodium has been contaminated during sampling, the analysis will reflect this contamination. In particular, the atmospheric contaminants, oxygen, water vapor and carbon dioxide can enter through a leaky sampler, or by use of improper sampling technique.

There are several methods for taking sodium samples, such as dip sampling through a port, withdrawing sodium into an evacuated container or circulating through a removable section of tubing. This latter method which utilizes the flow-through sampler is perhaps the better of these three.

A flow-through sample tube is shown in Figure 3. It is a length of metal tubing with compression type fittings installed. The tube is connected to a sample station on the sodium system, and is evacuated and heated by a length of trace heater. The fittings must be vacuum tight! Once it is determined that the sampler is leak-tight, sodium is circulated through the sampler for a minimum of 1 hr but preferably for 4 hr. It appears that the sodium flowing through the tube will effectively remove any oxide film on the inside surface of the tube. Also, this circulation period cleans the sample station connections which are exposed to the atmosphere during the removal of the sampler. The APDA sodium technology loop has an inert atmosphere box around the sample station which eliminates this latter problem.

Also shown in Figure 3 is a device used in sampling static retorts. The sampler is assembled and leak checked on a helium mass spectrometer leak checker. The sampler is connected to the sample valve on the retort, evacuated, heated and back-flushed with helium to outgas the internal surfaces. The sampler is re-evacuated, the vacuum valve closed and, the sample valve on the retort opened to allow sodium to be drawn into the sampler.

Mine Safety Research (MSAR) sampled a sodium loop by means of a dip sampler. The sampling assembly was connected to the sampling valve on the loop, evacuated, and then filled with inert gas. The sampling valve was opened and the sampling cup lowered into the sodium with a rod operating through a shaft seal. The sample was then withdrawn from the loop and protected from the atmosphere by a valve on the sampling assembly.

D. CHEMICAL ANALYSIS

Following the sampling procedure, the next step is to obtain a chemical analysis for the impurities. The analysis of impurities in sodium has received considerable attention in recent years so that procedures and techniques have seen considerable improvement. One of the major improvements is the use of the inert atmosphere glove box for the determination of oxygen in sodium. The most common procedure for oxygen determination is the mercury amalgamation method. Prior to the use of the glove box, the lower limit for this procedure was about 50 ppm. Now the lower limit is perhaps 5 ppm.

To perform this analysis, the sodium sample is added to mercury in a separatory funnel. After the sodium dissolves, the bulk of the amalgam is drained from the vessel and fresh mercury added. By repeating this extraction several times, the amount of sodium remaining in the mercury is reduced to well below 1 ppm. For example, if 1 cc of amalgam is left in the vessel and 25 cc of fresh mercury used for each extraction, it is obvious that the residual sodium is vanishingly small. However, the oxygen content of the sodium remains as sodium oxide which floats on the mercury. Therefore the mercury from the last extraction is treated with water to dissolve the oxide. The sodium content is then measured on the flame spectrophotometer, or by titration with dilute acid.

Unfortunately, there are some blanks associated with this procedure. The extraction vessel contributes ~5-ppm equivalent oxygen to the final result. This value has been determined by adding oxygen free amalgam to an extraction vessel and running through the regular procedure. The final oxygen result is that contributed by the extraction vessel.

The sample tubing also contributes to the oxygen blank. The flow-through sampler contributes ~2 ppm and the retort sampler contributes about 7 ppm. Thus, there is a total blank of 7 to 12 ppm in the oxygen analysis procedure. However, a skilled analyst can determine oxygen in sodium readily at the 5-ppm level. As an example, some high purity sodium prepared by distillation analyzed 1 to 2 ppm of oxygen.

Another procedure for oxygen in sodium is the vacuum distillation method. In this method a sample of sodium is distilled in vacuum at ~400°C after which sodium oxide residue is determined. Bergstresser and co-workers at Los Alamos have studied this method. They were able to analyze for oxygen in sodium down to ~1 ppm. Rutkauskas utilized this procedure in his work on the determination of the solubility of oxygen in sodium.

Argonne National Laboratory personnel at EBR-II are working on an in-line vacuum distillation unit for the primary sodium system. One obvious advantage of this method is that the sampling and analytical blanks should be sharply reduced. Another advantage is that larger sodium samples can be used. In the mercury amalgmation method about 5 gm is the maximum sample size which can

can be used. In the vacuum distillation method a sample of 25 gm or larger can be used which should improve both the precision and accuracy of the method. Vacuum distillation for oxygen in sodium may be the procedure that is finally adopted for reactor application.

Activation analysis methods have been investigated briefly for oxygen in sodium. Bombarding a sodium sample with fast neutrons produces activity by the reaction

$$^{16}O(n, p)\ ^{16}N\ .$$

The nitrogen product has a 7-sec half-life and decays by emission of high energy γ-rays. However, other interfering activities limit this method to ~50 ppm oxygen. A second reaction is

$$^{16}O(\gamma, n)\ ^{15}O\ .$$

The sodium sample is bombarded with high energy gamma rays. The resulting oxygen-15 product is a positron emitter of ~2 min half-life. Lutz at the Bureau of Standards has determined oxygen at <10 parts per million by this technique. This method probably will not find wide application.

ANL personnel are investigating a proton activation method for determining impurities in sodium. The reactions of interest are:

$$^{18}O(p, n)\ ^{18}F\ ,$$

$$^{13}C(p, n)\ ^{13}N\ ,$$

$$^{14}N(p, \alpha)\ ^{11}C\ .$$

It would appear that considerable development work is required since all the resulting activities are positron emitters.

The next impurity of particular interest is carbon. Carbon gives problems in analysis as well as being troublesome in a reactor. Most of the laboratories in the country determine carbon by a combustion procedure. The sodium sample

sample is oxidized in a stream of helium and oxygen in the presence of silica. Carbon dioxide is formed by the reaction

$$2Na + C + SiO_2 + 1.5O_2 \rightarrow Na_2SiO_3 + CO_2 \ .$$

The silica acts as a high temperature acid to release carbon dioxide. The CO_2 is trapped at liquid nitrogen temperature and then determined on a gas chromatograph.

At Atomics International, a section of the sample tube is removed from the tube with a tubing cutter, loaded in a combustion chamber with silica wool and heated at 1100°C. The lower limit for this procedure appears to be 5 ppm.

At the EBR-II site the "oxyacidic flux" procedure is used in which a chromate salt acts as the high temperature acid. They report carbon values between 1 and 2 ppm for the primary sodium. Thus, this procedure may be an improvement as lower values can be determined.

The hydrogen content of sodium is of interest, particularly in reactor operation. Hydrogen in sodium has an adverse effect on plugging meters (to be discussed later). Also, the early detection of a water leak hopefully will be based on rapid detection of hydrogen.

Sodium samples are analyzed for hydrogen by vacuum extraction at Atomics International. The sodium sample is loaded into a stainless steel container covered by an iron membrane. The container is heated to 700°C in vacuum. Hydrogen diffuses through the membrane and is measured by means of a manometer. This procedure is useful at the 1-ppm level.

APDA has developed an interesting method for determining hydrogen. The sodium sample is dropped into mercury in a closed system. The amalgam is refluxed at a few hundred degrees. Any hydrogen compounds are decomposed so that hydrogen collects in the gas space. The gas space is sampled with a syringe and the sample is then injected into a gas chromatograph and the hydrogen is determined. This method also will determine hydrogen at the 1-ppm level.

Nitrogen in sodium can be determined by reacting the sample with water, distilling the ammonia formed from the nitrogen and determining the ammonia by titration. Nitrogen is usually not considered to be a problem, however, with special alloys such as niobium base alloys it is possible to nitride the alloy. In these systems, nitrogen would be of interest.

Metallic impurities in sodium can be determined in several ways. The most common method is to convert the sodium sample to sodium chloride and run the sample on the emission spectrograph. The sensitivity varies widely for different elements and the precision is rather poor.

If higher precision is desired, individual metal impurities can be determined by atomic adsorption spectroscopy. A lamp for each element of interest must be used. At Atomics International, iron, chromium, nickel, cobalt and manganese have been run on 1-gram sodium samples.

Various "wet" methods can also be utilized to determine specific elements as desired.

E. SODIUM SPECIFICATIONS

As previously pointed out, the principal impurities of interest in fast reactor application are oxygen and carbon. In the earlier days when sodium cooled thermal reactors were being developed, limits were set on elements with high thermal neutron capture cross sections. However, in the fast reactor these specifications are no longer of great importance.

When the fast reactor cladding program was started at Atomics International a set of specifications for the impurity content in sodium was chosen. The specification is shown in Table 1. Most of the choices were empirical and were based on what was considered reasonable for the state-of-the-art. The original limits for carbon and oxygen were 15 and 10 ± 5 ppm. As the program progressed it became obvious that it was possible to operate the loops and retorts below these impurity levels.

F. INSTRUMENTATION

The instrumentation to be discussed in this section is primarily analytical in nature. However, one important instrument which by itself is not an analytical tool is the electromagnetic flowmeter. The flowmeter consists of a permanent magnet mounted across a pipe with voltage probes tack-welded to the pipe perpendicular to the poles of the magnet. The flowing sodium induces a small voltage which varies with the flow rate. The device is illustrated in Figure 4. The flowmeter is useful to show flow through sample stations or when loading retorts.

TABLE 1

SYSTEM QUALITY SODIUM SPECIFICATIONS

Element	Ref. 500°F System (ppm)	Ref. 1200°F System (ppm)
B	<1	<1
C*	<15	<15
Ca	<10	<10
Cd	<3	<3
Cl (halogens)	<20	<20
Co	<1	<3
Cr	<5	<20
Fe	<25	<50
K	<200	<200
Li	<5	<5
Mn	<5	<5
Ni	<10	<25
O*	10 ± 5	10 ± 5
Pb	<10	<10
Rb	<50	<50
Sn	<10	<10
H	<10	<10
N	<5	<5

*Controlled values.

From the analytical standpoint, the flowmeter forms a part of a very useful device, the so-called plugging meter. The plugging meter consists of a small orifice or a valve with a notched plug preceded by a section of piping provided with cooling. Generally a finned section of pipe is used and air is blown over the fins. An immersion thermocouple is positioned at the outlet of the plugging orifice.

To operate the plugging meter, the insulation is removed from the finned section and cooling initiated. Both the flow and temperature at the orifice plate are continuously recorded. When an impurity begins to precipitate in the orifice, an immediate decrease in flow is noted. Usually the decrease in flow is due to the precipitation of sodium oxide so the plugging meter is a type of an oxygen meter. However, hydrogen in sodium will also cause plugging.

In actual practice, the plugging meter just described does not measure the saturation temperature of the system with respect to oxygen. For example, assume the oxygen content of the system is ~13 ppm which is equivalent to a saturation temperature of 400°F. The observed plugging temperature may be 325°F which is equivalent to 4.5-ppm oxygen. The actual plugging temperature is somewhat dependent on the cooling rate. It is possible to calibrate a plugging meter by sampling the system and determining the oxygen level at the observed plugging temperature. However it is essential to use the same cooling rate for each run.

An improvement on the plugging meter is the oscillating plugging meter. McPheeters at Los Alamos was one of the first investigators in the United States to study this device. Actually, the oscillating plugging meter is an ordinary plugging meter, but the mode of operation is based on decreasing and increasing the temperature at the orifice. In practice a plugging run is initiated in the usual manner. At the point at which the flow decreases, cooling is stopped. Either the finned section can be heated or the hotter sodium will warm the orifice. In either case, the temperature begins to increase. When flow begins to increase, cooling is again applied, etc; thus, the term oscillating. The resulting information is shown in Figure 5, which is McPheeter's work. In this figure, it can be seen that two temperatures exist at which oxide is neither precipitating nor dissolving. These temperatures are 216 and 218°C. Assuming the true saturation temperature is 217°C, the sodium contained ~17 ppm oxygen

This method has been rather crudely tested at Atomics International by manual operation of the blower and heaters on a plugging meter. It appears that the higher the oxygen content, the more nearly the two temperatures coincide.

The British have developed a device which they call the continuous plugging meter. This device is shown in Figure 6. The principle is quite similar to the oscillating plugging meter. The principal difference is that some sodium always bypasses the orifice plate. The orifices consist of notches cut in the perimeter of the orifice plate. The bypass flow is through the center of the orifice plate. The pipe ahead of the orifice is finned and surrounded with a jacket for the cooling air.

In operation the flows through the orifices and the bypass are adjusted to be equal by means of the throttling valve in the bypass leg. Cooling is then initiated. At the first decrease in flow, the cooling air flow is decreased by a control valve activated by the flow meter circuit. The result is that the device operates with a partially plugged orifice at practically constant sodium temperature. It was reported that this instrument operated as low as 125°C which corresponds to 1 to 2 ppm of oxygen.

The next instrument to be discussed is the electrochemical oxygen meter. This instrument was developed by United Nuclear Corporation under contract to the AEC. The electrochemical cell is shown in Figure 7. The heart of the device is the probe which consists of a solid electrolyte composed of thoria - 15 wt % yttria, a copper-copper oxide half cell (or reference electrode) inside the probe and the electrical lead. The housing is installed at an appropriate point on the sodium system and the probe then installed in the housing. The other half cell is sodium-sodium oxide so that the overall cell reaction is

$$2Na + Cu_2O \rightarrow Na_2O + Cu \quad .$$

The theoretical voltage of the cell is $\sim$1 volt. The 15 wt % yttria in the electrolyte produces oxygen vacancies in the thoria lattice so that oxygen can be transported electrolytically. The indicating device is a high impedance electrometer so that no appreciable current flows. Thus, the actual transport of oxygen through the cell is negligible.

A number of these cells have been tested at various installations. Figure 8 shows some results obtained with one electrode at Atomics International. When the cell is initially placed in operation, a few days are required for stabilization. When the sodium system was operated at essentially constant conditions the electromotive force (emf) of the electrode was fairly constant. Also, in the one experiment where oxygen was added to the system, a sharp decrease in voltage resulted.

The electrode is sensitive to temperature, both to sodium temperature and to the temperature in the vicinity of the housing. Therefore it is necessary to control these temperatures or to obtain data on the effect of temperature on the electrode.

The operating temperature limit for the electrode is ~600°F. Thus, a cooler-heat exchanger is required when the electrode is used with high temperature systems.

Two electrodes installed in the same system give different emf readings so that each electrode requires a separate calibration curve.

To date, the meter has not been tested in an operating reactor. There have been a few preliminary tests of the effect of radiation on the cell but the results are not conclusive. It is planned to install one of the meters in the primary sodium system at EBR-II. This test should determine the utility of the device.

Figure 9 shows some calibration data for a meter at Atomics International. Oxygen was added to the system, samples were taken, and the plugging meter was then operated in the oscillating mode. The analytical results and the plugging meter results are shown on the figure. During normal operation with the cold trap operating at 250°F, the meter read 1.172 volts. It was assumed this reading is equivalent to 1-ppm oxygen in order to complete the calibration curve.

Workers at Brookhaven National Laboratory have studied some modifications of the meter. In one, they used a sodium-sodium oxide reference electrode. One of the advantages of this cell is less sensitivity to ambient temperature.

Carbon meters are being developed at both UNC and BNL. UNC now manufactures a commercial device which is shown in Figure 10. The device is constructed so that part of the flow is bypassed through the carbon cell. A cartridge heater heats the sodium to 1400°F, which is the operating temperature of the cell. The cell is a thin iron membrane through which carbon diffuses. A stream of argon with a little water vapor and hydrogen passes over the iron membrane and reacts with carbon on the surface of the iron. This maintains a constant flux of carbon through the membrane. The carbon monoxide which is formed in the gas stream is subsequently converted to methane and determined on a flame ionization detector. The amount of methane is a function of the amount of carbon in the sodium. The function remains to be determined. There are a number of charts showing the carbon meter behavior in MSAR quarterly progress reports. Their work does show that the meter responds to changes in carbon, however the results are erratic.

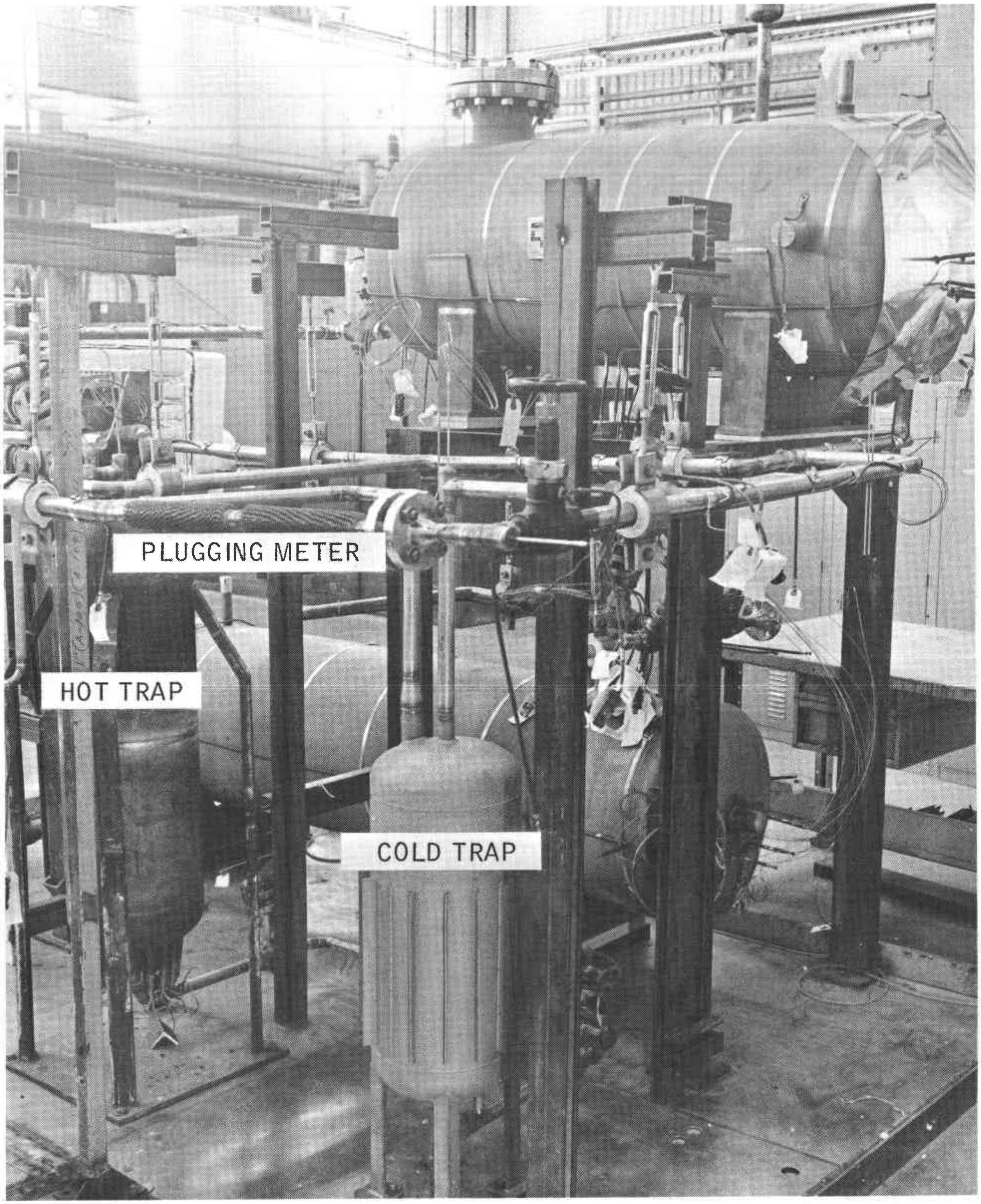
The BNL meter is an electrochemical device. They have developed two systems. In one, the electrolyte is calcium carbide dissolved in lithium chloride and in the other, the electrolyte is a mixture of sodium and potassium carbonates. The electrolyte is contained in an iron cup which dips into the sodium. The amount of carbon picked up by the iron is a function of the carbon in the sodium. The emf developed by the cell is a function of the amount of carbon in the iron. This work is reported in recent BNL quarterly progress reports.

There is also some development effort on an in-line hydrogen meter. UNC is working on an electrochemical hydrogen meter, however, little information is available. APDA has been developing a diffusion type hydrogen meter; the active element is a nickel tube lined with palladium. As the sodium stream passes over the inside of the tube where the hydrogen is converted to water vapor, the water vapor content of the gas stream is determined on a gas chromatograph. The device has been tested in the laboratory, however there appears to be a problem with the palladium becoming poisoned so that the flux of hydrogen decreases with time.

G. SUMMARY

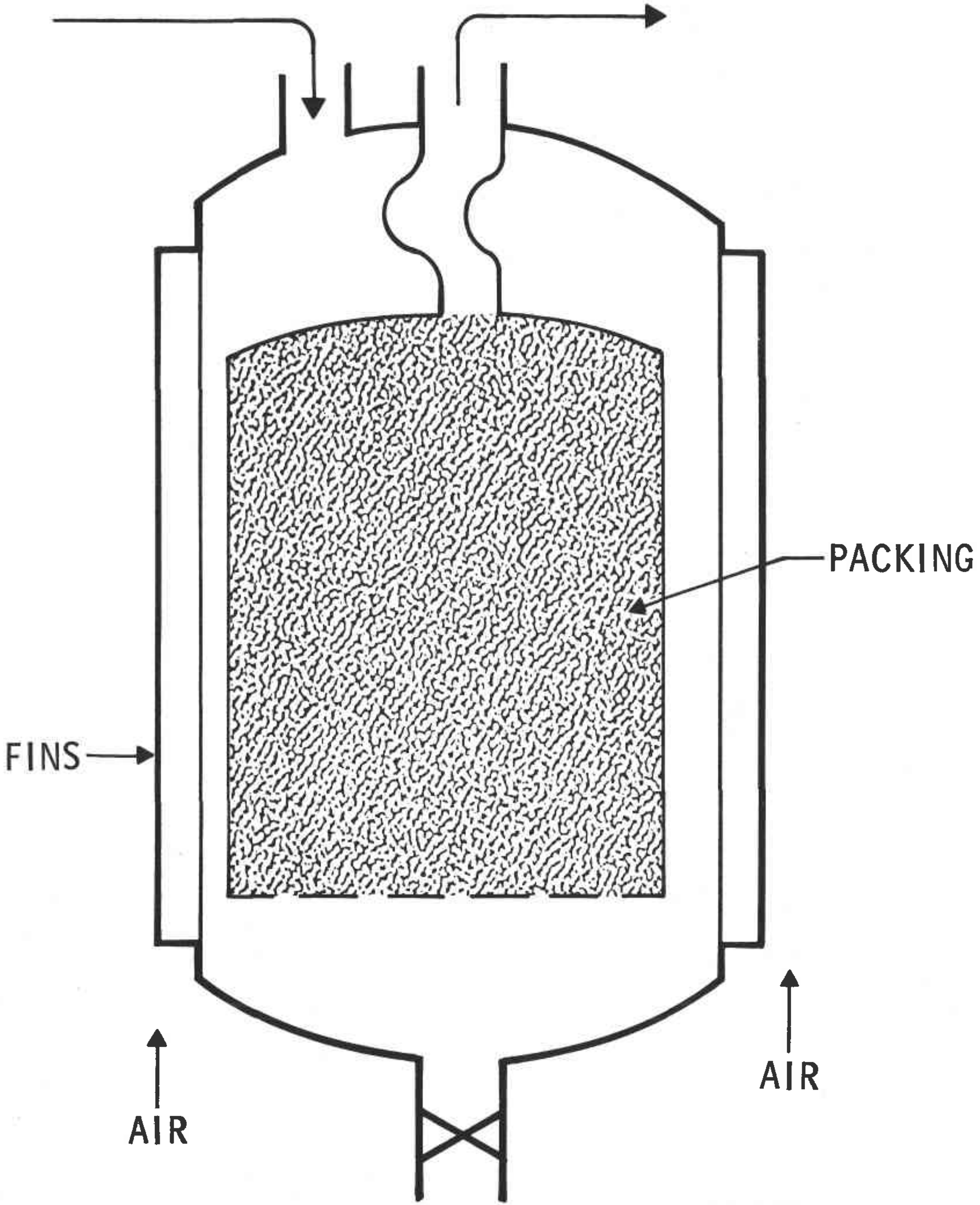
To summarize this section, the most important impurity elements in sodium are carbon and oxygen. However, the concentration of these elements can be controlled by means of traps. The analysis of sodium for impurities has improved considerably in the past few years, and should continue to improve. Instrumentation is being developed and the next few years should result in more developments. The electrochemical oxygen meter is ready for reactor testing now and a carbon meter should be ready for reactor testing in the near future.

FIGURE 1. SODIUM SUPPLY LOOP



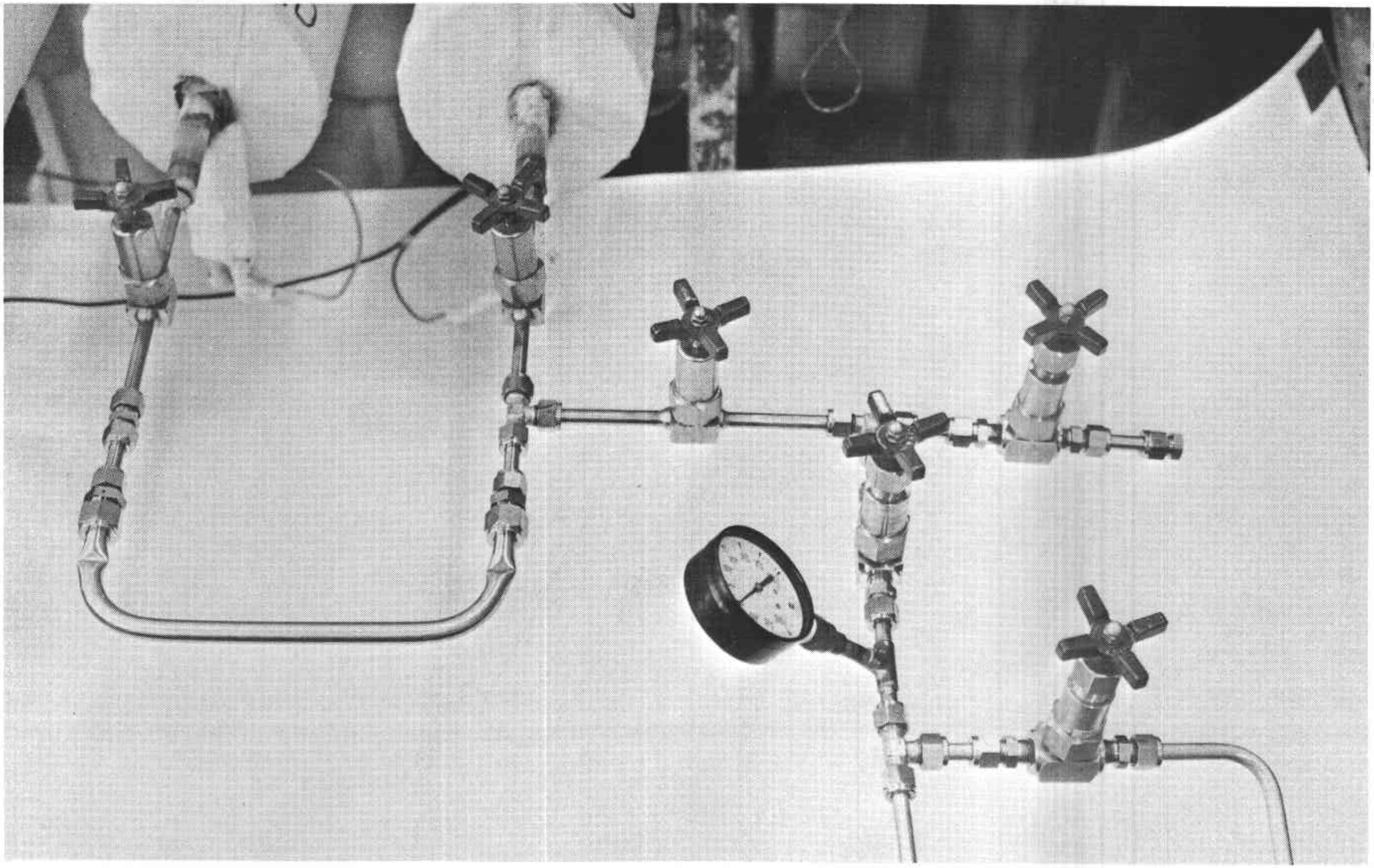
70-MA1-48-169

FIGURE 2. SCHEMATIC OF TRAP



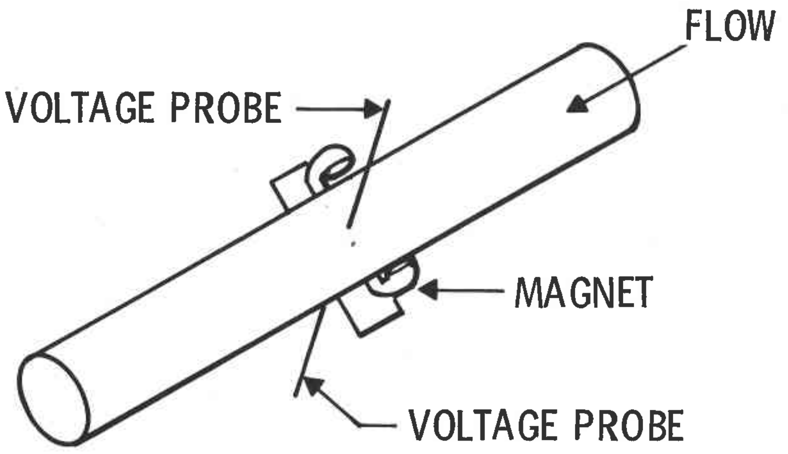
70-MA1-48-170

FIGURE 3. SODIUM SAMPLERS



70-MA1-48-17

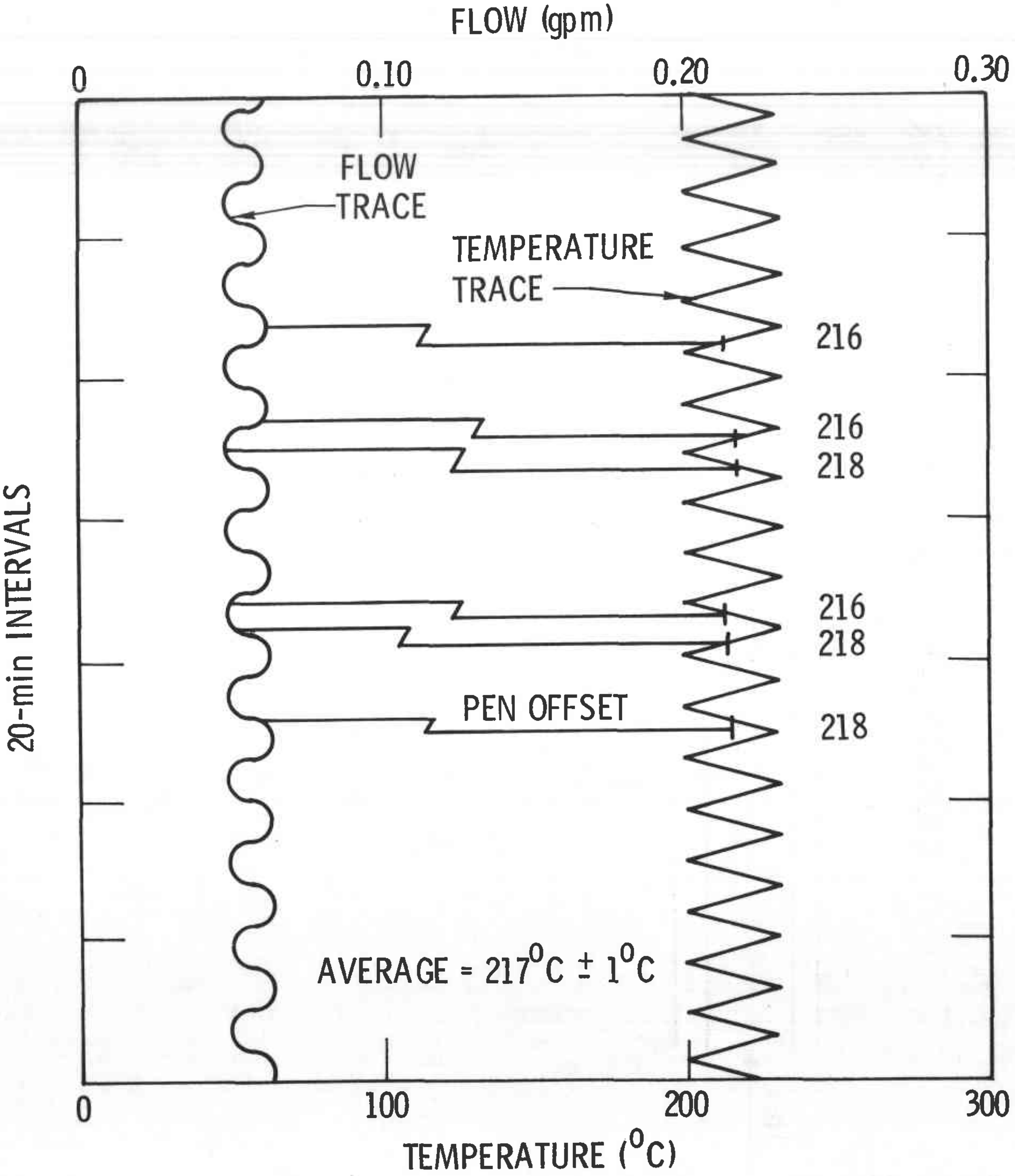
FIGURE 4. EM FLOWMETER



70-MA1-48-172

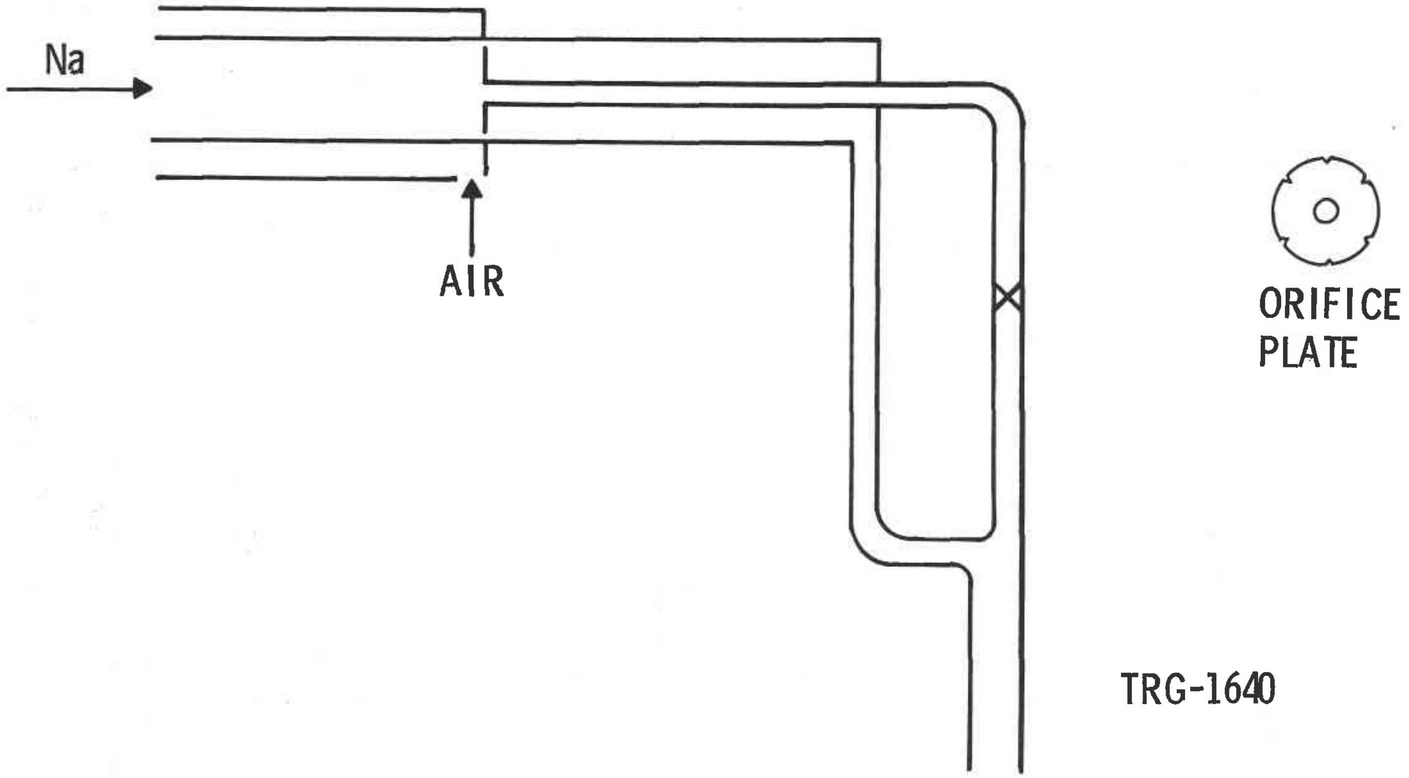
FIGURE 5. SECTION OF CHART READING

(OSCILLATING PLUGGING METER)



70-MA1-48-175

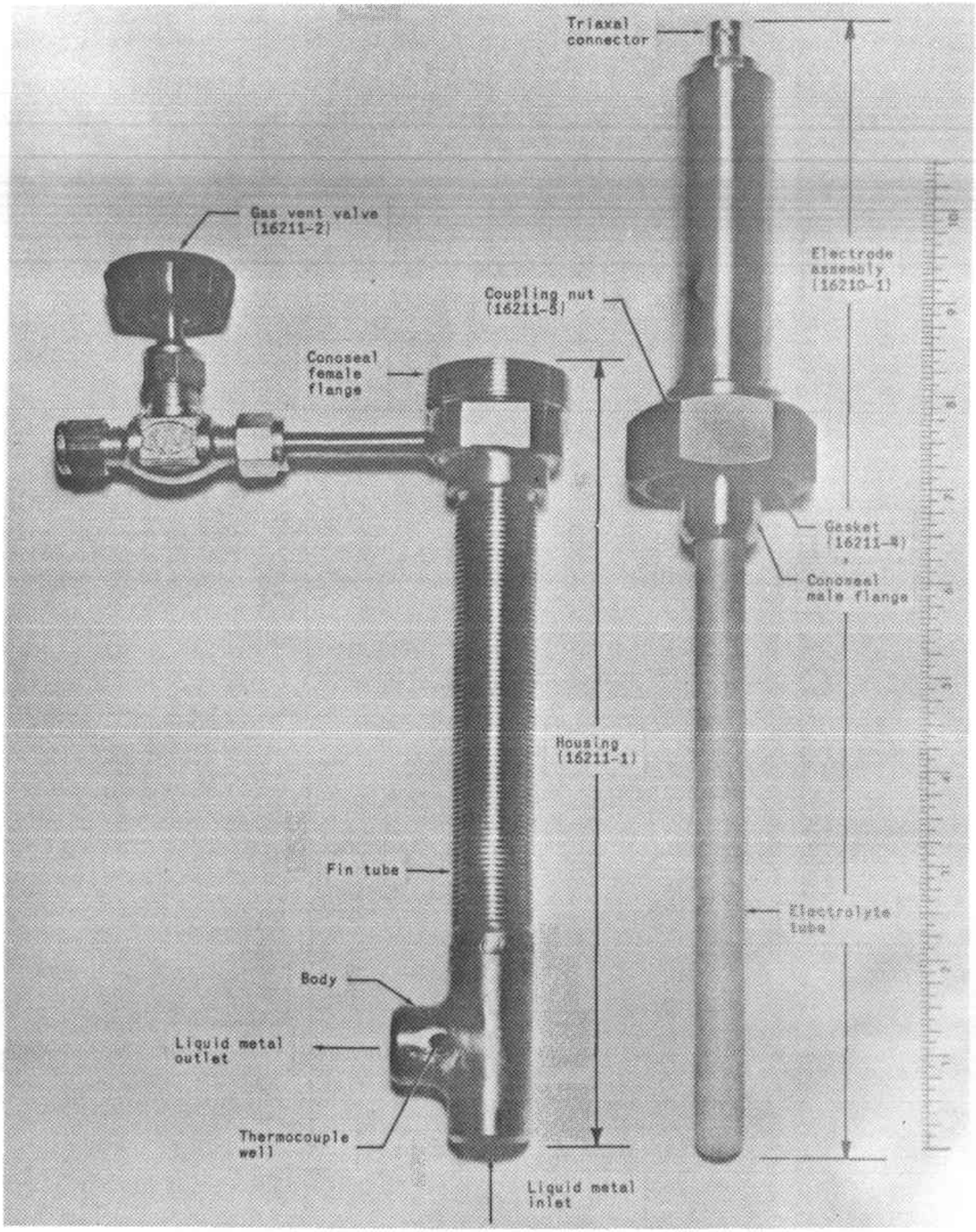
FIGURE 6.
CONTINUOUS PLUGGING METER



TRG-1640

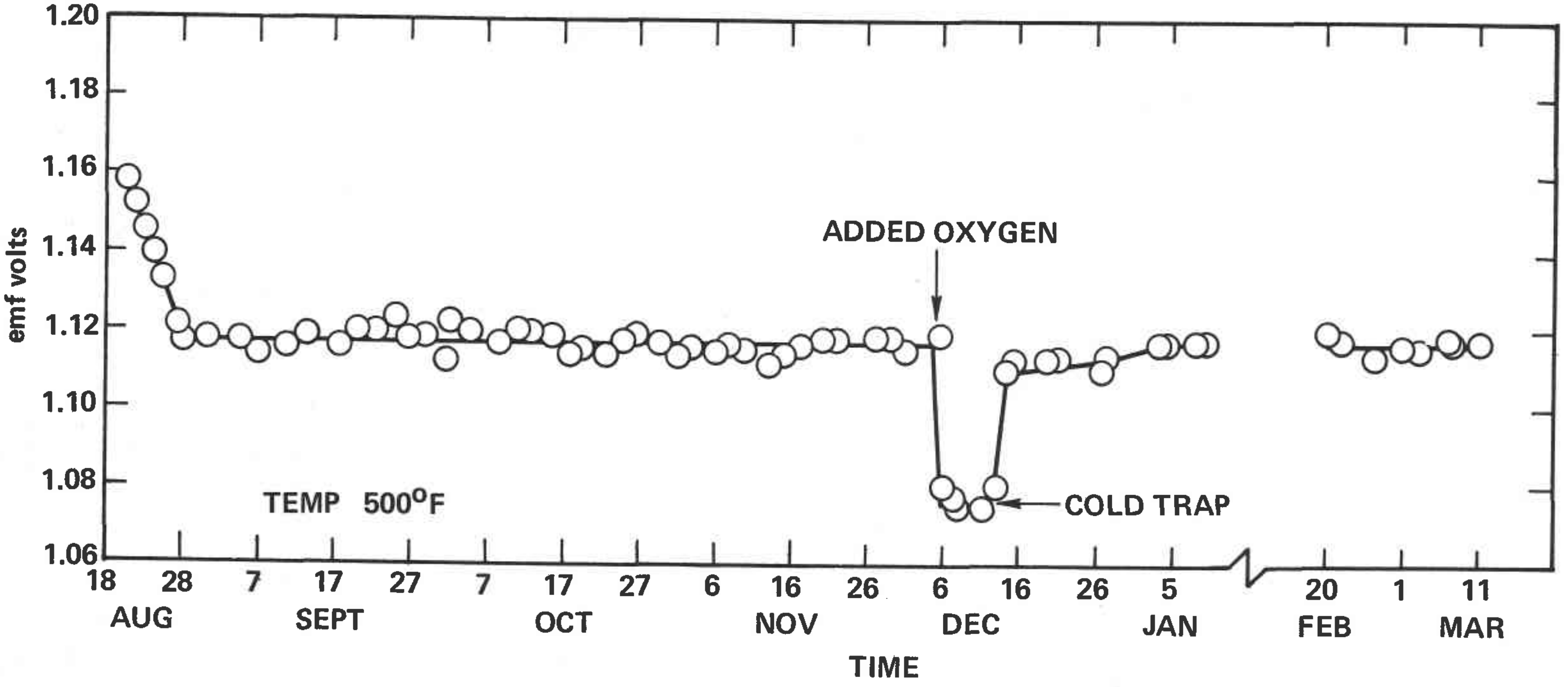
70-MA1-48-173

FIGURE 7. SENSOR



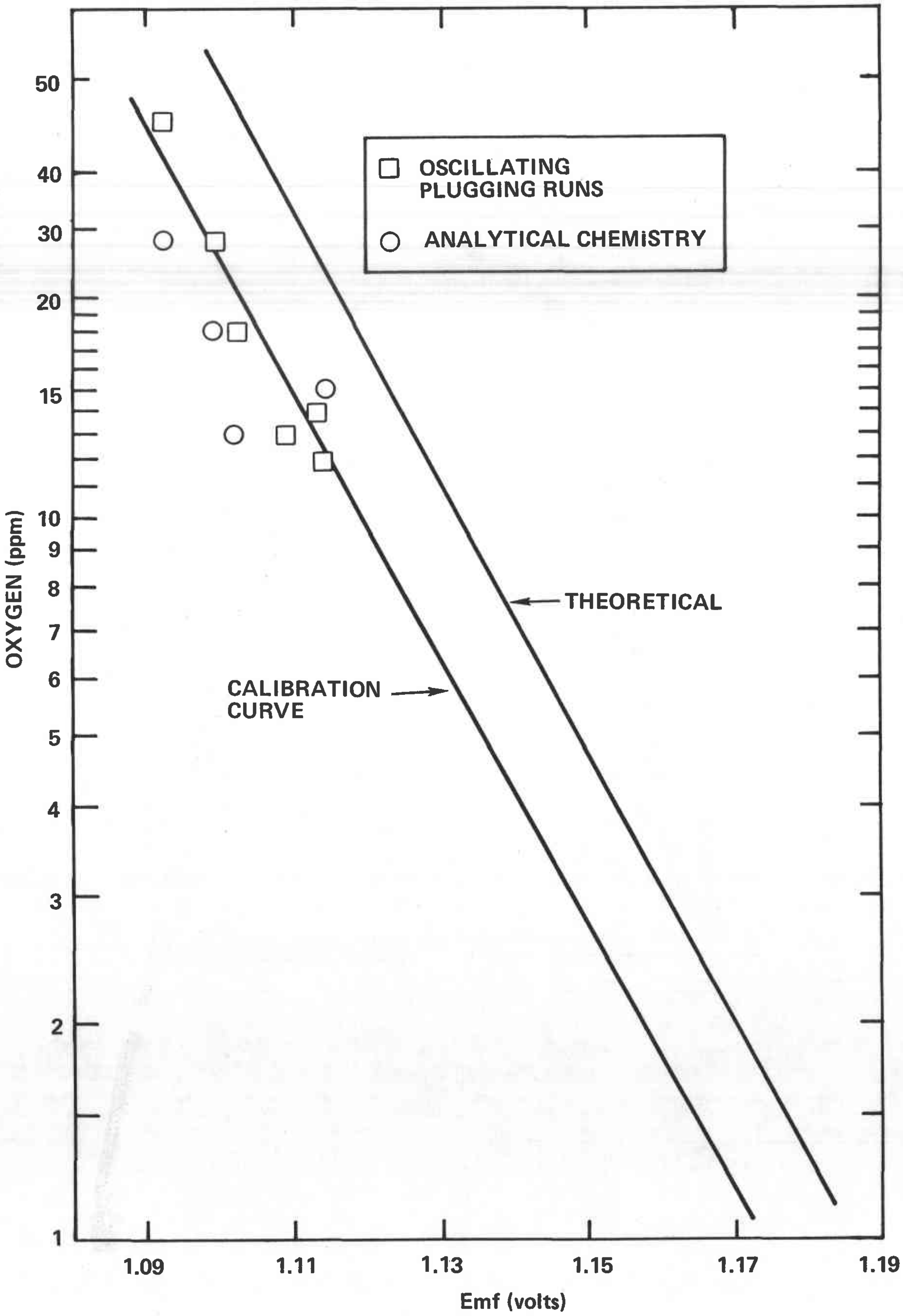
7-MA1-48-117

FIGURE 8. OXYGEN METER RESULTS



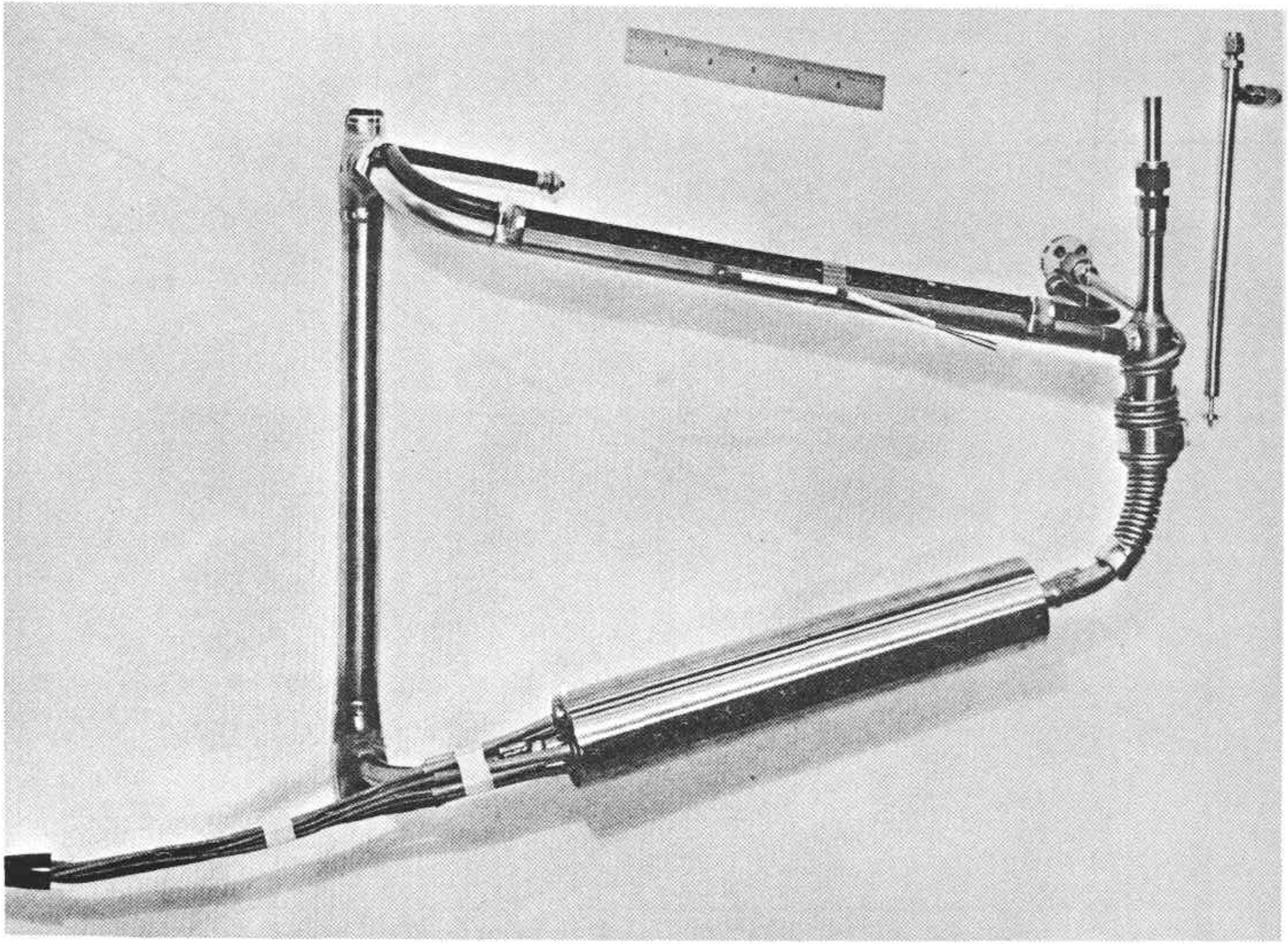
70-MA19-48-174

FIGURE 9. EXPERIMENTAL RESULTS AND OXYGEN METER CALIBRATION CURVE



70-MA1-48-197

FIGURE 10. UNITED NUCLEAR CARBON METER SIDE LOOP AND PROBE



70-MA1-48-198

SODIUM ENGINEERING

- SODIUM PURFICATION
- SAMPLING
- ANALYSIS
- IMPURITY LIMITS AND SPECIFICATIONS
- INSTRUMENTATION
- CHEMICAL INSTRUMENTATION

70-MA1-48-21

SODIUM PURIFICATION

- FILTRATION
- COLD TRAPPING
- HOT TRAPPING
  - CARBON
  - OXYGEN
- SOLUBLE GETTERS
- OTHER METHODS

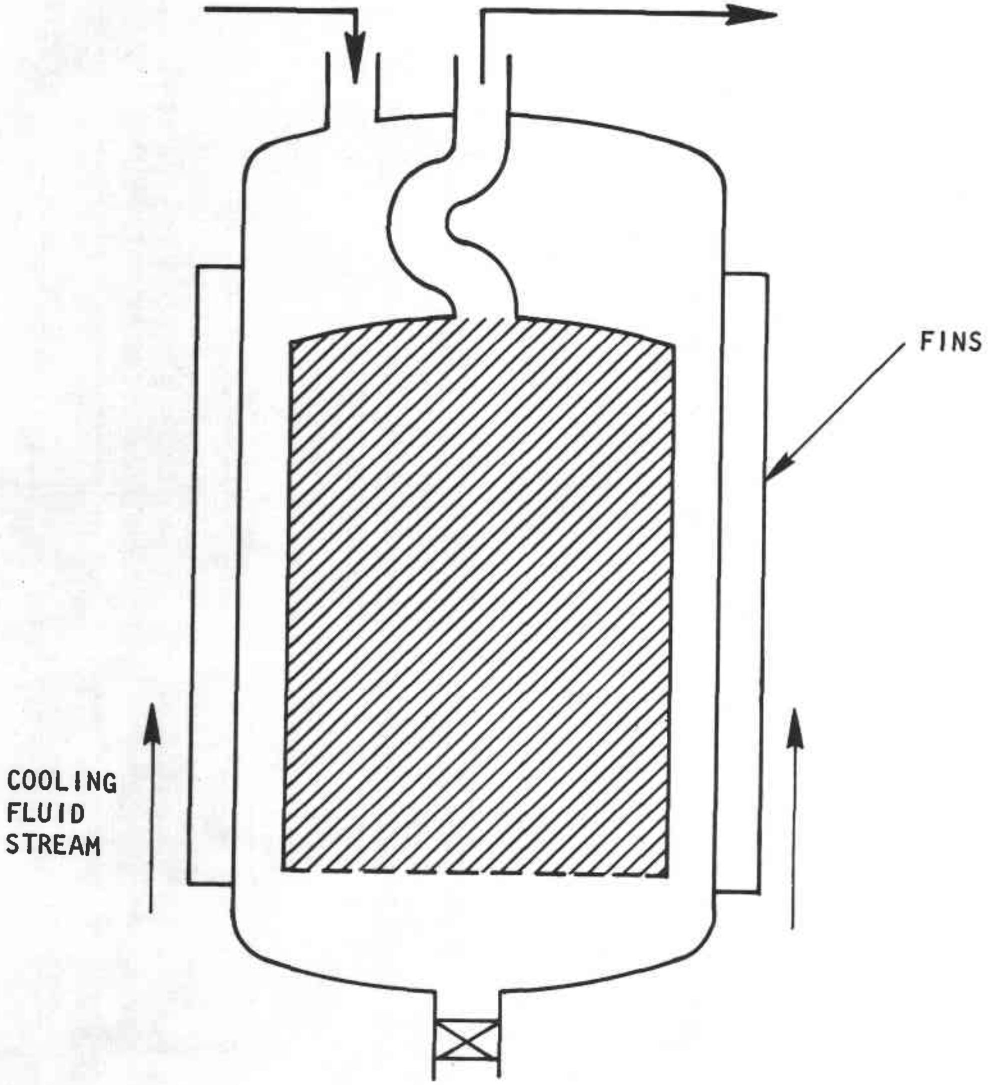
FILTRATION

- REMOVES OXIDES
- REMOVES PARTICLES
- USEFUL IF SODIUM IS DIRTY
- PRESENT DAY SODIUM DOES NOT NEED FILTRATION IF IT IS PROPERLY HANDLED

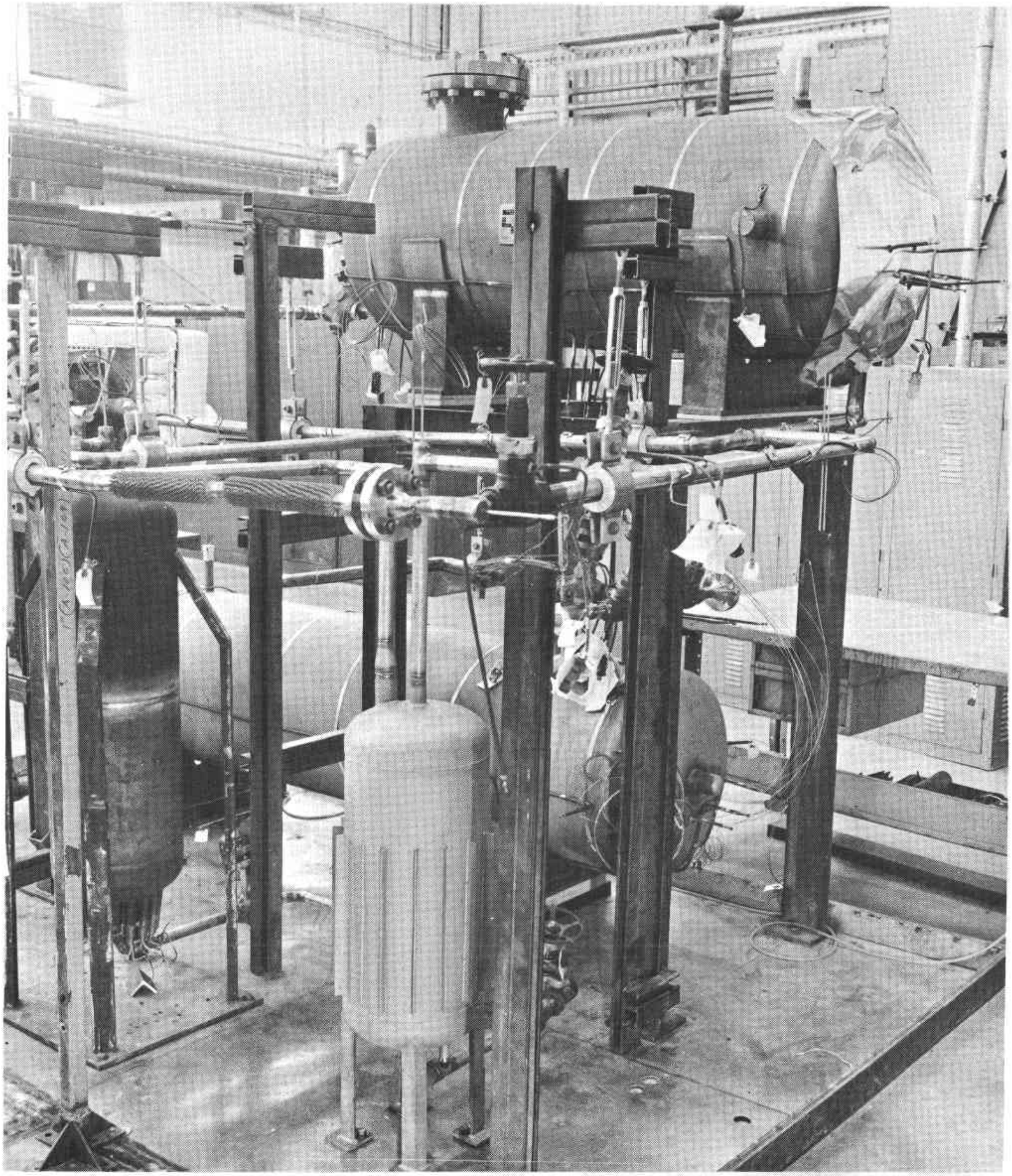
COLD TRAPPING

- OXIDE SOLUBILITY
- COOL SODIUM TO ~250°F
- ECONOMIZER
- FRACTIONAL FLOW SIDE STREAM

COLD TRAP



COLD TRAP, ONE-INCH LOOP



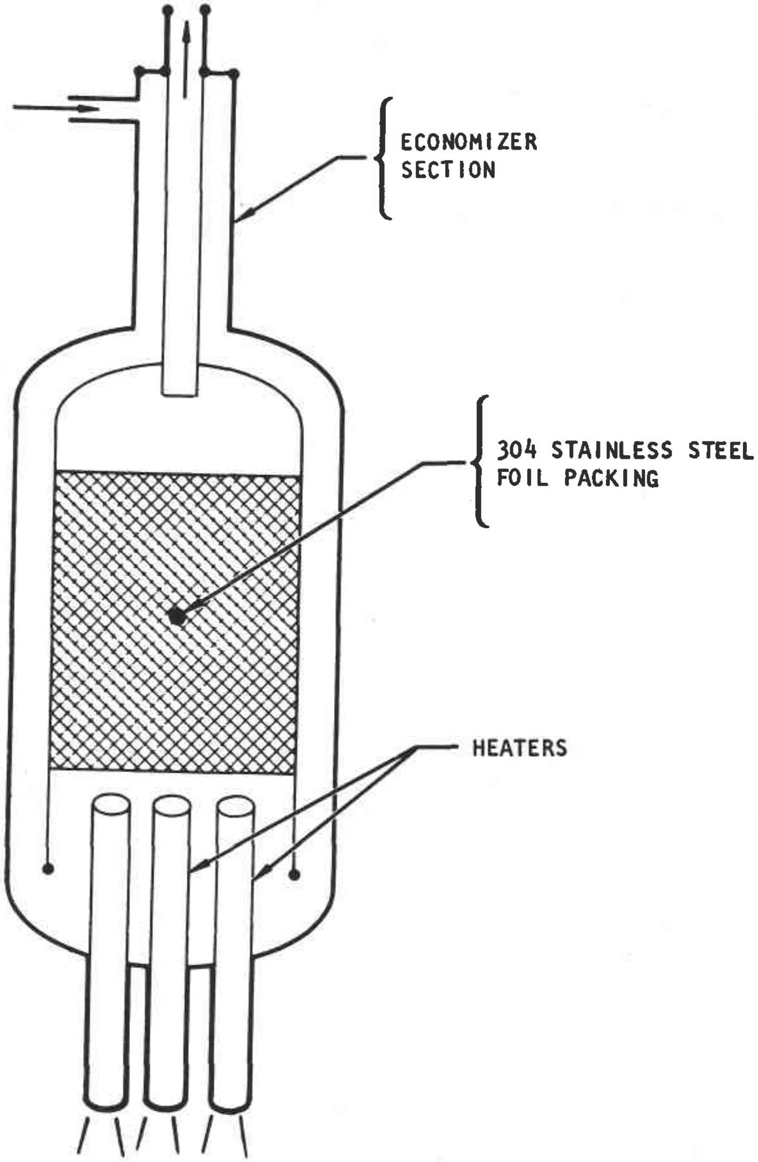
70-MA1-48-176

HOT TRAPPING

- CARBON
  - GETTER WITH HOT 304 STAINLESS STEEL
  - HEAT SODIUM TO 1200°F
  - ECONOMIZER
  - FRACTIONAL FLOW SIDE STREAM
- OXYGEN
  - GETTER WITH HOT ACTIVE METAL
  - HEATING > 1200°F MAY NOT BE NECESSARY
  - FRACTIONAL FLOW SIDE STREAM

70-MA1-48-26

HOT TRAP



70-MA-1-48-27

SOLUBLE GETTERS

- REACT WITH OXYGEN
- DEPOSIT PRODUCTS IN COLD TRAP
- LITHIUM
- ALKALINE EARTHS
- BE WARY OF SIDE EFFECTS

OTHER METHODS

- CENTRIFUGE

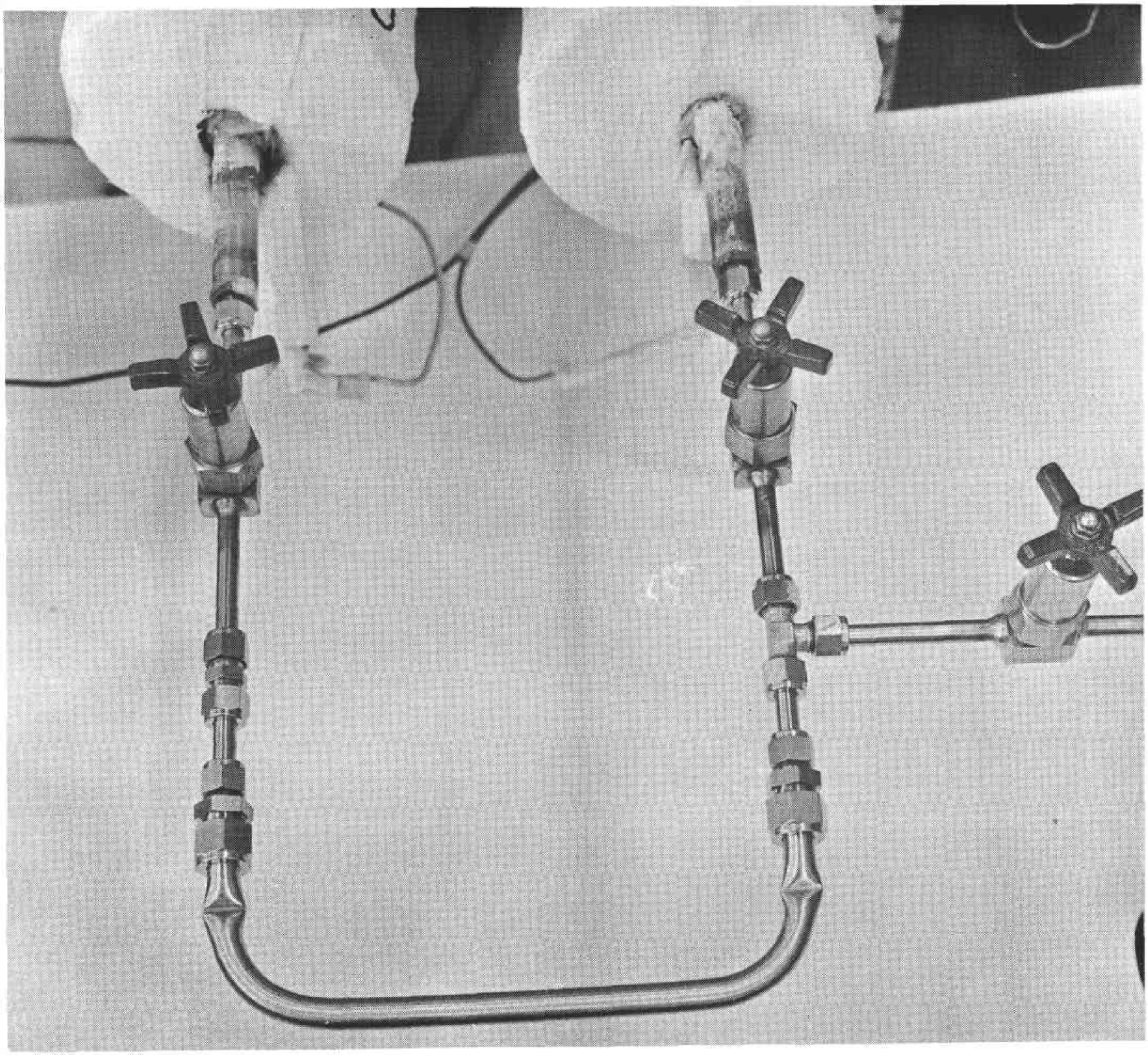
  MATTE AND TOTH, APDA-243 (1969)

- SETTLING

SAMPLING

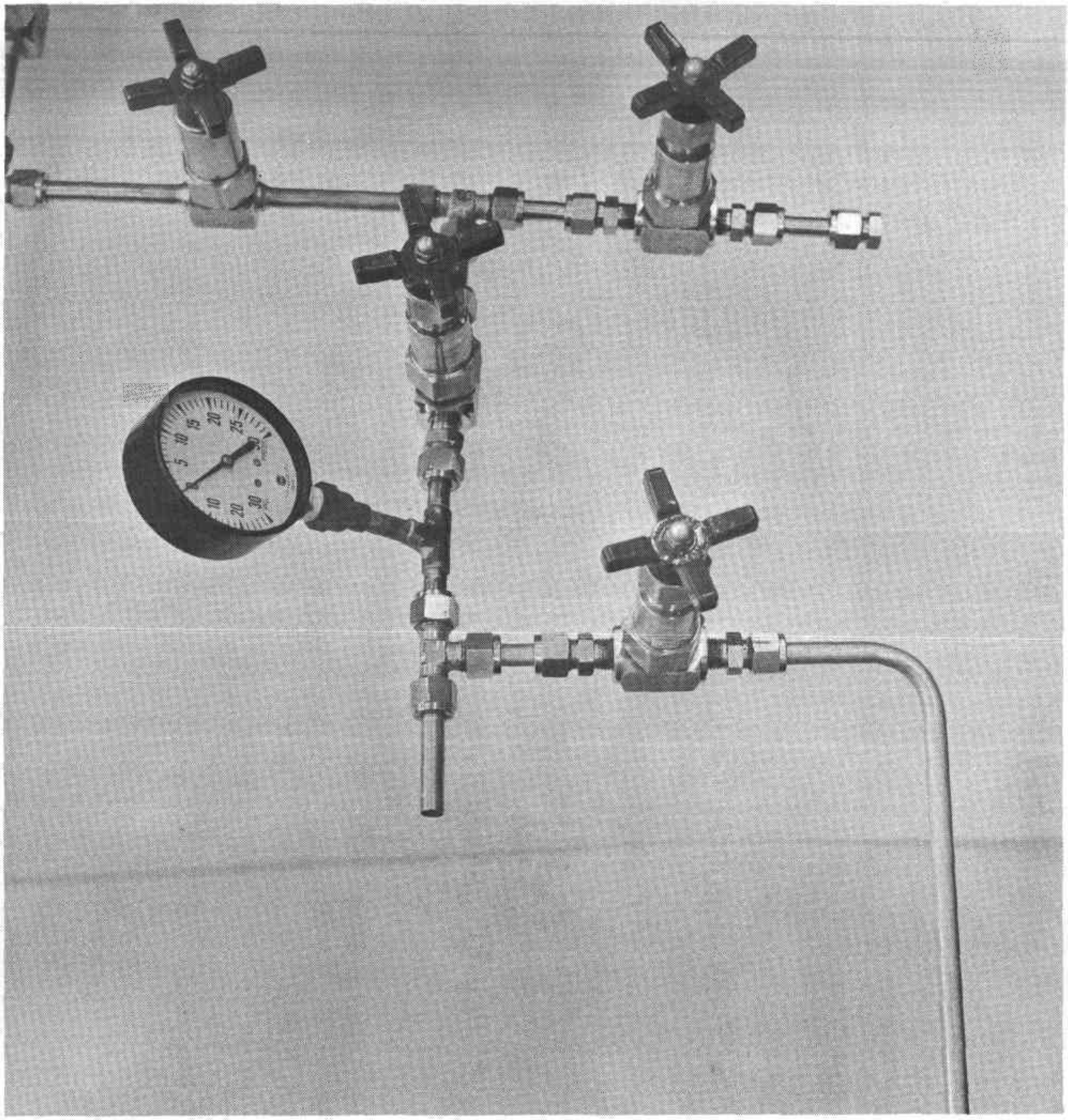
- AVOID CONTAMINATION
- FLOW-THROUGH SAMPLER
- GRAB SAMPLE
- DIP SAMPLE
- SAMPLING BLANKS IN ANALYSIS

FLOW THROUGH SAMPLER



70-MA1-48-167

GRAB SAMPLER



70-MA1-48-168

SAMPLING BLANKS OXYGEN

- FLOW-THROUGH SAMPLER

3/8 IN. STAINLESS STEEL TUBING	3.2 ±0.8 ppm O
3/8 IN. NICKEL TUBING	2.0 ±1.0 ppm O

- RETORT SAMPLER

3/8 IN. STAINLESS STEEL TUBING	7.4 ±1.5 ppm O

MURBACH, NAA-SR-12616 (1968)

ANALYSIS

- OXYGEN
- CARBON
- HYDROGEN
- NITROGEN
- METALS

REVIEW PAPER

DUTINA CONF-650411 (1965) GATLINBURG

OXYGEN ANALYSIS

- PEPKOWITZ - "MERCURY INSOLUBLES"

$$Na + Hg \longrightarrow Na(Hg) + \text{insol } Na_2O$$

ANALYSIS BLANK

- SCARBOROUGH & DE VRIES, NAA-SR-12250 (1967)

DRY OVERNIGHT 150°F VACUUM	3.9 ±1 μgm O
DRY OVERNIGHT 190°F VACUUM	3.0 ±0.1 μgm O
DRY OVERNIGHT 300°F VACUUM	2.7 ±0.1 μgm O
DRY OVERNIGHT 300°F VACUUM AND TRANSFER IN VACUUM	1.3 ±0.3 μgm O

- WEEKS, EDITOR, BNL-50065, 50111, 50123, AND 50161 (1968)

OXYGEN ANALYSIS

- DISTILLATION

  EVAPORATE Na, Na_2O REMAINS

  BERGSTRESSER et al, LA-3343 (1965)

  RUTKAUSKAS, LA-3879 (1968)

- ACTIVATION

$^{16}O(n,p)\,^{16}N$, β^- 6 Mev	7.4 SEC
STEELE et al, GA-5982 (1964)	
$^{16}O(\gamma,n)\,^{15}O$, β^+ 1.74 Mev	124 SEC
$^{18}O(p,n)\,^{18}F$, β^+ @ 0.65 Mev	111 MIN
ANL-7661 (1970)	

CARBON ANALYSIS

- HIGH TEMPERATURE OXIDATION

$2\ Na + C + 3/2\ O_2 \longrightarrow Na_2CO_3$

$Na_2CO_3 + SiO_2 \longrightarrow Na_2SiO_3 + CO_2\ (g)$

APDA-64 (1964)

AI-AEC-12799 (1969)

LUTZ AND DE SOETE, ANAL CHEM 40, 820 (1968)

- OXYACIDIC FLUX

$Na + C + K_2Cr_2O_7 \longrightarrow CO_2\ (g)$

MILES, ANAL. CHEM 41, 1041 (1969)

- ACTIVATION

$^{13}C(p,n)\,^{13}N$, β^+ 1.19 Mev, 10 MIN

ANL-7661 (1970)

70-MA1-48-35

HYDROGEN ANALYSIS

- $\mathrm{Na(H)} \xrightarrow[\text{MEMBRANE}]{\text{IRON}} \mathrm{H_2\,(g)}$
- $\mathrm{Na(H)} \xrightarrow[\text{REFLUX} \quad 200^{\circ}\text{C}]{\text{MERCURY}} \mathrm{H_2\,(g)}$
- $\mathrm{Na(OH)} \xrightarrow[\text{REFLUX} \quad 370^{\circ}\text{C}]{\text{MERCURY}} \mathrm{H_2\,(g)}$

MEACHAM AND HILL, APDA-183 (1966)

NITROGEN ANALYSIS

- KJELDAHL

  N (Na) $\longrightarrow$ NH_3(g)

- ACTIVATION

  $^{14}N\ (p,\alpha)\ ^{11}C,\ \beta^{+}$ 0.96 Mev, 20 MIN

  ANL-7661 (1970)

70-MA1-48-37

METALS ANALYSIS

- EMISSION SPECTROGRAPH
- ATOMIC ABSORPTION
- SPARK SOURCE MASS SPECTROMETER

IMPURITY LIMITS & SPECIFICATIONS

- IN GENERAL DICTATED BY EXPERIENCE O AND C MUST BE KEPT LOW

  STAINLESS STEEL: O ~ 10 ppm; C < 10 ppm

  REFR. METALS: O < 1 ppm; C < 5 ppm

- METALS ACHIEVE STEADY-STATE

SODIUM PURITY SPECIFICATIONS FOR SYSTEM QUALITY SODIUM LOOP

ELEMENT	ALLOWABLE CONCENTRATION (WPPM)	ELEMENT	ALLOWABLE CONCENTRATION (WPPM)
Al	10	K	200
B	2	Li	5
Ba	10	Mg	10
C*	15	Mn	5
Ca	10	N	5
Co	5	Ni	10
Cr	5	O*	10 ±5
Fe	25	Pb	10
H	10	Rb	50
HALOGENS	20	Si	10
		Sn	10

* CONTROLLED VALUES

MURBACH et al, NAA-SR-12327 (1967)

INSTRUMENTATION

FLOW

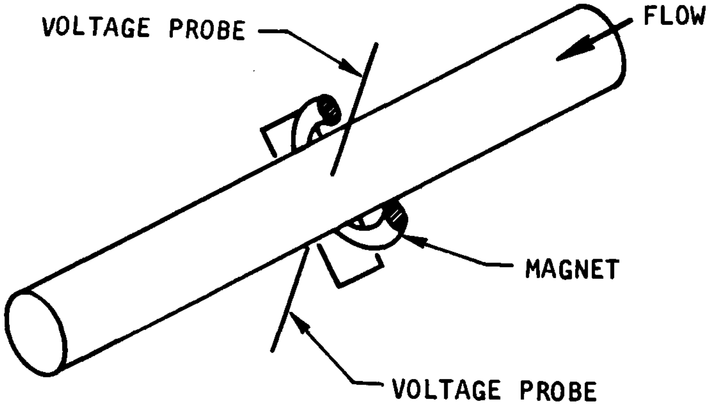
- EM FLOWMETER

TEMPERATURE

PRESSURE

- REVIEW - PAPERS IN ANL-7380 (1967), IDAHO FALLS

EM FLOWMETER



70-Ma1-48-42

CHEMICAL INSTRUMENTATION

- PLUGGING METER
- RHO METER
- OXYGEN METER
- CARBON METER
- HYDROGEN METER

PLUGGING METER

- OPERATING PRINCIPLE

  SOLID SODIUM OXIDE DEPOSITS IN AN ORIFICE. THE FLOWRATE THROUGH THE ORIFICE IS DECREASED AND THE FLOW VS TEMPERATURE DATA IS INTERPRETED TO YIELD THE "PLUGGING TEMPERATURE"

- ORIFICE METER

- OSCILLATING METER

  McPHEETERS

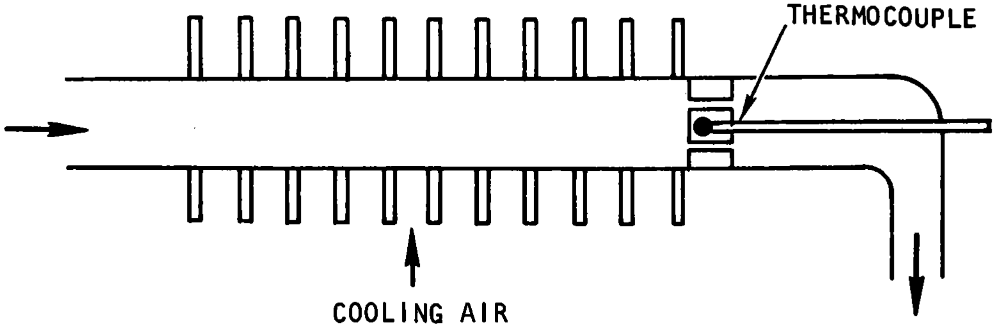
- CONTINUOUS METER

  EVANS et al, PROCEEDINGS OF LONDON CONF. ON FBR,
  BNES, 17-19 MAY (1966)

  DAVIDSON & ROACH, TRG REPT. 1640 (1968)

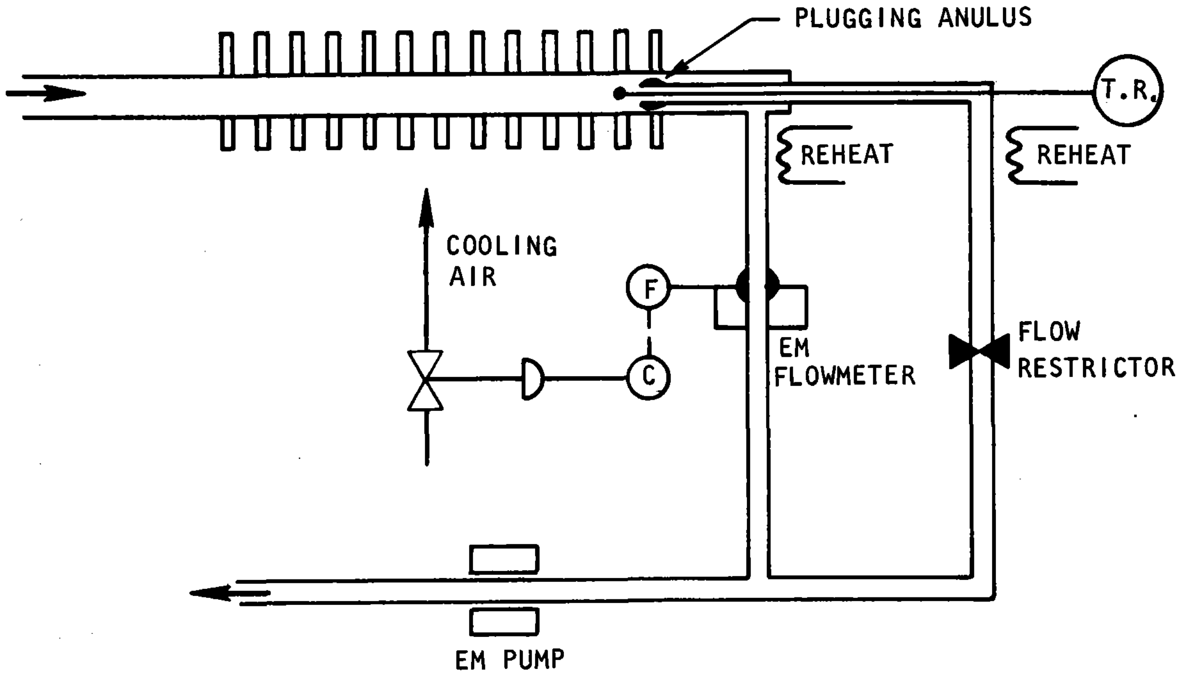
70-MA1-48-44

PLUGGING METER



70-MA1-1-48-45

CONTINUOUS PLUGGING METER
(EVANS et al)



70-MA1-48-46

RHO METER

- RESISTIVITY
- IMPURITY DEPENDENCE

BLAKE, "RESISTIVITY METER TO INDICATE OXIDE CONTENT OF SODIUM",
PAPER 3278M INST. OF ELECT. ENGRS (1960)

PETREK, ANL-7380 (1967), p 102
APDA-149 (1962)

OXYGEN METER

ELECTROCHEMICAL

$Cu-Cu_2O$ / ThO_2-15% Y_2O_3 / $Na-Na_2O$

O_2-Pt / ThO_2-15% Y_2O_3 / $Na-Na_2O$

CALIBRATION

STABILITY

QUALITY CONTROL

OPERATION IN A GAMMA FIELD

MINUSHKIN, CONF 650620 p 271 (1965)
UNC-5141 (1965)

MINUSHKIN AND NEWMAN, BNL-50219, BNL-50207

70-MA1-48-48

CARBON METER

- DIFFUSION METER

  IRON MEMBRANE - 1400°F

  $C + Ar + H_2O + H_2 = CO + H_2 + Ar$

  $CO + H_2 \overset{\text{CATALYST}}{=} CH_4$

  ANALYZE CH_4 IN FID

- PROBLEMS

  HEATER CAPACITY

  ORIFICE

  FLOW REGULATION

  CAPLINGER; UNC-5229
  ANL-7520 p 254

70-MA1-48-49

CARBON METER

- ELECTROCHEMICAL

$$\mathrm{Fe,\ Fe_3C}\ /\ \begin{matrix}\mathrm{Na_2CO_3}\\ \mathrm{Li_2CO_3}\end{matrix}\ /\ \mathrm{C}\ \text{(IN SODIUM)}$$

- IRON MEMBRANES

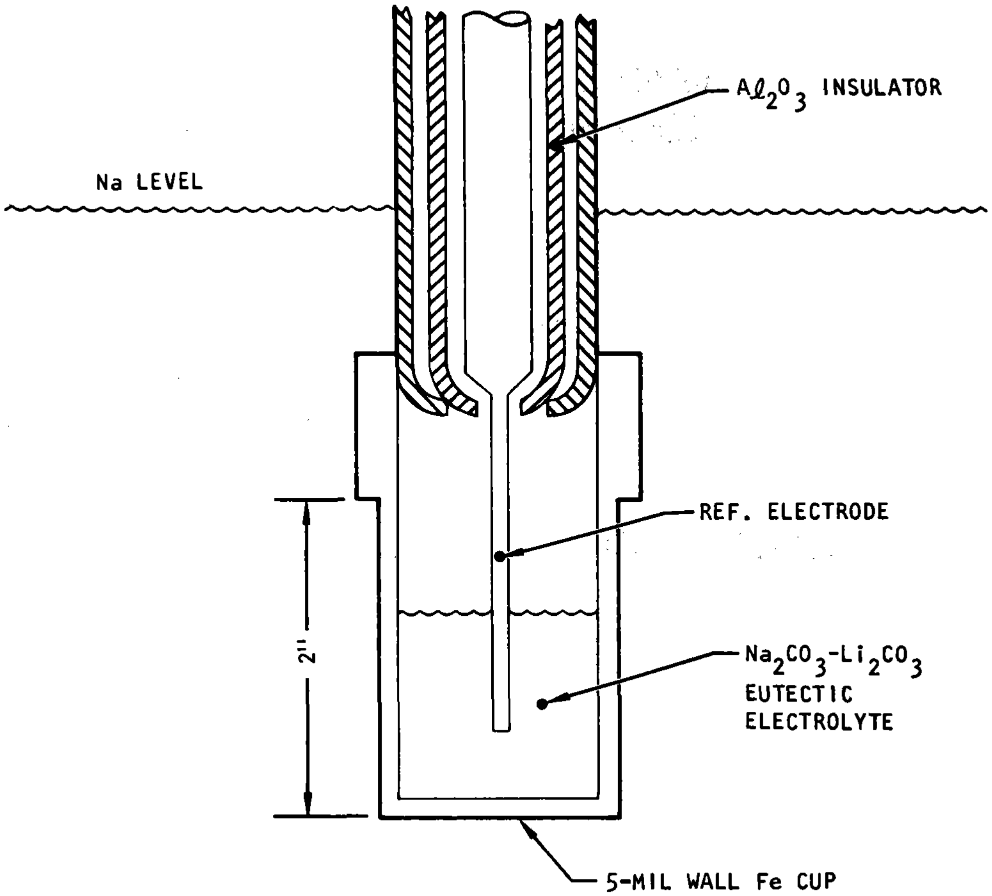
$$\mathrm{C} = \mathrm{C}^{+4}\ (\text{IN } \mathrm{CO_3^{=}}) + 4e^-$$

$$\mathrm{C} + 3\mathrm{O}^{=} = \mathrm{CO_3^{=}} + 4e^-$$

SALZANO et al, BNL-14508 (1970)
BNL-50219 (1969)

70-MA1-48-50

ELECTROCHEMICAL CARBON METER



REF BNL-14508

70-MA1-48-51

HYDROGEN METER

- DIFFUSION

  Ni-Pd MEMBRANE

  $H_2 + (Ar + O_2) = Ar + H_2O$

  MEASURE H_2O ON CHROMATOGRAPH

  APDA -

HYDROGEN METER

- ELECTROCHEMICAL

  H_2-Ar/LiCl-$CaCl_2$-CaO/H (IN Na)

  H_2 (OR 2H) $+O^{=}$ (FROM CaO) = $H_2O + 2e^{-}$

  NICKEL MEMBRANES

  REPRODUCIBLE CELL EMF'S

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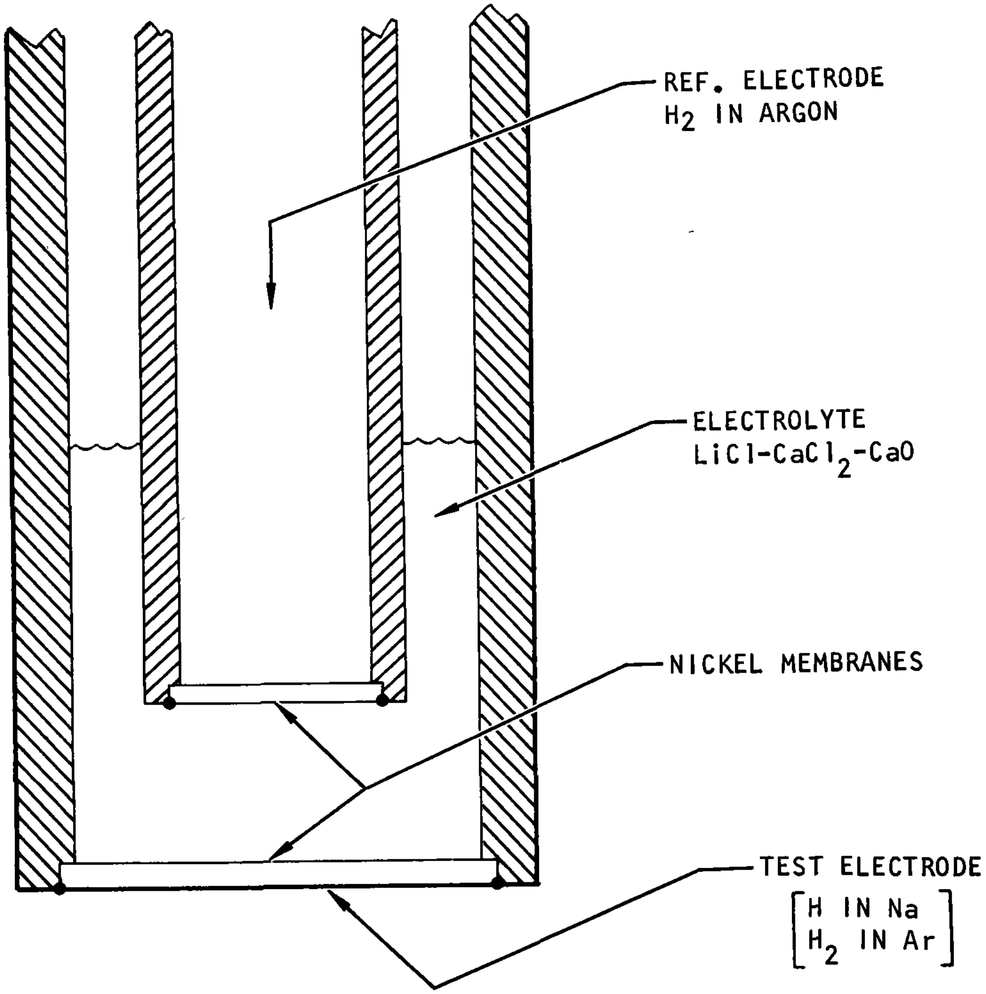
70-MA1-48-53

HYDROGEN METER



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SODIUM TECHNOLOGY COURSE, SESSION II

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SODIUM TECHNOLOGY COURSE, SESSION III

SODIUM SYSTEMS

H. O. Charnock

Previous lectures in this series have covered the basic properties of sodium. This lecture takes these basic properties and transmits them into useful system designs. We have defined process systems in the past as the veins and arteries which carry the process fluid of any process from one piece of equipment to another. Let's accept this definition and take a quick look at a simple sodium system. (III-A-1)

This system is a very simple sketch of a 500-megawatt heat transfer loop. Here we have a reactor where heat is picked up through the reactor core. The heat is transmitted in the intermediate heat exchanger to a secondary sodium loop where, in turn, the heat is transmitted to a steam system in the steam generator which generates steam. The steam, in turn, provides electricity in the turbine/generator. This is a very simple system. However, it does show some important aspects of a sodium system. First, the question of a primary and a secondary loop. The sodium in the primary system which comes in contact with the nuclear core is very highly radioactive. We would prefer that this not be in close proximity to the water which is in the steam generator because, should we ever have a leak, this could result in a loss of radioactive sodium. This could be a very serious accident. Therefore, we separate the radioactive primary sodium from the water by means of a secondary sodium loop.

You will notice that there is a difference in elevation between the core and the intermediate heat exchanger; and, in turn, between the intermediate heat exchanger and the steam generator. This has a very definite purpose in an AI system. We use natural convention flow in case we loose pump power, which gives us a means of removing the after glow heat from the core independent of a need for electricity. You will notice that the heat exchangers are in countercurrent flow with the hot fluid on the primary side flowing downward and the cold fluid on the secondary side flowing upward. This is true in the intermediate heat exchangers; and also in the steam generators.

This obviously is a very crude sketch and is not complete. We need a pump to force the sodium around these loops. So we'll look at the next slide showing a forced convention system. (III-A-2) This system now contains pumps in both the primary and secondary systems. Also, you will notice that we've provided expansion space or free surface of sodium here in the reactor; and for the sodium in the secondary loop by means of an expansion tank. Also not shown in this sketch is an overflow line from the pumps back to the expansion space. If you will notice later on, you will find there is also a free space in the sodium pumps themselves. This sodium space is established at the level of sodium space in the systems.

One useful tool in the design of sodium systems is an elevation diagram. (III-A-3) I have one of a suitable system here that will show the usefulness of this diagram. Here we have the reactor. The sketch shows the intermediate heat exchanger at an elevation above the reactor, and in turn the steam generators at an elevation above that. These elevation differentials provide the natural convection capability. You will notice in this particular sketch the primary sodium pump is at the second highest elevation in the primary system. The distance that we can permit between the centerline of the core and the upper portion of the intermediate heat exchanger is fixed by the atmospheric pressure. (III-A-4) We can see in this slide the maximum height of a column of sodium which we can suspend above the primary pump free surface; or above the maximum level in the reactor as function of temperature and also as a function of elevation; and we can see that we can have a maximum of approximately 36 ft. For purposes of obtaining maximum natural convection circulation we actually would try to have approximately this much elevation between the minimum operating surface of sodium and the top of the loop. Let's look in a little bit more detail at the overall system.

(III-A-5) This sketch shows the addition of a sodium service system for purposes of storing the sodium in tanks; for transferring the sodium from the tanks to the system and back by means of a pump; and to provide purification for the sodium. We have a purification system sketched as a cold trap here. You will notice that the primary sodium system has its own storage tank, EM pump and purification system; and the secondary sodium has also a similar but independent system. These systems are kept completely independent for the reason that we never want any chance of primary sodium leaking into the secondary sodium system. You also notice that the nozzles on the tanks are shown on the tops of the tanks. This is a safety measure to prevent the possibility of a pipe rupture resulting in draining the tanks. The sketch of a cold trap here is the basic purification system which we use in sodium systems. However, there may be other methods of purification, for example, carbon traps or high temperature oxygen traps for higher temperature systems.

This system obviously is not quite complete so we will add a bit more detail. (III-A-6) Here we see an inert cover gas system blanketing the sodium surfaces. We see a vapor trap here at this point, and also at the high point of the secondary system. We see the same thing on the service system. The use of the inert cover gas is to prevent the entry of air into the sodium system. Air obviously contains oxygen, moisture, carbon dioxide and other elements that could be deleterious to the sodium system. As we go to an inert cover gas, we have introduced two additional systems into the complex. We have introduced the helium supply system and the R/A vent system. We must also have a vent system on the secondary sodium system which is not radioactive.

In design of the sodium system we always design so that we can permit complete drainage of the system. Also, we must have capability of complete venting of the system. (III-A-7) You will see here for example, at the top of the intermediate heat exchanger, a freeze trap. You will see the same thing at the top of the steam generator. These freeze traps are used to permit complete venting of the system. You will also notice that there are drains at each low point in the system. Here the low point of the intermediate heat exchanger, for example, we have provided a drain. The lines in a sodium system are sloped at approximately 1/8 to 1/4 in. /ft. The use of the freeze trap is for areas where we do not expect gas to exist during operation. The vapor trap, in turn, is used as a vent for the high points where there is a gas space. In design of sodium systems, and particularly the primary system, we are very careful to assure that there are no places in the system below the intended free surfaces where gas can collect. The problem here is that, if gas becomes entrained in the system and collects at some point in the system (let's assume this point for example), at a later time there is always a possibility that a gas bubble will be drawn through the core of the reactor resulting in a reactivity spike.

This system is obviously not complete, since sodium melts at 208°F we must have the piping system at least at that temperature before we can fill the system. (III-A-8) So we have an electrical preheat system. This sketch shows the electrical preheat system symbolized by dashed lines around the equipment. You will notice that all the systems are preheated — even to the freeze traps and vapor traps — the vapor lines themselves are preheated. The reason for this is obviously that sodium vapor can collect in the vapor lines and freeze up the lines.

With the electrical preheat system we also need electricity so we have an electrical system here (III-A-9) symbolized by the letter E. The electrical system supplies the cold traps, the electrical preheat, the pumps and even the freeze traps. You may question why we have electrical supply to the freeze traps. The reason is that, at any time we desire to vent this system and completely drain it, we must melt the sodium out of the freeze traps; and the electrical heater is provided for that purpose. You notice that we have not provided an electrical preheat on the steam system. At AI, we plan to preheat the steam generators by supplying steam to the steam generator system from an auxiliary boiler.

We have also added a feedwater supply system and a main steam system to our sketch which now shows the main product of the system — the steam for power production. We had a system at AI several years ago, which someone was trying to describe, and they stated that the basic objective of the main heat transfer system was to remove heat from the reactor core. This is not true. The basic objective of the main steam heat transfer system is to generate steam so that we may generate power and produce electricity. More recently, the basic objective of this system is to make money for the utility. The necessity of removing heat from the core is a secondary service called the main heat transfer system.

This system is not quite complete in that we have already stated that the primary sodium system is radioactive, thus we have to put that into a shielded vault. (III-A-10) This sketch shows the shielded vault around the primary sodium system. Now as we go to the shielded vault we have introduced considerable complicity into the system. For example, we use nitrogen gas as an inert gas in this vault. In case of leakage of the radioactive sodium, there can be no fire; and we will not lose radioactive sodium to the surroundings in the form of airborne oxides of sodium. Thus we need a nitrogen system. Also, since these vaults are gas tight to prevent the escape of radioactive dusts or gaseous matter, we must provide pressure control and a ventilating system for the cells. Finally, the sodium system is hot and gives off heat to the cells, both as sensible heat and as gamma heating of the cell walls. We must provide a cooling system in the cells to take away this heat. Now, since we do not permit water in close proximity to sodium — and particularly radioactive sodium, the coolant we use in this sodium system is preferably not water. If we are forced to use water, we provide some means of preventing the entry of water into the cell itself in case of a water leak. The same concept is true in case of a sodium leak. We want to prevent the entry of sodium into the area of the cooling coils.

Another problem is now apparent. The fact that we have the primary sodium system inside of a sealed cell means that any mechanical equipment inside of this cell must be remotely operated. This then introduces another complexity into the system. Where possible, we keep as much of the mechanical equipment out of the cells as we can. What we must have in there we try to design remotely removable for maintenance.

We mentioned the possibility of sodium water reaction. At this one point in the plant-in a steam generator, in a superheater, and in the reheater, we can't eliminate the need whereby sodium and water exist together. Since the steam in this plant is at approximately 3000 psi pressure and the sodium at this point is perhaps up to 200 psi, it is quite obvious that a steam generator leak would be water into the sodium side. While we hope that this never happens, we must be prepared to take care of such a leak, and we prepare ourselves by the means of a steam generator rupture relief system. (III-A-11)

In the steam generator rupture relief system, each piece of equipment is provided with a rupture disc whereby, should we have a leak and experiment this rather severe reaction, the products of the reaction are discharged through the discharge system into a separating tank where the hydrogen gas is separated into the atmosphere. This rupture release system is maintained blanketed in ~~a nitrogen inert cover gas~~ because, should we get a reaction with air in this system, we would have an immediate hydrogen explosion which would probably do severe damage to the system containment and probably to the surroundings.

I'd like to show another type of sodium system which is a variation of the system we have been discussing. (III-A-12) This is the pool type system vs the piped system which we have been discussing. In a pool type system the entire primary sodium system is contained in a large vessel. Here you see an IHX, primary circulating pump, and the nuclear reactor core. To the right, you have the conventional pipe primary system which we have been discussing up to now. Both of these systems have their advantages. The pool type system has the advantage of a simplified primary system. However, the pipe system has the advantage that some of the equipment is provided where it can be reached for maintenance. Also, design and construction of the larger vessel for the pool type system is a considerable more difficult job than design of the smaller reactor vessel for the pipe system. The decision between these two systems obviously is an economic matter and to date it has not been determined which is the most economical.

I would like to summarize some of the work that we have done up to this point and then I would like to get into some more specific problems. We have discussed a sodium system which consists, not only of a sodium system, but of a good many auxiliary systems. So let's take a quick look at these auxiliary systems and see what our problems are. (III-A-13) We have the Sodium Heat Transfer System, which is basically to remove heat from the nuclear reactor core and transfer it to the steam generator for the purpose of generating steam and ultimately making electricity. This system is supplied by the Sodium Storage and Purification System with the function of receiving and storing the sodium into the plant; of removing oxides and perhaps other impurities; and of monitoring the condition of the sodium. We have the helium supply system which supplies an inert cover gas over the sodium and thus prevents the entry of moisture, air or other contaminants to the sodium system. Since the primary sodium system is radioactive and since the cover gas must breathe, we have a radioactive vent system to remove the radioactive gases from the system. We have a secondary sodium vent system which is not radioactive but which serves for ventilating purposes. We must have electrical preheat or some other form of heat input so that the sodium will not freeze on initial fill of the system.

The Steam System obviously is the ultimate product of the heat transfer system and provides steam to the turbine generator. This consists of the main steam system and also a steam preheat and startup system which is necessary during preheat of the system and during low power operation or for afterglow neat removal. The feedwater supply system provides feedwater to the steam generator. In the AI concept we are using once-through steam generators, which means that the feedwater must have zero solids or practically absolute purity of the water. Otherwise we would have trouble with deposits in the steam generator which would eventually result in plugged tubes, corrosion, and failure. The electrical supply system services the various pumps and the preheat system and other miscellaneous equipment. The Vault Cooling System is used to remove ambient heat from the sodium vaults to keep them at a normal or acceptable temperature. We anticipate the possibility, however remote, of a leak in the steam generator which must be accommodated by the Steam Generator Rupture Relief System to avoid serious damage to the reactor cooling system. Finally, the entire system is tied together with an Instrumentation and Control System which controls the entire reactor complex.

Now, this has been a rather simplified description of a sodium system. In actual practice, this simplified system would be seriously complicated by the fact that we must have at least two separate means of heat transfer from the core, which means a minimum of two of these heat transfer loops. This also means that the control system is seriously complicated by having to control two or more systems together. The control system must be designed, for example, to divide the total plant lead between two or more loops and prevent instabilities between them.

We started out and we were discussing a series of auxiliary system affectionately called "plumbing garbage" by some of our physics types. I'd like to take a look at just how important is the heat transfer system in the overall picture. (III-A-14) This shows a breakdown of cost — of one of our cost estimates for a 500-megawatt power plant and gives, in terms of percentages, how the cost is distributed to the various major parts of equipment. And here you see the heat transfer system in the nuclear section of the plant constitutes nearly 40% of the total plant cost. In the balance of the plant, the heat transfer system is not so great; but something on the order of 25 to 30% of the total plant cost can be attributed to the heat transfer system. To summarize, I estimated that the sodium heat transfer system alone constitutes perhaps 24% of the total plant cost and perhaps 29 or 30% approximately of the cost of the plant are attributed either to the sodium heat transfer system or to the various auxiliary systems that serve it. Now, if we assume a value for a 500-megawatt electrical plant at say $200/kilowatt, we are talking of approximately 30 million dollars cost for the heat transfer, I trust that I have been able to impress on you the fact that this is not "garbage" but is a rather expensive portion of the electrical generating facility.

From here I would like to go on to some of the more detailed design factors that we would consider in designing a sodium system. (III-A-29) A prime consideration is to contain sodium to prevent any possible sodium leaks; and to prohibit the entry of oxygen or other deleterious contaminants into the system. As a general statement, almost any contaminant in a sodium system is deleterious because of the chemical nature of this coolant. The design is rather specialized in that we use all welded construction where possible, even to the manholes. If we need manholes we use welded caps as manholes. The instrumentation is designed so that there are no penetrations into the sodium envelope at the instrument connections. Where we do have required entry into the systems, we try wherever possible to make the entry in the cover gas space rather than below the sodium liquid level. One reason for this is that, when hot sodium leaks out into the atmosphere, it is possible to form sodium peroxide which is very highly corrosive and would cause rapid deterioration of the system containment itself. Wherever we require seals, we often use frozen sodium as the sealing medium. Finally, as we mentioned once before, all openings are on the top of the tank or vessels, where possible, so that, should there be any cause for breaking a pipe, it would not be below the sodium level, and we would not lose sodium to the surroundings.

(III-A-30) We make every effort to keep oxygen and moisture out of the system. Some of the measures that we use are as follows: we maintain the inert cover gas over the sodium at all times. Where necessary, if the supply of inert gas is not absolutely pure, we provide driers or other purifiers for the inert gas supply. We maintain the pressure of the inert gas slightly above atmosphere so that should there be a leak, it will be leakage of the inert cover gas to the surroundings rather than leakage of the atmosphere into the sodium system. Where necessary, where we do need penetrations in the system, we use special seals such as bellows, freeze seals, or back pressured seals to prevent the loss of sodium. For small systems we can completely fill the system with sodium by using compensators to absorb the expansion of the sodium on changes of temperature. When removing sodium equipment from the system, we provide temporary closures to prevent entry of air into the system at that time. In design of a plant for sodium systems, we do not even permit the entry of water into the sodium containing areas of the plant. You will be hard pressed to even find a water fountain in a sodium plant. The sodium systems are provided with adequate vents and drains and the lines are sloped to permit complete drainage or complete filling of the system as the case may be. Finally, we provide the system with cold traps or other means of removing oxides or other contaminants should they enter the system.

I'd like to look at a few of the means we use whereby we provide these specialized seals. (III-A-31) This is a sketch of one of the valves developed here at AI in conjunction with a commercial valve manufacturer showing how we seal the valve stem. The sodium flow is up from the bottom and out – it is in from the side and out the bottom with the valve disc at this point. Now, the stem passes through the frozen section of sodium here, frozen by means of some fins on the outside of the unit. Thus, since we have frozen sodium in this annular space we cannot have leakage; but that is not sufficient for all our purposes. One of the problems obviously is to prevent the entry of air into the frozen sodium section which would result in binding of the valve stem in the frozen sodium. So we must prevent the entry of air. We do that in this valve by means of a bellows seal at this point. But even that is not sufficient, because we assume the possibility that the bellows might fail and leak sodium to the surroundings; so we back that up with a stuffing box at this point. Now, since the valve must be vented to permit forming the frozen sodium seal, we have a vent line at this point. We also have a moderating line at this point to tell us should there be a failure of the bellows back-up seal.

(III-A-32) For our intermediate heat exchangers, we use what we call a hockey stick type in this particular plant so that the tubes are permitted to flex in this area independently of the expansion or contraction of the shell. Now you will notice that the manholes on this unit are all welded construction. Should we ever have to enter the system itself, we would have to take a saw and cut the manholes off. It doesn't show in this picture, but we would have a vent just underneath this tube sheet to prevent the accumulation of gases at this point and to permit full venting of the system on fill and drain. We would also have drains at the bottoms of the two sides of the system to permit complete drainage.

(III-A-33) One of the worst problems we have is designing the sodium system is the pump seal, since this is a rotating seal that must be maintained during plant operation. We placed this seal above the gas space in the pump so that the seal is actually in the gas space rather than in a sodium space, thus the name "free surface" pump. I would like to point out some of the details on this seal to show you how very careful we are. The amount of oil provided the main bearing of the pump is strictly limited. We also have a monitor here that we observe at periodic intervals to assure that there is no leakage of the oil. Actually one of the problems with pump seals is not only preventing the loss of cover gas, which may be radioactive, but preventing the entry of the oil from the bearing housing into the sodium, since carbonaceous material is very deleterious to the system, should it enter the sodium. Now this seal is made by means of a rotating face seal at this point. Down below the rotating face seal is a slinger type seal with a leak off chamber so that, should the face seal fail, the oil would be collected in this leak off chamber and could not enter into the pump proper. This leak off chamber is sufficiently large to contain all of the oil in the system. We have a second slinger arrangement and leak off chamber below that which permits draining off should there be some failure or loss of carbonaceous material.

(III-A-34) I have another slide here that perhaps shows this a little better and it also shows another feature of the pump seal. Here's the upper oil catch basin; the rotating face seal; the slinger arrangement; and the second oil catch basin. Down here we inject a small flow of inert gas into this system. This inert gas then passes in two directions, first it passes downward around the pump shaft into the sodium containing portion of the system. This is to prevent sodium frost formation on the pump shaft which we'll discuss later. The second portion of the flow passes through the slinger arrangement, past the freeze seal, and out of the system. Now this upward flow is to pick up any possible carbonaceous vapor that may leak through the sodium seal and possibly get into the system.

(III-A-36) We talked about the electrical preheat system. I'd like to look at a typical electrical preheat system on one of our pipes. This sketch shows the general concept of how we put a preheat system together. We use an electrical resistance element very similar to "Calrod" unit you would find in a modern electric range. It consists of an electrical resistance element within the inside, mineral insulation; and a stainless steel sheath on the outside. The heater element would be on the order of 1/2-in. diameter. Now, we would put these onto the surface of the pipes, so that they are in contact with the pipes. We use a stainless steel oven around the outsides of the heaters. This oven serves two purposes — first, it acts as a reflector to reflect the heat from the heater into the pipe. Perhaps, more import, should we get little flakes of insulation between the heater and the pipe, it is conceivable that we would burn out the heater; so this oven serves a secondary purpose of preventing the insulation from contacting the heaters. Outside of the ovens we have an insulation of some sort, perhaps a hydrated calcium silicate, and finally we have some kind of a protective outer sheath for the insulation. Indoors, of course, it would be an interior insulation finish; or, should it be an outside installation, it would be waterproof. Each section of the heater is controlled by an individual preheat thermostat which I have indicated on the bottom here. You will notice that the thermostat of the thermocouple is at some distance from the heaters themselves so that we get a reasonable reading.

In design of the preheat system we have to be very careful about where we put our thermocouples and how we connect the heaters. (III-A-37) The system must always be open to a free surface above the sodium, should we happen to need to melt out a system containing frozen sodium. The reason obviously is that, as the frozen sodium changes from the frozen to the liquid state, it expands. Therefore, it must be exposed to a free surface where the sodium can expand inside of the containment. Thus, when we connect up our preheaters, we connect them so that we can start preheating from some free surface. For empty systems, we have a limit as to the rate at which we can preheat the system — this rate is something on the order of 50°F an hour. However, there are some large pieces of equipment that are very difficult to heat. For these large pieces of equipment, the permissible rate of preheat is established by the design of the equipment itself. In particular, preheating of the sodium reactor and the intermediate heat exchanger are quite often the limiting factors as to how quickly we can preheat. The reasons for this is that our preheaters are on the outside of the equipment. Now if we take a look at an intermediate heat exchanger which consists of a bundle of many, many tubes and we start to heat from the outside, we would find the heat cannot penetrate to the interior of the tube bundle at a very fast rate. Thus, we would have the outer shell of the bundle at a much higher temperature than the tubes on the inside and we have introduced an unacceptable temperature difference there. So you can see that the rate of preheating is very important in the case of some of our larger equipment.

In preheating, quite often we control the preheating in a step-like manner by stepping up the set points of the controls, perhaps 20°F at a time until the section of line that is being preheated has reached that temperature; after which time the set point is again advanced until we have reached preheat temperature, which normally is on the order of 350°F. There is another limitation on preheating a sodium system, and that is the limitation of the cold traps. We have found that once a system is full of sodium at preheat temperature, we can cold trap until we get a relatively low plugging temperature. Then, as we increase the temperature of the system, we find that the plugging temperature goes very high again; and we must hold the system temperature rise until we can again cold trap down to an acceptable plugging temperature. The reason for this phenomenon is what we call "hide out oxygen," oxygen is always on the surfaces of a system that has not been properly cleaned prior to the use of the sodium itself. As the system temperature rises, this oxygen comes into solution in the sodium as sodium oxide, and must be removed. This phenomenon persists until system temperature reaches the neighborhood of 700°F.

Let's take a look at a few of the maintenance problems that we would also have to consider in design of a sodium system. (III-A-39) First, we have mentioned that the sodium is highly radioactive. The bulk of that radioactivity is caused by sodium-24 with a relatively short half life. Therefore, where we expect any possible maintenance procedure necessary, we would provide for access after sodium-24 decay. We must also provide for complete drainage of the sodium (as we'll get into later). Even a small amount of sodium remaining at the low points may contain appreciable radioactivity that would inhibit access. Wherever possible, we design our major equipment so that any maintenance that we would anticipate can be made without cutting into the sodium envelope if possible. Where access is restricted (such as in the primary sodium vault), we provide adequate remote leak detectors to tell us should there be a leak in the system. We must remember that in more critical sodium systems all welds must be fully radiographed. Design must accommodate this and must recognize the need for this radiograph examination. Where the system is thought to be radioactive, we must provide whatever capability we can for maintenance of the systems external to the radioactive envelope. In some cases, there are areas where we anticipate we would never be able to enter. The reactor cavity itself is an example of this type of area. Where we expect the possibility of failure, we would provide spare equipment to assure that, should one piece of equipment fail, a second piece can be wired or connected into the system.

(III-A-40) Let's look at a few of the procedures that we might consider in providing for maintenance in design. This sketch shows a main pump where the pump itself is underneath the floor. The entire pump is removable by means of a flange connection at the floor level. If you will recall, we had a sodium level somewhere down in the barrel of the pump; so this flange connection is never in sodium but is always in the gas space. In removal, the entire pump is removed through the top without touching the pipe connections. In this particular sketch, you will notice that the pump has been removed out into a plastic bag which is full of inert gas. In all probability, in the case of a primary pump, we would have a shielded cask which would then also be full of inert gas. Now the reason for the inert gas is that, as the pump comes out, it is covered with a thin film of sodium which would oxidize in the air should it be exposed to the air. This oxidized sodium could become dispersed, spreading radioactivity as well as a chemical hazard. Notice of course that we have arranged this system so that the pipes are not cut during maintenance. As soon as the pump is removed a temporary cover would be put on the flange connection to prevent air entering the system.

Over here we see an intermediate heat exchanger and temporary shielding walls provided to permit access to the manhole covers. Shadow shielding will be provided around the manhole cover. The manhole cover is cut and by means of remote tooling, we would then be able to reach the end of the tubes for plugging. We anticipate that the main source of maintenance in the intermediate heat exchanger would be failed tubes.

Down here we see a valve installed in a radioactive area where the valve stem is led up through the floor through an extension stem to an operator above the floor in an accessible location. Thus the operator (which is the mechanical portion of the valve) is accessible for maintenance. Should we need lubrication below the floor, we would have provisions for remote lubrication of the bearings from the accessible area. Again, we would provide the capability for approaching this valve for maintenance after shutdown and decay of sodium-24. (III-A-41)

In normal maintenance procedures we would be doing some or all of these operations — we would be cutting pipe and in cutting the pipe we must provide protection from the atmosphere. This is provided quite often by means of plastic covers that we put over our work as we work. As soon as the cutting is complete temporary covers would be placed on any open ends of the pipe. In welding we use the tungsten inert gas arc without a filler arc for the first pass. This gives us an impervious weld at the first pass without contaminating the sodium envelope. In some cases in maintenance we must remove the component and provide cleaning which we will discuss later. Wherever possible we maintain the inert gas blanket in a system because, should we not do this, air can enter the system, pass downward through the pipes and oxidize the sodium on the various surfaces of the metal. This oxidation results in some deterioration of the metal where it cannot be observed and where we are not aware of it.

(III-A-42) A small very simple procedure for cutting small lines is to freeze the sodium inside of the line; then we can cut the entire line including the frozen plug of sodium. In repair of such a system, we dig the sodium out from the ends of the cut for perhaps 4 in.; then we can proceed to reweld the system in place. Thus the only oxidization that takes place is the very surface of the sodium at the cut which is then removed when we replace the system. In larger lines, say above about 4 to 6-in. lines, it is not feasible to cut a frozen line; so we must have the entire system completely drained and isolated. We leave the inert gas blanket in as best we can. Should the system be in the radioactive portion of the sodium system, we would have to purge out much of the inert gas to remove any gas borne radioactive material in the pipe. Finally we would cut and, as soon as the cutting is complete, we would protect the open ends with plastic. In repair we would have to clean the area close to the repair free of sodium, then make the reweld.

Where possible we clean only that portion of the material that we have to clean because cleaning is a rather difficult job. (III-A-54) Let's take a look at some of the problems we have in cleaning. Cleaning generally involves a chemical reaction to oxidize the sodium, thus reducing the hazard. There are a number of agents that we can use. Dowanol is a mixture of some of the higher alcohols which react slowly with sodium and we can use this reaction to clean up a piece of sodium for maintenance. Alcohol is similar but it reacts faster, and the reaction is somewhat more difficult to control. Steam, we found, is a very effective means of cleaning equipment, particularly since we have found that we can control the rate of reaction by introducing moisture into nitrogen and use moist nitrogen in place of pure steam. Where we have no desire to use the system to minimize damage; but are attempting to destroy the presence of sodium on the surface (as prior to disposal), we can often do this simply by turning a water hose on the system. Naturally this procedure must be used in the open where there is no chance of explosion; and furthermore, it probably is not advisable for use in a radioactive system. Ammonia is a very good solvent for pure sodium. However, sodium oxide is not soluble in ammonia and therefore, ammonia is not useful where we have some oxides in the system. A word of caution: liquid ammonia can react with sodium oxides, forming amides, which, in turn, can convert to azides in air. These latter compounds are explosive. Thus, use of ammonia must be controlled carefully. The use of liquid ammonia is rather difficult since high pressures are needed at normal temperatures. We can evaporate sodium by vacuum melting which is a rather expensive means of removal, although applicable to special situations.

In any case where we must clean, the first procedure would be to melt and drain all possible sodium out of the system because it is much easier to melt and drain than it is to chemically react. Finally, we have worked with hot oil where the sodium containing equipment is immersed in a pot of hot oil and the sodium is simply melted by the heat of the hot oil and runs to the bottom of the vat. This particular method is not the best where the piece is to be repaired and reused because it very probably leaves a film of oil on the surface of the equipment which is very difficult then to remove. So, therefore, we would normally not use the hot oil except where we are disposing of the equipment. One other possibility, in the case of thin film on scrap material, the material may be simply exposed to the atmosphere for a time.

In cleaning procedures, we would first remove the excess sodium by hand, by melting and draining, or by scraping off the bulk sodium and for small components probably Dowanol or alcohol is a good approach. For the larger components steam with the nitrogen gas carrier. For very light coatings of sodium we can use water by just very slightly moistening a rag and wiping the surface. This must be done with very strict control because excess water would result in a violent reaction on the surface. Finally, in any case of any of these cleanings we would rinse with distilled water and dispose of the sodium by reacting it with water where it could be done safely.

I would like to speak now about some of the instruments we use, since we did mention that all instruments are designed for complete closure of the envelope. The basic chemical control instrument is the plugging meter. (III-A-58) The plugging meter gives us a measure of the temperature at which sodium oxide starts to precipitate out from the sodium. This in turn is a function of temperature and the content of oxygen in the sodium and is a very good routine control measure. In this sketch we see sodium coming into the plugging meter from the top left and passing out into the system. At the right we see an orifice at this point where the sodium passes through an orifice and a magnetic operator at this point. You will notice that the entire sodium envelope is solid welded construction so that there are no chances of leakage to the outside. In conjunction with the plugging meter we have an EM flowmeter which also is completely enclosed. (III-A-59) This is a little better sketch showing our standard AI sodium plugging meter. The sodium comes in here through a regenerative heat exchanger. Heat is removed in this area by means of some fins with air blowing across it. The sodium passes through the orifice and back out through the regenerative heat exchanger. So you see there are no places where the sodium can leak to the outside.

Now we have mentioned that this plugging meter system also contains a magnetic flowmeter. (III-A-60) Let's take a look at a schematic of this. The magnetic flowmeter looks exactly like a piece of pipe. Perpendicular to the pipe is a magnetic field, and perpendicular to the magnetic field are a pair of electrodes where the signal is taken off. Thus the flowmeter looks exactly like a piece of pipe as far as the sodium envelope goes and there is no chance of leakage at this point.

One of the most difficult problems in measuring sodium is the problem of measuring level or pressure in the sodium system. Where possible we would measure pressure in the gas phase. However, in certain places, such as at a pump discharge, we cannot measure in the gas phase, so we have a diaphragm type differential pressure gauge which gives us a completely sealed pressure measurement. (III-A-61) The sodium system would be down in this area with a diaphragm which isolates it from the external system. From this diaphragm we have a capillary tube which is full of NaK. NaK as you know, is a liquid metal compatible with sodium so that, should we get a break in the diaphragm, we would have compatible fluids. Also, should we get a break in this diaphragm or should the sodium leak out, it would freeze in this capillary, thus arresting leakage to the outside. This diaphragm is then backed up by a second diaphragm at this point which in turn transmits the pressure signal to another system full of another liquid of some sort. We have the same system here on the other side of the differential pressure transmitter where the pressure of the reference, for example, the gas phase, is transmitted to a diaphragm, through a NaK filled capillary and in turn through a second diaphragm and to the measuring device. Thus you see, to lose sodium from a system through this type of pressure device would necessitate a failure of at least two diaphragms plus a postulation that the capillaries are at a temperature at which sodium will flow. This is very difficult.

(III-A-62) For measuring temperatures we use thermocouples. This sketch shows a thermocouple where the thermocouple wires are welded to the end of a solid tube. The tube would then be welded into the pipe so that there is no chance for sodium leakage. (III-A-63) Another method of liquid level measurement is the probe which was developed here at AI, in which a probe measures the inductance of the surroundings by insertion of an induction coil into a solid metal tube. Again you see the solid metal tube is completely enclosing the sodium and the induction coil is lower down into the tube to sense the level.

We have talked about purification systems and we have mentioned that the basic purification system is the cold trap. (III-A-64) Let's take a look at a cold trap system for a minute and see what it does. Sodium passes into the cold trap through this pipe here; down through a regenerative heat exchanger; and into a mesh region at this point. Now, surrounding this mesh region is an upward flow of cold nitrogen which takes heat away by means of some fins on the outside of the unit. So as the sodium passes down through the mesh region, it is cooled and as it cools the contained oxide tends to precipitate. As it precipitates, it is gathered by this mesh and is retained in the cold trap. The temperature is controlled by a thermocouple at this point after which the sodium passes back up through a central pipe; through the regenerative heat exchanger; and back to the system. This is entirely enclosed except for one connection here which is a special flange joint to permit insertion and removal of the trap. The traps are disposable when they become plugged.

Let's look at a system containing a cold trap to see what additional is required besides the trap itself to make it functional. (III-A-65) Here's the cold trap in this sketch, with an inlet and an outlet pipe. We obviously have isolation valves. We must have a freeze trap to permit complete venting when we install a new trap and also to permit drainage as we change the trap. We have a blower to blow nitrogen or air past the ducts and a thermocouple control that controls the flow of air. If the flow of air becomes too low, the trap becomes too hot and does not work effectively. On the other hand, if we have an excessive amount of air, we could cool the trap below the sodium freezing point and freeze it up. This sketch also shows an intermediate heat exchanger or a regenerative heat exchanger between the system and the trap. The reason for this is that the trap itself is disposable and the regenerative heat exchanger within the trap is purposely small for economy. Thus, should the system be at a very high temperature, let's say about 600°F, we would put a permanently installed regenerative heat exchanger at this point to minimize the heat exchanger required within the trap. Finally, I've shown a flow recorder/controller device at this point. Now, quite often when we are operating these traps in an actual system, we use the main pump as a driving force. However, the pressure of the main pump is a function of the power at which the system is operating. Thus, without flow control at this point, the flow through the cold trap would vary with power on the main heat transfer system, and would result in a rather ineffective cold trap operation.

(III-A-66) Here we see in effect the complete sodium purification system and I'd like to point out a few rather important points we may have missed so far. In this particular cold trap you will see that the nitrogen is in an enclosed circuit. Now we would use an enclosed circuit for the cold trap in the primary system because the nitrogen at this point becomes quite hot — possibly 200 to 300°F and we don't want that hot nitrogen discharged into the cell. Therefore, we would use an enclosed nitrogen circuit with a cooler inside. You will also notice over here that we have shown an oxygen hot trap and a carbon hot trap. Now where would we use these? The carbon hot trap is a means of removing carbon should the system ever become contaminated with carbon — a basic means of preventing carbon damage in the system is to keep the carbon out in the first place; and to prevent any possibility of entry of carbon. However, should the system ever become contaminated, then we must have a means of removal and we use the carbon hot trap. Also, for very high temperature systems, even the amount of oxygen that enters the system from the cold trap is not acceptable. This is true particularly if the metals that we call the refractory metals such as molybdenum, titanium, and zirconium are present in the system. Should the system contain these metals, then we must use a much more effective getter than the cold trap which is a hot trap consisting of zirconium foil inside of a tank or vessel. At approximately 1000°F this absorbs essentially all of the oxygen in the system.

(III-A-67) There are standardized Codes and Standards which we use in design of sodium systems and also generalized inspection procedures which we would use to inspect the equipment. For nuclear power systems, we use the ASME boiler and pressure vessel code, Section 3, "nuclear vessels," which is supplemented by code interpretation case 1331 for our temperature service. Section 3 of the ASME pressure vessel code is specifically for nuclear vessels and it differs from the other portions of the code in that it requires complete transient stress analysis and a complete fatigue analysis of the equipment. For non-nuclear systems we would use a somewhat less expensive approach. We would use the ASME boiler and pressure vessel code, section 1, "power boilers" for the steam generating equipment or section 8 "pressure vessels" for the other portions of the system. Now, section 8 has recently been divided into two portions — division 1 for "normal pressure vessels" and division 2 which is "alternate rules for pressure vessels." Division 2 of section 8 is quite similar to section 3 in that it also requires a fatigue analysis of the equipment. We also have the USA standard code for pressure piping No. B31.1.0 which was issued in 1967. We have a new USA standard No. B 31.1.7 which is for nuclear piping. It is for note that many of our present-day standards were written with water cooler reactors in mind. Care must be used in their application to assure pertinence to sodium systems.

The standards which we apply to the design of sodium systems are the various ASTM material specifications as applicable depending on the choice of materials. USA standards are used as applicable for pipe and fittings. We sometimes use the MSS standard practices. The American Nuclear Society and the USAEC are generating some new standards which will be available in the near future. One of the standards that these people are attempting to generate now are standards for pumps and valves. However, to date, the standards that have been developed apply strictly to what we call "water cooled reactors" and, therefore, are not applicable to the design of sodium systems.

In use of standards and codes, I would like to point out the need for the designer to read very carefully and to understand what is in the code. I am reminded of the time I bought a pump for a reactor back east and in specifying the pump, I specified that it would be cleaned very thoroughly and protected against dirt and contamination in transit. This was a necessity because the pump was to be used in a radioactive coolant. Our materials man got hold of the purchase order as it left the mill and inserted our standard packing and crating specification which was copied basically from the U. S. Army packing and crating requirements for overseas shipment. The packing and crating requirements specified that the equipment would be taken apart and be properly greased to assure that no moisture could get in and then wrapped in waterproof paper. The first I heard of this was when the manufacturer called and asked me whether I wanted my pump clean or whether I wanted it greased. So you see, arbitrarily inserting a standard specification is a very dangerous thing to do.

Now, once we specify what we want using the various codes and standards, we must inspect the equipment to assure that we have in fact gotten what we have asked for. (III-A-68) First we must inspect the materials and I have summarized some of the basic inspection procedures that we would go through in inspecting raw materials. All of the material used in fabricating code equipment must have certain inspections — they must have a chemical analysis and must have certain mechanical tests — tensile strength, usually in 2 directions. In the case of nuclear vessels, we have bend properties to be tested; and, of course, elongation and hardness to determine whether the material is brittle. The material should be inspected for dimensional accuracy and for surface finish. The designer may desire special tests such as ultrasonic inspection, radiographic examination, impact testing or cleanliness. Impact testing, incidentally, is a special requirement of section 3 of the code.

Now, for pipes and tubes, basically the same types of tests are required with one addition. Pipes and tubes must have a hydrostatic pressure test at the mill. Also, cleanliness is a rather important feature of the material, particularly to avoid the presence of deleterious materials which may react with the sodium. Some of these deleterious materials could be such things as dye penetrans materials, greases, or lubricants used in drawing or rolling the material. Any material containing chlorides are ruled out by specification, since stainless materials are subject to chloride stress corrosion and are very dangerous. Cleanliness in general is not something that an outside agency is going to inspect for you. This is the basic responsibility of the purchaser.

(III-A-69) Once the material that goes into building a vessel has been inspected and accepted; then, of course, it becomes necessary to inspect and test the vessel itself. In inspection of all code vessels, a hydrostatic or a suitable substitute for hydrostatic is a requirement. The code inspector will require a check of the welding procedure and certification that the welding procedure and the welder himself are qualified to build a code quality vessel. The inspection capability of the manufacturer is checked out and, in the case of most vessels except for ASME section 8, division 1, 100% radiograph of weld seams are required. Now, in some rather unimportant vessels, we may use spot radiograph or sectioning rather than 100% radiograph. The designer may desire additional optional inspection procedures. For example, dye penetrant inspection of the edges of the material may tell whether there are laps in the material or dye penetrant examination of the welds themselves may turn up cracks, laps, or other defects in the weld. Ultrasonic inspection is another approach to verifying the quality of the weld, as is magnetic particle examination. Hammer test is occasionally used by an inspector to determine if a weld is brittle. Impact test of weld specimens is often required to determine whether a weld is brittle, or a bend test may be required to determine if they have sufficient strength and ductility. Inspection for conformance to dimensions; for cleanliness and dryness; and helium leak tests is strictly the responsibility of the purchaser.

I would like to call your attention to the fact that a code inspector has only one objective in mind; and that is to ascertain the safety of the equipment. The code inspector is not interested in conformance to dimension, in cleanliness and other factors that are very important to the purchaser, so this again is the responsibility of the designer and the purchaser to assure that the vessel conforms to his requirements.

In design of welds for sodium service, we are very careful that the welds are full penetration welds. (III-A-77) I have a few sketches here showing some reasonably good practices for sodium service and some that are not acceptable. Over here you see a butt weld, a double butt weld, and some other types of welds where the welds are full penetration. Now in making double butt welds or double fillet welds of this type, we would lay the first pass on one side and then back chip the reverse side to bare metal to assure that there is no weld splatter or other contaminants trapped inside of the weld. Over here we see welds that are not full penetration — that leave voids which are not acceptable for sodium service.

Now, the fact that a weld is or is not acceptable by the code doesn't necessarily say that it is or is not acceptable as a sodium weld. (III-A-79) I have a couple of slides here that show actual acceptable welds in accordance with the code but some of these are not satisfactory for sodium service. You will notice that this is a full penetration weld and would be probably satisfactory. However, we do have a bad situation here in that there is an area where weld splatter could collect and could result in later failure of the material. Many of these have hidden areas where we could collect contaminants and result in future deterioration. We will not accept such welds for sodium design. Now we will take a look at this. (Figure UW-16-1,(U)) This is a full penetration weld. There are no places where contaminants could crack, could collect and crack, these welds would be quite satisfactory for sodium design.

I would like to call your attention to one in particular. (III-A-78) Here are a number of welds that are quite acceptable to the code. This is quite satisfactory for sodium service. This is and this is. This one is not. (Figure UW-16-1(d)) We had an incident at Hallam where a baffle was installed inside of a tank with exactly this type of construction, with a small void area behind the weld. Since the baffle was not a pressure part, the inspector did not consider this worthy of inspection. What actually happened was some of the flux from the welding process collected inside of this chamber. This flux contained some fluoride materials which resulted in stress corrosion cracking and ultimate failure of the entire vessel by stress corrosion cracking. So we are very sensitive to any weld that would permit any material to collect; and will not permit these types of welds to be used in design of sodium systems.

Now, we have another problem that perhaps we have mentioned, and I would like to go into a little more detail. That is the problem of sodium frost. Sodium normally has a slight vapor pressure, as we go above 1000°. Perhaps as we go up around 1200° the pressure becomes appreciable; and the cover gas over the sodium contains a measurable amount of sodium vapor. This vapor, in turn, can collect and condense on the cooler surfaces in the gas space. It can even freeze on the very cold surfaces, and remains as a sort of a frost. Then, in turn, should we get any oxygen into the system, even small traces, this oxygen would collect in the sodium vapor and result in a frost of sodium oxide. This is very difficult or perhaps impossible to remove from normal sodium systems. Therefore, we make every effort to prevent this sodium frost from forming in critical areas.

(III-A-80) This picture shows sodium frost. To try to clarify the picture, this is looking down here to a sodium reactor and if you will see the meniscus here on these rods, that is the sodium level. Anything below there is nothing more than a reflection of what is coming down from the top. But as we start at the meniscus and work up, these rods depart from the hot sodium surface, these rods are cooler under normal operating conditions, and at this point we have apparently reached the temperature where the sodium is collecting and freezing, and you will see quite a large collection of sodium frost up in this area. The rate of growth of the sodium frost has been quoted as something like a hundredth of an inch/year. I'm not sure that this is a very reliable number but perhaps it does give us a feel.

We do have a proposed system whereby we try to combat this sodium frost problem. (III-A-81) This sketch shows a possible design for the top rotating shield. This is the loading face shield of a reactor; and this is the edge of the reactor vessel, something possibly on the order of 18 ft in diameter. This plug has to rotate. The bearings shown at the top of the sketch, so that we must have a good clear, free area between the plug and vessel wall, so that there is no rubbing. We have rather large clearances in here. Of course, it is really too expensive to design this for close clearances but, if sodium should collect up in this area, and it will, then the top shielding cannot be rotated and we have no provision for removing that frost. Therefore, we have arranged to introduce a gas purge at this point which continually blows down this annulus and prevents the entry of the sodium bearing gases above the narrow gap labeled vapor barrier. So, if the sodium vapor cannot enter this area, then it is obvious that we would not have sodium frost at this point.

While I am looking at this slide, I would like to point out another problem that we have and that is the problem of maintaining a uniform level in the reactor. In this design we have a continuous overflow of sodium from here off into an overflow line and into a retaining vessel. There is one problem here that has the sodium overflows down into here, we get a great deal of surface turbulence which could entrain some of the cover gas. This, in turn, could then go back through the primary system and possibly even pass up into the reactor, causing reactivity spike. This is one of the problems we still have to work out.

(III-A-82) Let's look at the supply of cover gas we have to purge the annulus; and we find that in itself is a rather complicated process. We take gas off of the reactor and through a supply tank here, which happens to be the overflow tank. This gas is contaminated with sodium vapor up to possibly a 1000°F equivalent. If we were to pump that back into the annulus, we would be right back where we started the first time. We would have sodium frost from the very helium that we are using to prevent frosting; so we must take the sodium vapor out of the helium stress. This particular system shows a surface where the temperature of the material is dropped to approximately 600°F and the large majority of the condensed sodium vapor goes back into the supply tank. Even at 600°F at the flow rates we anticipate, we would not be able to tolerate the sodium vapor that would be in the stream; so we pass that sodium vapor up through a tower which has a counter-current flow of cold NaK at 150 to 200°F. As the gas passes up through the tower, the remaining sodium vapor is absorbed in the NaK; and the purified vapor free helium passes here to a circulating compressor; and into the annulus. Now, we have to design this entire system for a very low pressure drop for a good reason. We do not want this area to be on a negative pressure since there is a possibility of a leakage into the system. The circulating NaK system itself presents another problem. What happens should we get oxidation in this area? We would get plugging. However, by using a circulating pump and a cold trap, we are able to dissolve and remove sodium or potassium oxide and transfer them into the cold trap. We are adding heat with the incoming gas. We're also adding heat with the gas compressor at this point, so we have a coolant to remove that heat in the circulating NaK circuit. So you see it's somewhat more complicated to prevent this sodium frost than just wave a hand and say we want a flow of helium.

I'd like to discuss now a few of the very special problems that we have in mechanical design of components in sodium. (III-A-83) One is self welding. In sodium, which is a very strong reducing agent, all metals are basically pure metals whereas normally the metals are protected by some kind of an outside oxidized surface. This is particularly true of the stainless steels which owe their resistance to corrosion, not to the fact that they are stainless steel, but to the fact that they have an oxidized surface which protects them. In sodium, this oxidized surface is removed by the sodium we operate at high temperatures where, if two pieces of these metals are pressed together for long periods of time in a sodium environment and at high pressures, they will simply weld themselves together in a sort of a pressure weld. Seizing is basically the same tendency to self weld; however, seizing generally applies to dynamic rather than the static condition in which two moving pieces such as the pump shaft and bearing simply become welded at their point of contact by the fact that they are in a reduced state. Galling is a similar term in which two metals, usually a hard and a soft metal rub together. Bits of metal will be torn off the soft surface and will stick or weld to the hard surfaces, thus resulting in a gouging action on the softer of the two metals. We've found that these problems can be avoided by the use of certain hard facing materials.

(III-A-84) This shows an example of some of the places where we have to be careful. These happen to be two valves. The rubbing surfaces have been provided with hard surfacing material to avoid this problem. Stainless steel is notoriously bad with respect to such effects as galling and self welding.

Corrosion is another problem we have to watch and the resistance to corrosion has been pretty well determined. (III-A-85) Charts of this type are available which show that many of the materials which we are contemplating using are suitable up to approximately 1200°F. In general, they consist of the stainless steels and some of the high temperature alloys such as hastelloy and also some of the refractory metals. Incidentally, the refractory metals, in general, are subject to oxidation, so we have to take very special precautions in designing of the system to prevent oxidation in the system if it contains those metals. (III-A-86) This is the second sheet of the same chart which shows it up to around 1000 and 1200°. Many metals are satisfactory in sodium. Above that temperature we have to be very careful.

(III-A-87) In designing a system for rotating or for a wearing part, we have other considerations such as wear rates. This is one chart that has been developed showing wear rates as a function of temperature for various combinations of materials. As you see, the stellite vs stellites seem to be quite satisfactory. Some of the low alloys are not so good. For example, this chart here shows various combinations of low alloy steel and sodium, and it shows that these materials wear very fast if we operate at any appreciable temperatures. Normally we would use some hard facing alloy to prevent wear.

(III-A-88) Another factor that may be of importance is friction coefficient, which is somewhat different in that if we have bearings, for example, we want low friction at the wearing surfaces. This chart shows that the combinations of the stellites or some of the tungsten carbides might be quite suitable. One in particular is a rather exotic material with fused fluoride coating. However, I'm not sure that this has gotten out of the research stage. You see conversely that the various materials such as the carbon steels, the tool steels, incolloys, and the 300 series or various combinations of carbon steels are not so good as far as coefficient of friction goes. These again are often the combinations that would be susceptible to galling. (III-A-90)

We have a chart here that shows various couples that could be used for bearings at various load levels in sodium and I think you will find that the various stellites are quite satisfactory for low and medium temperatures. Here's an example of a combination of Stellite vs Kennametals and the Stellites have proven quite satisfactory. The stainless steels are not quite so good.

We have mentioned some of the problems that we would expect with radiological effects. (III-A-91) This shows some of the problems that we anticipate to run into from the results of the radiological effects of the sodium.

First, I've shown the two radiological reactions of sodium themselves — sodium-23 plus a neutron yielding sodium-24 plus a gamma. This material has a half life of 15 hours coupled with high gamma energies. However, this is not a most serious problem primarily because of the 15-hour half life. Within approximately two weeks the radiation from sodium-24 becomes basically negligible. Another reaction would be sodium-24 plus a neutron yielding sodium 22 plus 2 neutrons. This material is not formed in any great quantity because the reaction is a function of the neutron energy which has to be in excess of about 10 Mev per neutron; and there is only a very few of these in the reactor. However, this material does have a 2.6-year half life vs a 15-hour half life of sodium-24. After a shutdown for approximately 10 to 15 days, this becomes the significant sodium species.

Now let's see how the radiation implications affect systems design. During normal operation, if we look at sodium-24, we find a very high specific activity. We find a very high dose rate — 5 times 10^5 R/hr. In simple terms this means that a person could live approximately 2 seconds in the environment which was assumed next to an intermediate heat exchanger. The sodium-22 during normal operation is appreciable — 3 R/hr-but not particularly important. Now, we also have corrosion products. Various materials of construction in the core have corroded and have been transported into the intermediate heat exchanger where this particular calculation was made. We find 210 r/hr. At this level, perhaps 2 to 3 hours would be a half lethal dose if that were the only material there. Fission products constitute an appreciable radiation level but certainly insignificant as compared with some of the other materials. If we were to take 10 ccs of the reactor sodium during operation and spill it into a reactor building which is perhaps 140 ft in diameter by 140 ft high, we would exceed the permissible dose rate in that building.

(III-A-92) Now let's look at what happens when we shut the reactor down. Again we look at that sodium-24 and I assume that I have shut the reactor down and have immediately drained all the sodium out. We still have approximately 2000 R/hr at the surface; which means that you would get a lethal dose in perhaps 10 minutes. It's quite a high radiation level. You would have approximately 2 seconds working time immediately after shutdown after draining all of the sodium out, this due to sodium-24. Obviously we can't approach the sodium equipment immediately after shutdown. Now the sodium-22 is of much lower order of magnitude and if that were the only component we could work 30 hours in there before we got a limiting dose. Corrosion products though are limiting immediately after shutdown, and also fission products which would limit your working to perhaps 7 minutes, so obviously we don't go close to the sodium equipment immediately after shutdown. Let's look now at what has happened in possibly two weeks delay. Sodium-24 is down to 0.2 per mr/hr and we could work from now on next to the intermediate heat exchanger. However, look at some of these other materials we have previously considered insignificant. Corrosion products have not decayed appreciably so they still limit us to possibly 20 seconds working time before we get a limiting dose. Obviously, again we cannot approach the intermediate heat exchanger without shielding or other protection. Fission products also have not decayed and the sodium-22 has not decayed. However, it is not limiting. The limiting factors are the corrosion products and fission products. So you see, the intermediate heat exchanger must be designed for a low maintenance requirement; or for the maintenance applications in which we can work behind shielding walls.

One of the questions that we have not answered yet is why do we use sodium in the first place as a heat transfer medium. (III-A-93) Let's look at some of the heat transfer properties of sodium. I have prepared some comparisons here between sodium which is a liquid metal; water which is a very common heat transfer medium; and helium which is probably the best gaseous heat transfer medium which we can find. I have shown some of the various parameters that would go into a heat transfer calculation, temperatures selected uniformly at 500°. Look at the pressure. In this case, sodium pressure is almost 0 to 10^{-6} atmosphere is hardly measurable. Water is 16 atmosphere — something on the order of 700 psi which means that we would have to design a reactor vessel for that pressure. Helium being a gas at all pressures, I was quite arbitrary and picked 17 atmospheres as being a suitable comparative pressure. Now, let's look at the heat transfer coefficient. I came up with a comparative heat transfer coefficient of 8000 for the sodium, 4600 for the water — quite comparable — very high, and 199 for the helium which means that the helium is very low on a heat transfer basis. Let's look at flow velocities. I chose 8 for sodium and water and 150 for helium. Here again it was arbitrary. So you see the much higher pressure — much higher velocity required with the helium.

Now, 500° is a relatively low temperature for modern steam conditions. (III-A-94) Let's see what happens when we go to 1000°F which is somewhere near the temperature that we would operate a modern steam turbine. Again I have shown sodium, water and helium, and I have chosen 1000°F as the uniform temperature. Look at the pressure. Sodium is still approximately 1/100ths of an atmosphere or almost negligible vapor pressure. Water is up to 245 atmospheres which is something on the order of 3500 psi. That is quite arbitrary here because we are well above the critical temperature of water so I can choose my pressure to suit myself, but you see I have asked that we design a reactor for something like 3500 psi. Here again I stuck to the 17 atmospheres for helium which is quite common.

Now under these conditions, all liquid metals in this area can be operated as a liquid and let's see what happens to our heat transfer. Sodium actually has gone up from 8000 to 10,000, it has actually improved its heat transfer coefficient. Water has dropped from something on the order of 4000 to 300 and helium is approximately the same – 196. So you see, water and helium at this temperature are basically insulators vs sodium which has a very high heat transfer coefficient. Look what happened to pressure drop. Again, sodium has 8 to 12 psi/hundred feet at 8 ft/sec, the water which is now steam is whistling at 100 ft/sec, and the pressure drop has gone up from something on the order of 12 to 200 psi. So you see, the water is much poorer heat transfer agent than sodium at a 1000°F and actually it is quite comparable to helium.

(III-A-95) Let's go back and summarize what we have talked about so far and see if we can bring this to a reasonable conclusion. We've discussed the fact that there were far more than one system involved in a sodium system. There was the sodium heat transfer system whose basic objective was to transfer heat from the reactor core to the steam generating facility. We divided this into a primary and a secondary system for radiological purposes. To support this, we required a sodium storage and purification system. We required a helium supply system for cover gas and to prevent the entry of atmosphere into the system. Since the primary sodium is radioactive, we require a radioactive vent system and also we require a vent system for the secondary sodium system basically to control the pressure in the system and to prevent the entry of air.

We require an electrical preheat system to get the system up above approximately 350°F so that we could fill it. The steam system obviously is the key to the entire problem because the whole objective is to make steam which in turn is used to drive the turbine. The feedwater supply system must serve the steam generator. We need an electrical supply system to drive the pumps; to service the instrumentation system and to service the electrical preheat. We need a nitrogen system to prevent the possibility of sodium fire in case of a leak in the vault. We need a vault cooling system to remove the heat that is given off inside of the vault, and finally we have to be prepared for a sodium to water reaction in steam generators. Therefore, we have provided the steam generator rupture relief system. Finally, the entire complex must be tied together with a suitable instrumentation system. We went into a number of special topics. We discussed the influence of elevation on design and how we provide for natural convection circulation which is a necessity should we lost electrical power.

We discussed how we design a system to contain sodium by using all welded construction and by using special seals on valves and instruments and any other penetrations. Where possible we have used backups to the various seals so that in case of failure of one seal we still would not lose sodium into the surroundings. We discussed the fact that in case of a sodium leak, particularly at high temperatures, the sodium would form sodium peroxide which is very corrosive and causes a very rapid deterioration of the sodium envelope itself to say nothing of the possibility of sodium fires. We discussed the fact that the vent systems must have check valves to prevent back filling into the system. The vent system itself is a very complicated system because we have to be very careful that materials containing radioactive sodium vents are not mixed with those that are not radioactive. There is another possibility and that is that vents from areas which could have moisture in them must not be mixed with vents from sodium systems. So, you see, we're not speaking of one vent system, we're speaking of a number of them.

We spoke of the design of the preheating system which permits us to preheat the systems starting at a pre-sodium surface and thus prevents the buildup of excessive pressure as we preheat. We require the electrical and steam systems as service facilities. We discussed the fact that as we preheat some of the larger equipment we are restricted by the rate at which we can preheat by the rate by which we get the heat from the outside or from the electrical preheaters into the intermost part of the complex, thus avoiding the possibility of excessive thermal stresses. Incidentally, this problem obviously is much relieved when we get the system full of sodium because the sodium is a much better transmitter of heat than the helium cover gas.

We discussed some of the operations and maintenance problems that we are likely to run into — the fact that some of the equipment will be so radioactive that we cannot approach it. Where we installed the portions of the systems that would require maintenance if possible outside of the shielded vault. We discussed use of the shielded cask and plastic bags for preventing the entry of air into the system. We discussed the fact that we clean up sodium systems only when necessary. We found that sodium itself is one of the best cleaning agents we have. It is quite possible to remove much of the dirt or contamination from the sodium by means of filters or cold traps. We discussed cutting piping. In the case of small pipes, we would cut it full of frozen sodium, thus giving a very good seal against entry of atmosphere.

We discussed the fact that the system must always be preheated and particularly that the vents which could collect and freeze sodium are preheated. We use the vapor traps to remove the vapor from the cover gas before we permit the cover gas to enter the non-heated portions of the cover gas system. We discussed purification of the sodium, primarily the use of the cold traps and also the possibility that, in more elevated temperatures or using of more exotic materials, we will be forced to go to a more exotic means of removing oxides such as the hot traps. Also we may be forced at times to remove carbon contamination by carbon traps.

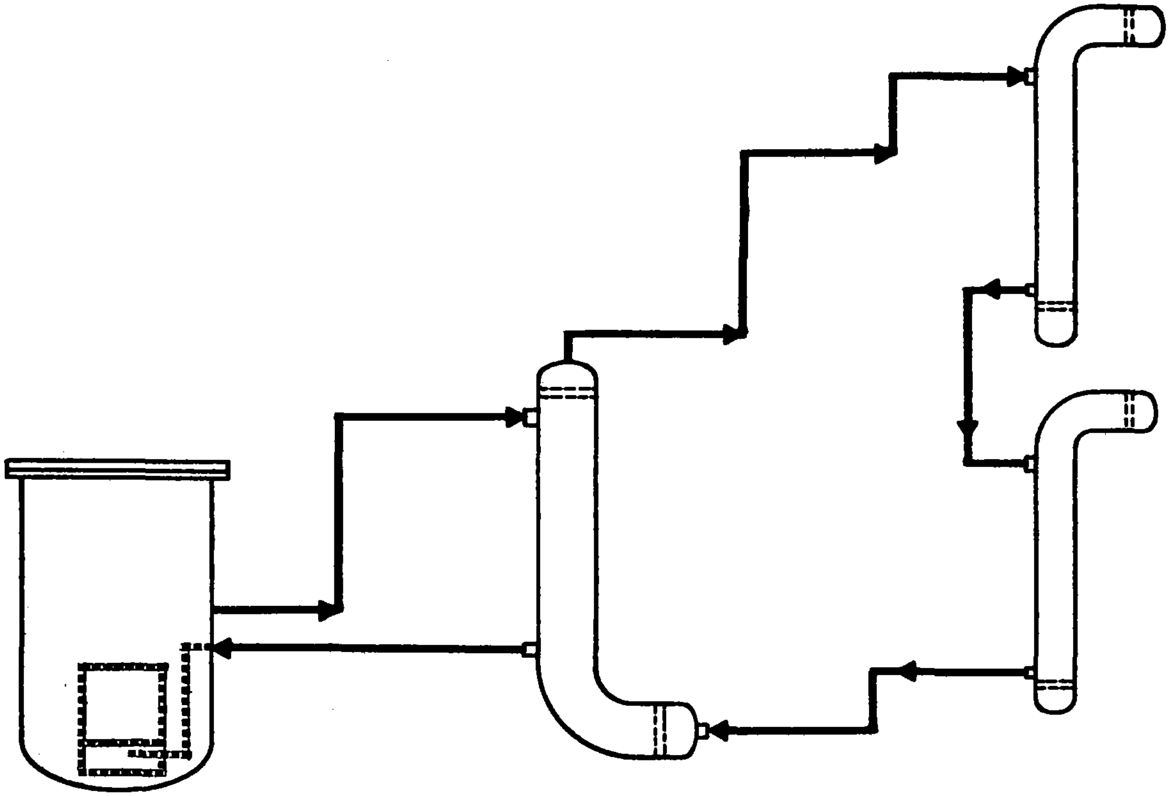
We discussed codes and standards and the fact that these can be a trap if we do not go over them very carefully and specify exactly what we want. We discussed welding where we would not permit a non-full-penetration weld or the existence of cracks or crevices behind welds to exist in sodium systems. We discussed the fact that, in specifying vessels, we must specify special tests and we must specify suitable inspection procedures, not only by the boiler inspector who is inspecting for safety of the vessel but by our own inspectors who must inspect for compliance with dimension requirement or cleanliness; for packing and for other reasons. We discussed the fact that, in welding of sodium vessels, we use the tungsten inert gas process which gives a nice clean weld next to the sodium envelope.

We discussed some of the special problems involved in designing a sodium system — sodium frosts, self welding, seizing and galling which can cause us very serious trouble. In the case of sodium frost we have such special systems which are used to control this problem. In the case of self-welding, seizing and galling, we are very careful to select hard materials that are compatible and that will not result in this problem. We discussed corrosion of sodium systems in which we found that most of the ferritic materials, and most of the common hard facing materials are quite resistant to corrosion up to approximately 1200°F. Above this temperature we would go to some of the refractory materials which are highly subject to oxidation and which necessitate the use of hot traps for oxygen removal or other special precautions.

We discussed the problems of radiological contamination, the fact that in many of our systems we are unable to approach for maintenance and, therefore, we have to design with this in mind — that either they be completely free of the requirement for maintenance, or that we have some means of removing the component that needs maintenance.

Finally, I would like to leave with you one more thought. We've discussed the fact that much of the primary sodium system is very highly radioactive. This is due to activation of the metals, to the existence of cobalt and other materials in it and, therefore, once we have sealed up the reactor cavity for the last time prior to normal operation, it probably will be impossible to ever enter that area. Now what happens when the plant becomes obsolescent and it is necessary to put it to bed, so to speak — to make the plant completely safe for abandonment? This, I think, is one of the problems that we must keep in mind at all times. The plant must be decontaminated with respect to sodium, it must be decontaminated or sealed with respect to radioactivity so that there is no chance, possibly for hundreds of years, for escape of the radioactive material. So, I think, this is one of the future design problems in sodium systems is how to design to permit final decommissioning of the plant. With that thought I'd like to close and I hope that this lecture has been of benefit to you in understanding the complexity and the extent of design of sodium systems. Thank you gentlemen.

REACTOR IHX STEAM GENERATOR



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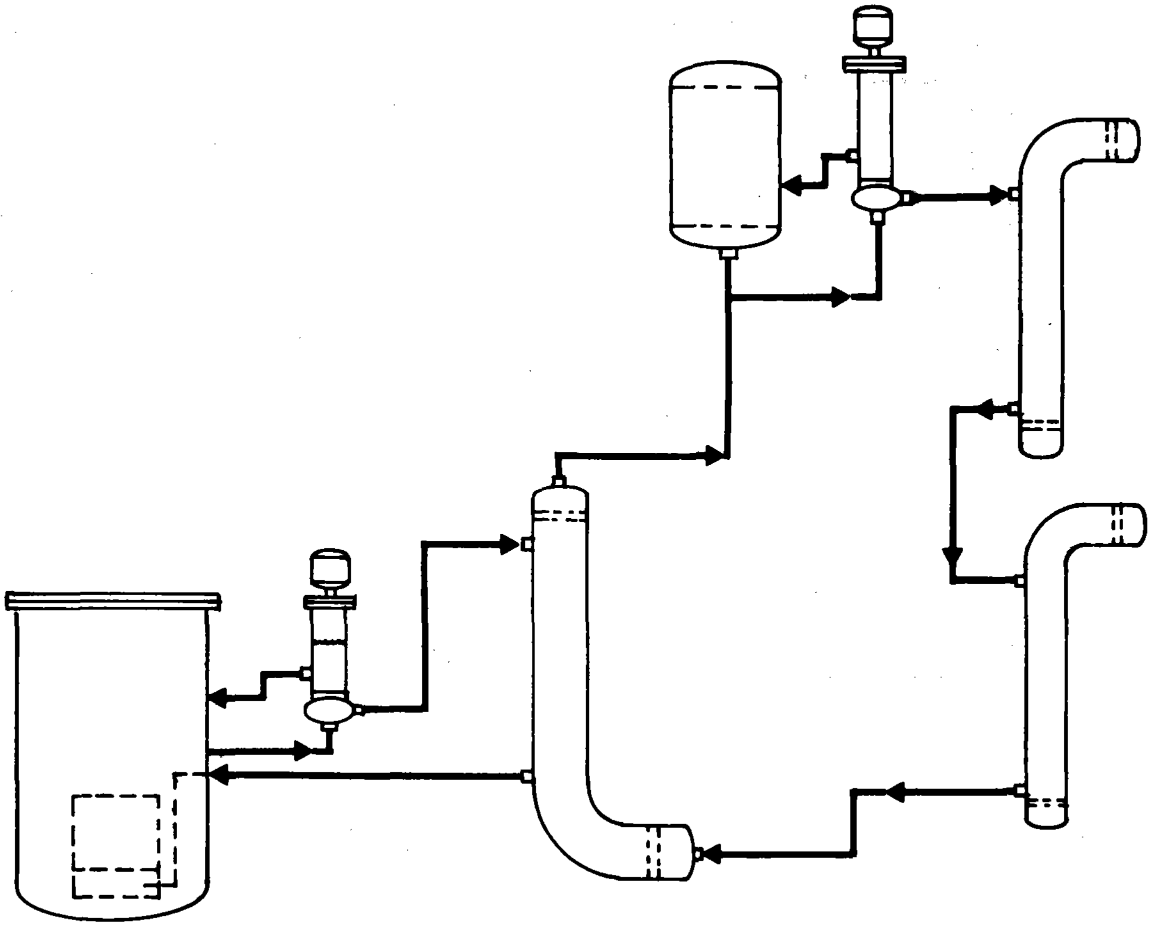
REACTOR PRIMARY PUMP IHX SECONDARY PUMP STEAM GENERATOR



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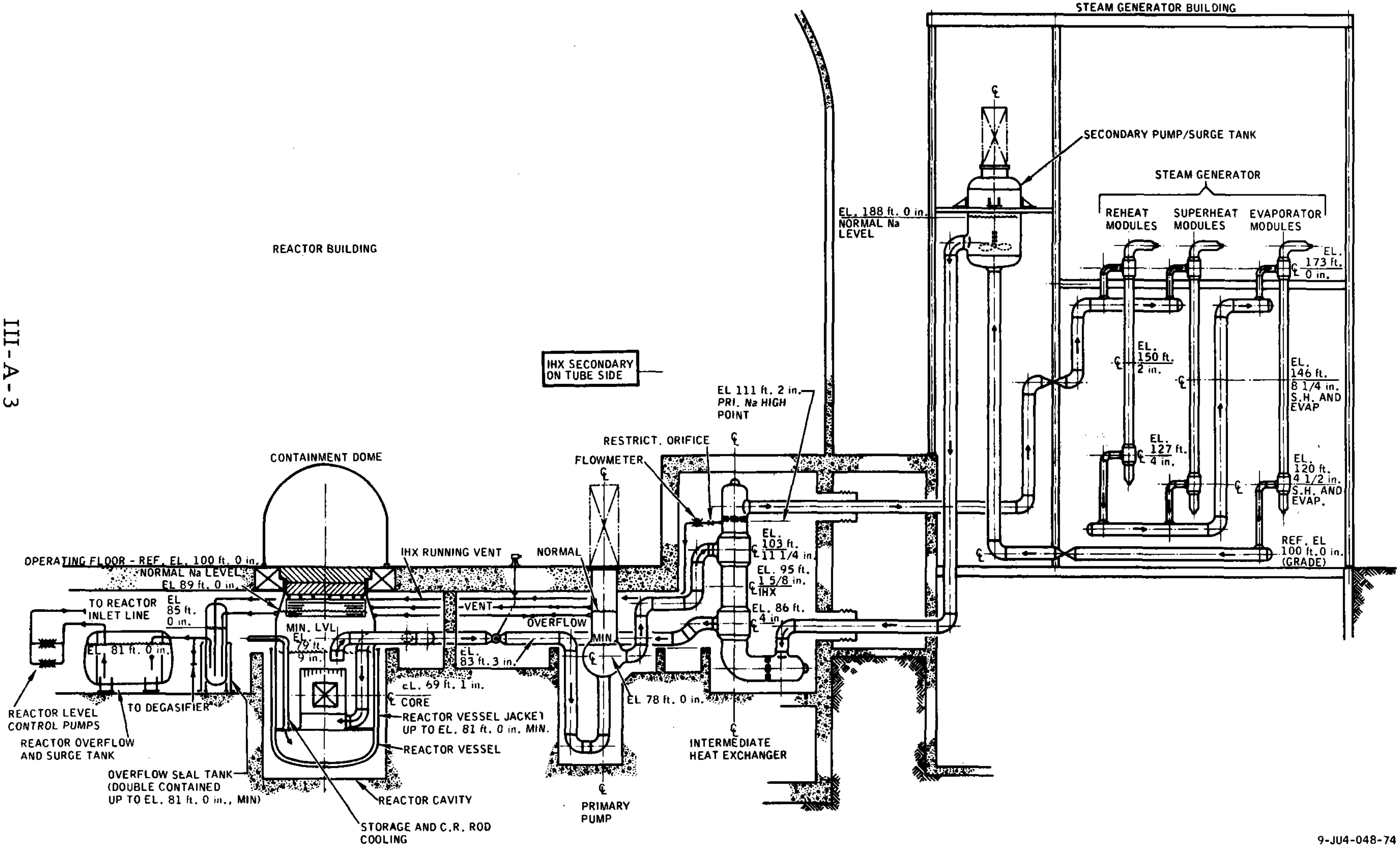
500 Mwe FBR - REACTOR AND HEAT TRANSFER SYSTEM ELEVATIONS



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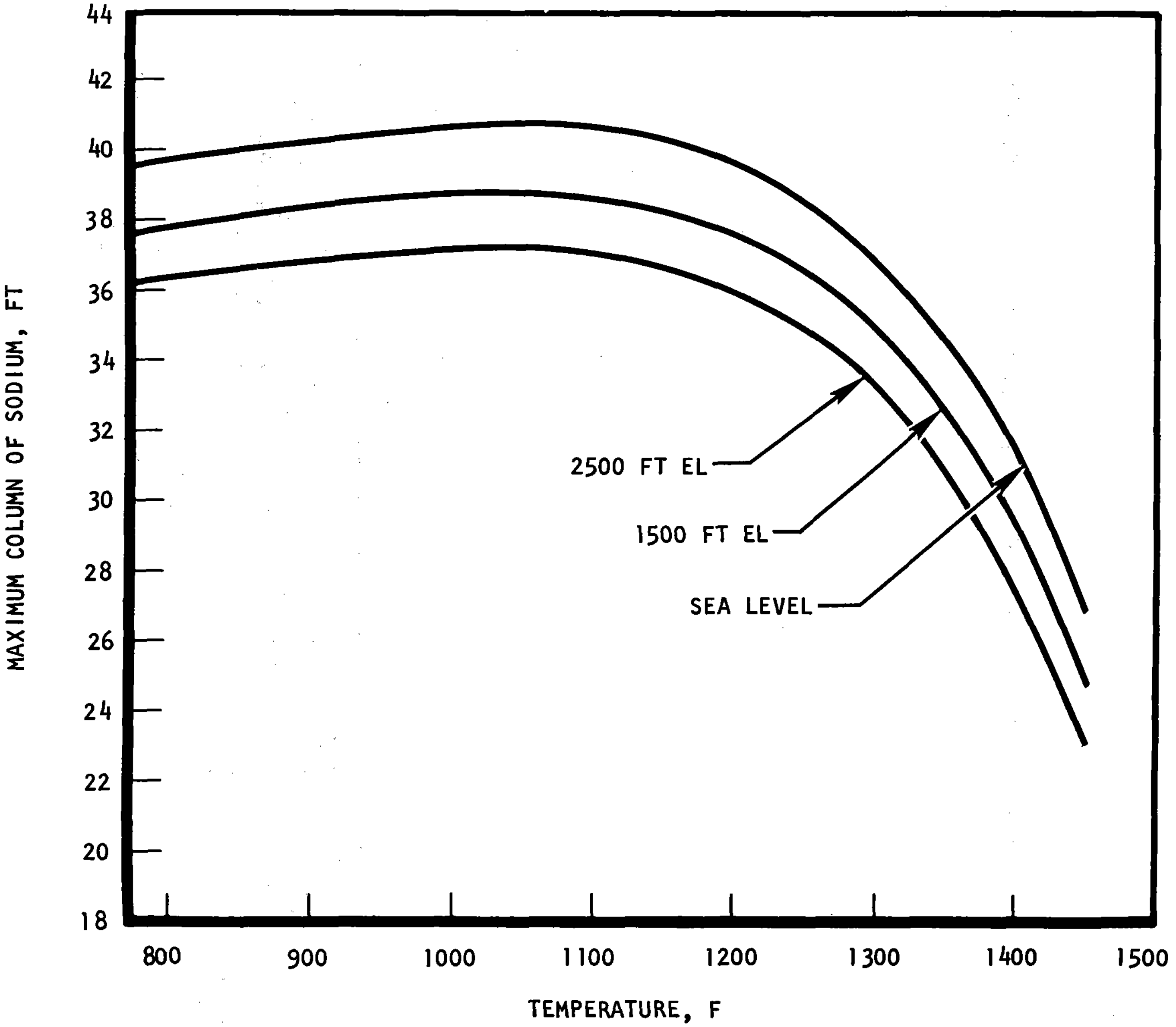
HEIGHT TO WHICH A COLUMN OF SODIUM CAN BE HELD AT ATMOSPHERIC PRESSURE



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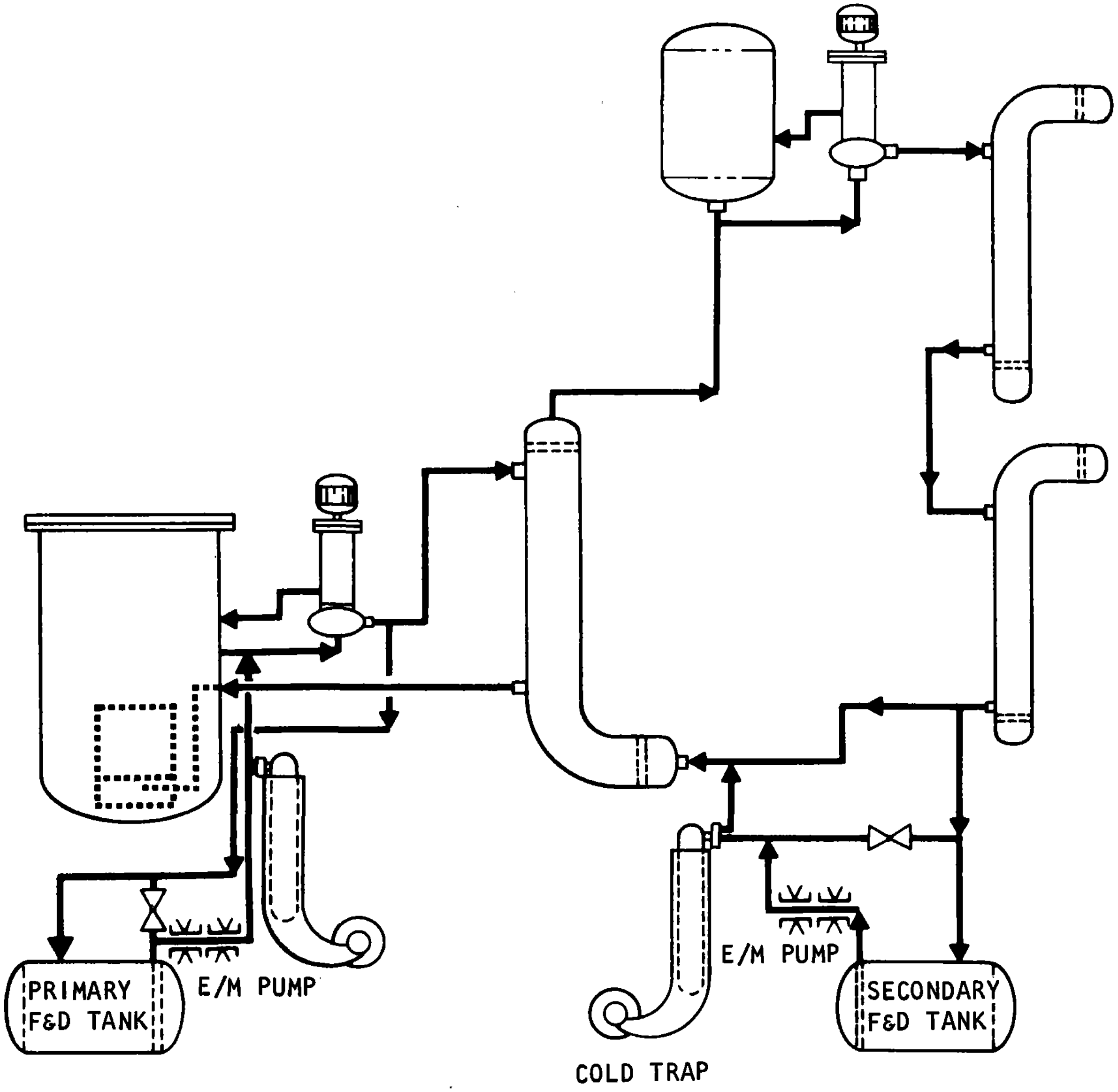
REACTOR PRIMARY PUMP IHX SECONDARY PUMP STEAM GENERATOR



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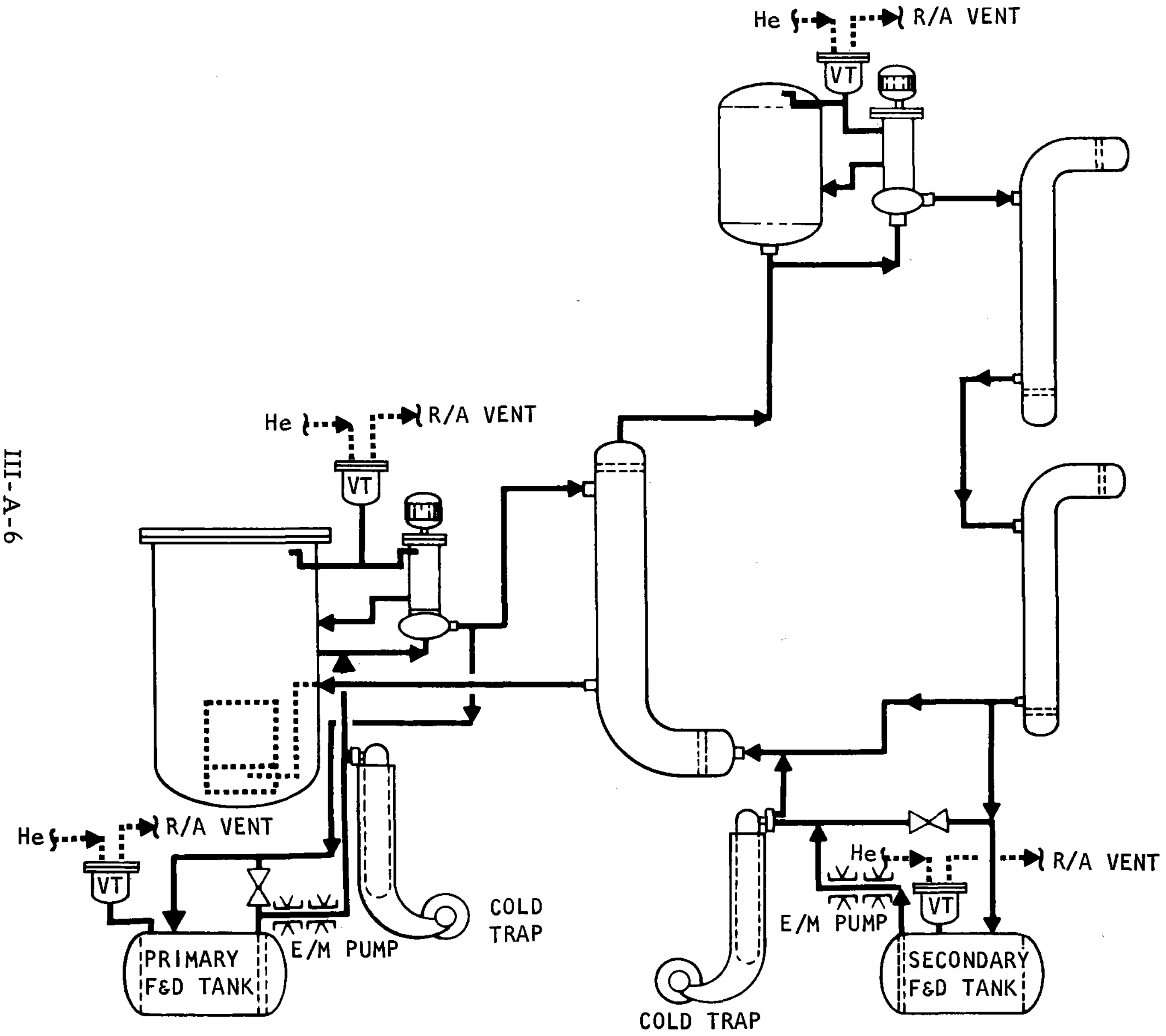
REACTOR PRIMARY PUMP IHX SECONDARY PUMP STEAM GENERATOR



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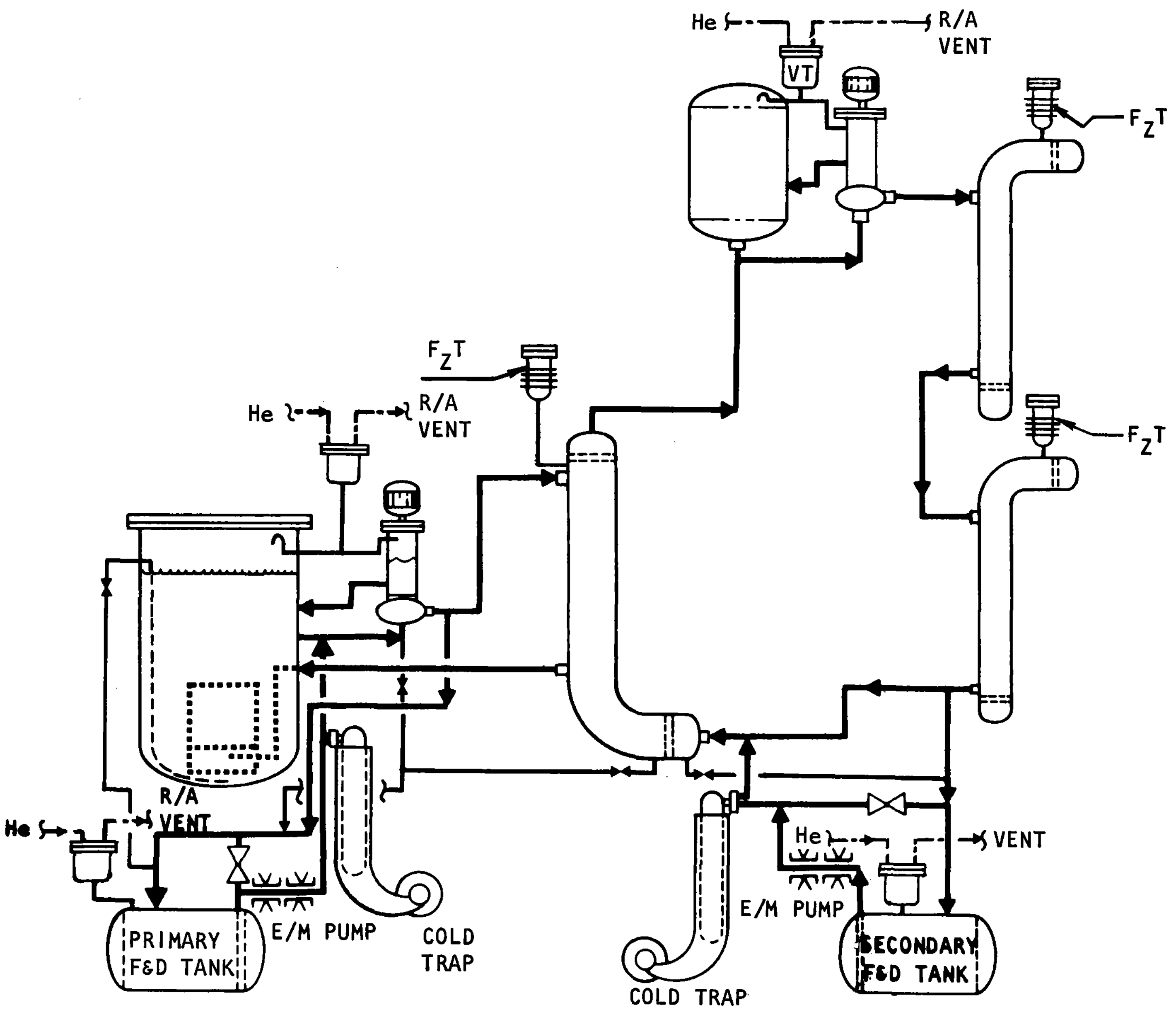
REACTOR PRIMARY PUMP IHX SECONDARY PUMP STEAM GENERATOR



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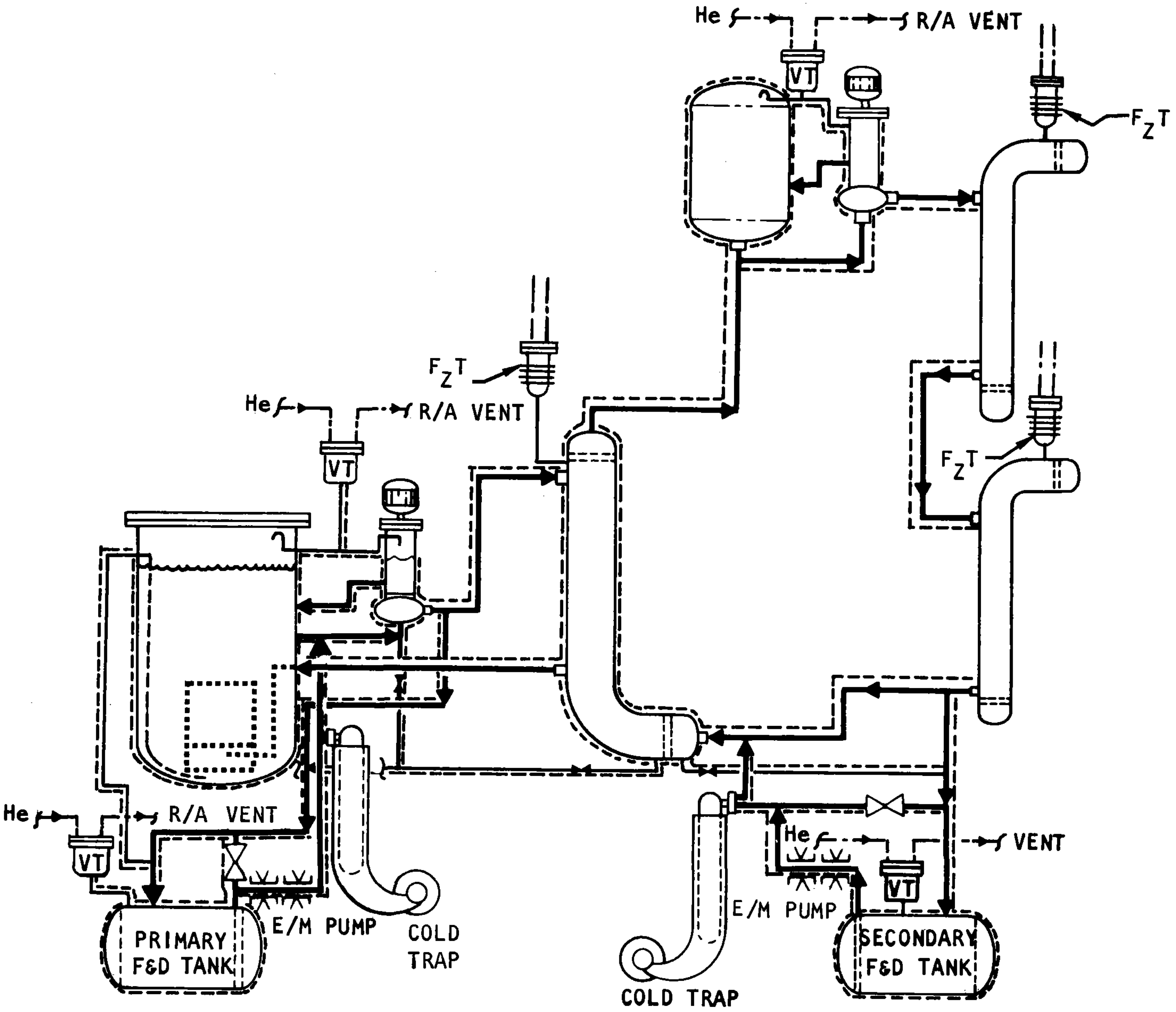

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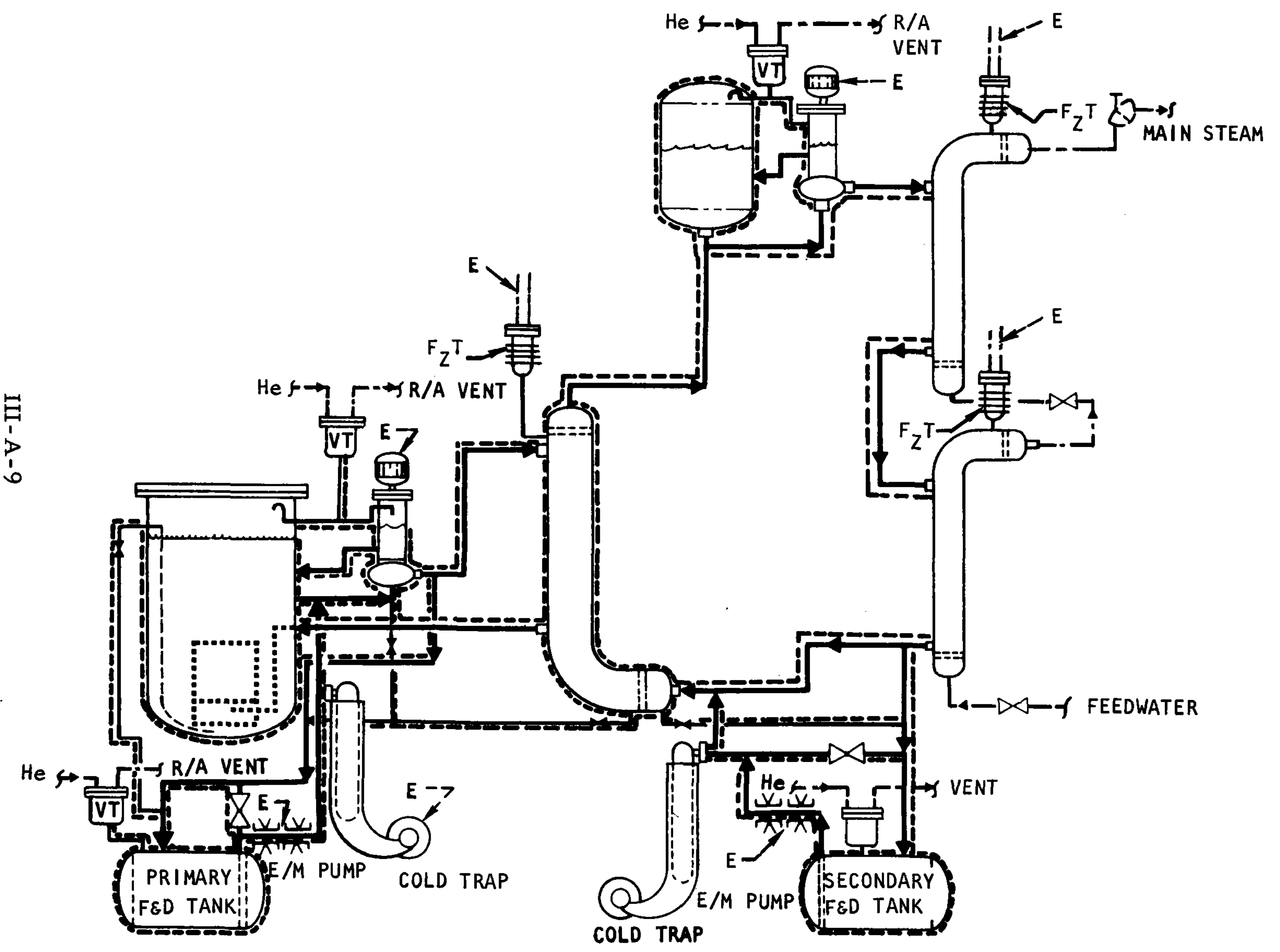
REACTOR PRIMARY PUMP IHX SECONDARY PUMP STEAM GENERATOR



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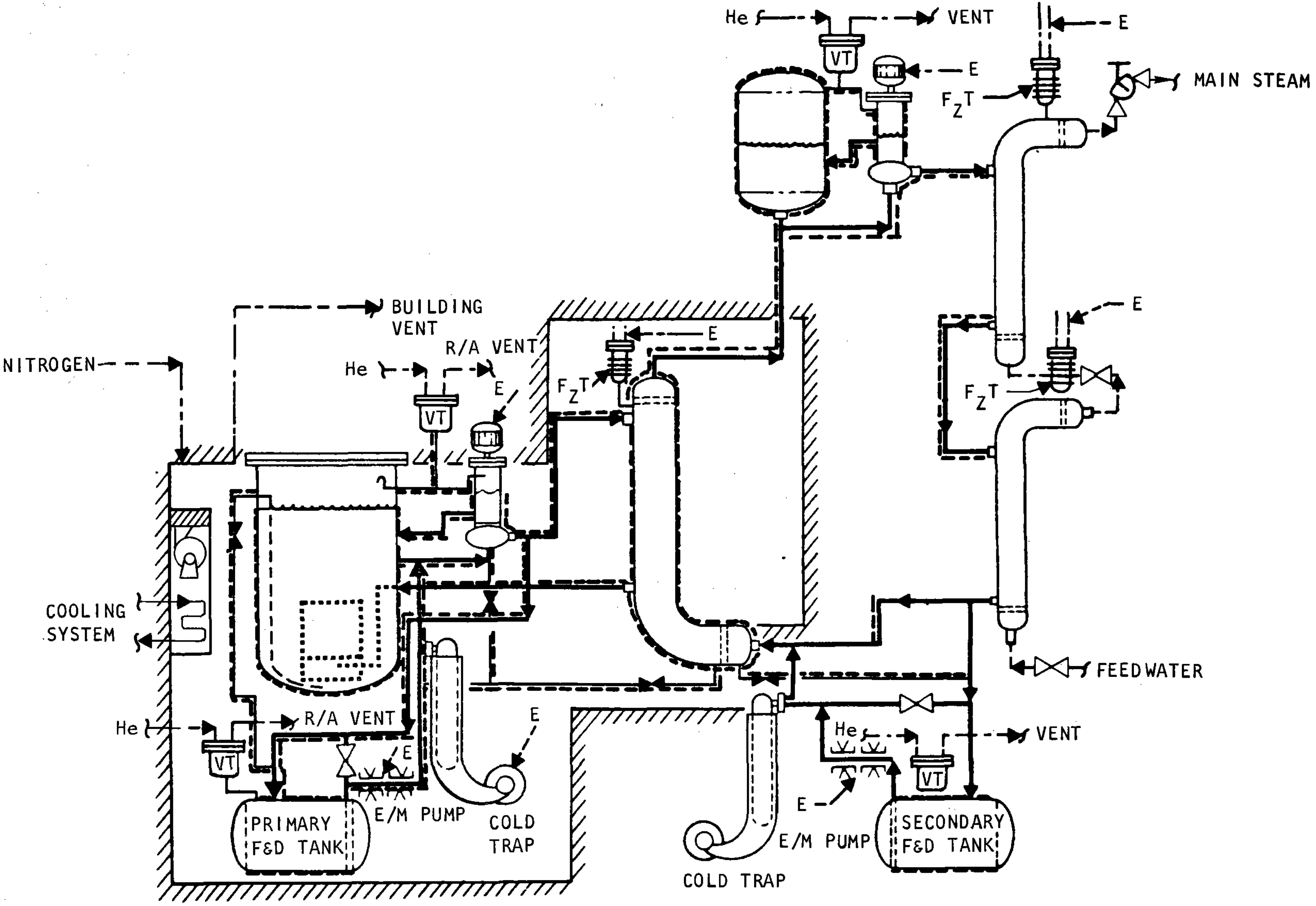

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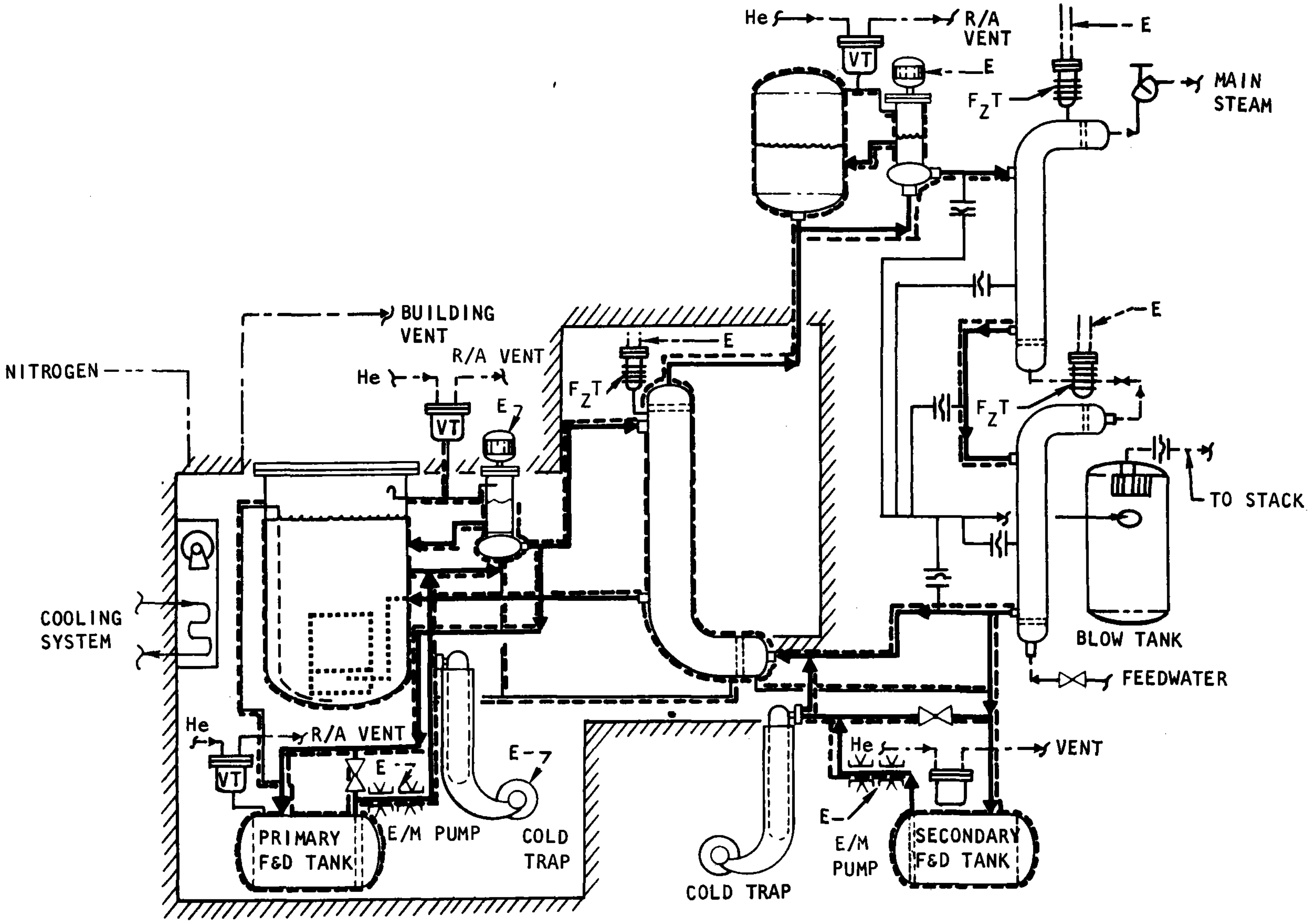
REACTOR PRIMARY PUMP IHX SECONDARY PUMP STEAM GENERATOR



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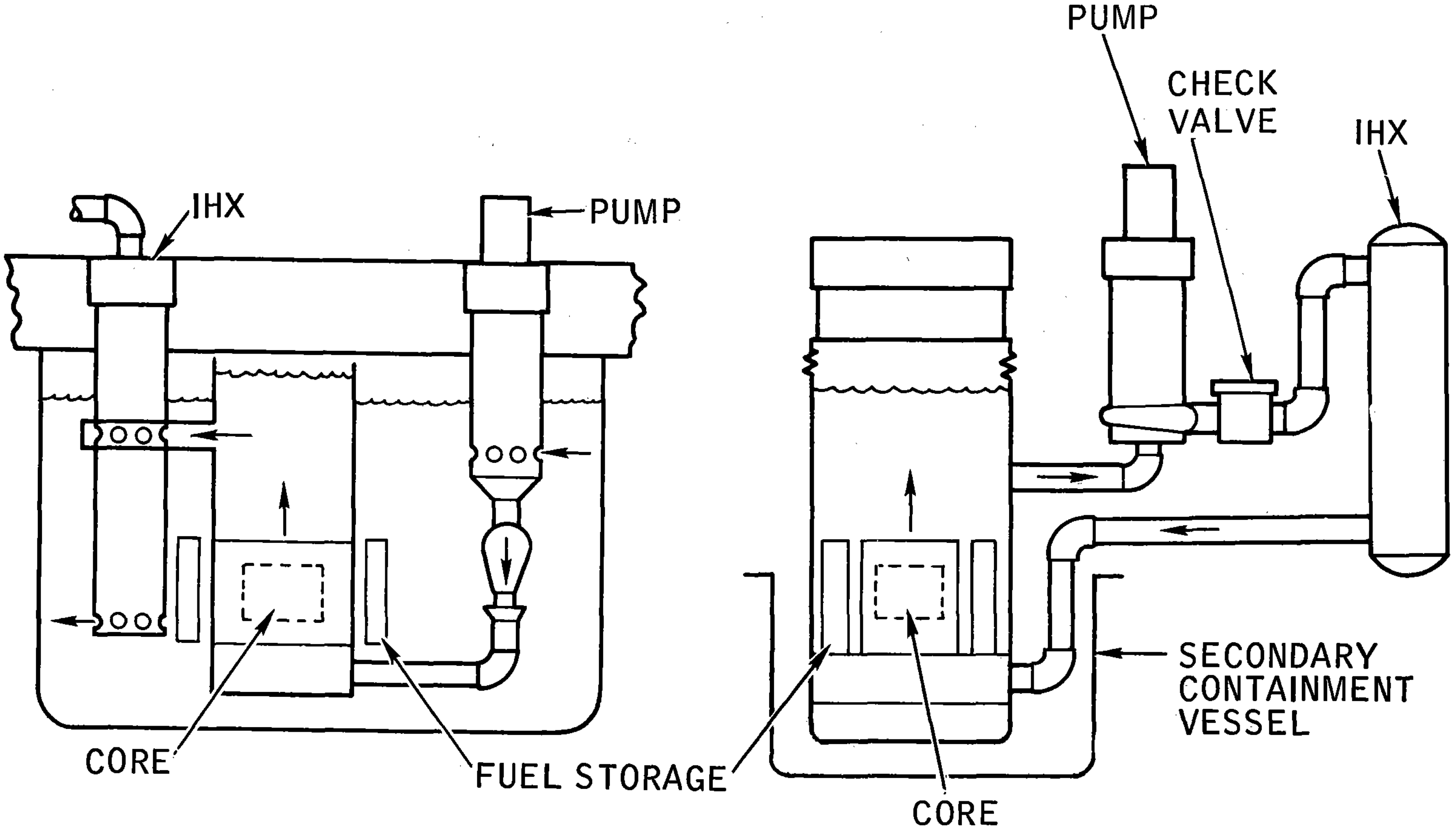
POOL (POT) vs LOOP COMPARISON



POT **LOOP**

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SYSTEMS

- SODIUM HEAT TRANSFER SYSTEM
- SODIUM STORAGE AND PURIFICATION SYSTEMS
- HELIUM SUPPLY SYSTEM
- R/A VENT SYSTEM
- SECONDARY SODIUM VENT SYSTEM
- ELECTRICAL PREHEAT SYSTEM
- STEAM SYSTEM
    - A) MAIN STEAM SYSTEM
    - B) STEAM PREHEAT AND STARTUP SYSTEM
- FEEDWATER SUPPLY SYSTEM
- ELECTRICAL SUPPLY SYSTEM
- NITROGEN SUPPLY SYSTEM
- VAULT COOLING SYSTEM
- STEAM GENERATOR RUPTURE RELIEF AND RECOVERY SYSTEM
- INSTRUMENTATION AND CONTROL SYSTEM

9-N18-129-67

SODIUM COOLED REACTOR
COST DISTRIBUTION TO PROCESS SYSTEMS

DIRECT COST ITEM:	NUCLEAR ISLAND (%)	BALANCE OF PLANT (%)	TOTAL PLANT (%)
REACTOR COMPLEX	9.3	—	5.7
HEAT TRANSFER SYSTEM	40.2	6.7	27.7
TURBINE/GENERATOR COMPLEX	-	54.4	19.4
INSTRUMENTATION SYSTEM	8.8	1.5	6.0
AUXILIARY SYSTEMS	7.6	7.8	8.5
ELECTRICAL SYSTEMS	2.5	12.6	6.6
SUPPORT EQUIPMENT	7.5	2.0	5.3
SITE AND STRUCTURES	24.1	15.0	20.8
TOTAL	100	100	100

SUMMARY:

SODIUM HEAT TRANSFER SYSTEM	24.0
AUXILIARY SYSTEMS, NUCLEAR PLANT	4.7
OTHER AUXILIARY SYSTEMS (PREHEAT IN THE NON-NUCLEAR PLANT)	0.3
PERCENT OF TOTAL PLANT ATTRIBUTED TO SODIUM AND AUXILIARY SYSTEMS	29.0

9-N10-129-36

FUNCTIONS OF THE MAIN HEAT TRANSFER SYSTEMS:

- TO MAKE STEAM FOR THE GENERATION OF POWER (IN THE CASE
- OF A POWER REACTOR)
- TO REMOVE HEAT FROM THE REACTOR CORE
- TO ASSURE COOLING OF THE REACTOR AT ALL TIMES, INCLUDING ALL FORSEEABLE EMERGENCY CONDITIONS

FUNCTIONAL REQUIREMENTS OF THE MAIN HEAT TRANSFER SYSTEMS

- THERE MUST BE AT LEAST TWO OPERABLE HEAT TRANSFER LOOPS AVAILABLE PRIOR TO POWER OPERATION
- SECONDARY SODIUM PRESSURE AT LEAST FIVE POUNDS HIGHER THAN PRIMARY SODIUM PRESSURE IN THE IHX AT ALL POINTS AND TIMES

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FIGURE 1.
SIMPLIFIED FLOW DIAGRAM

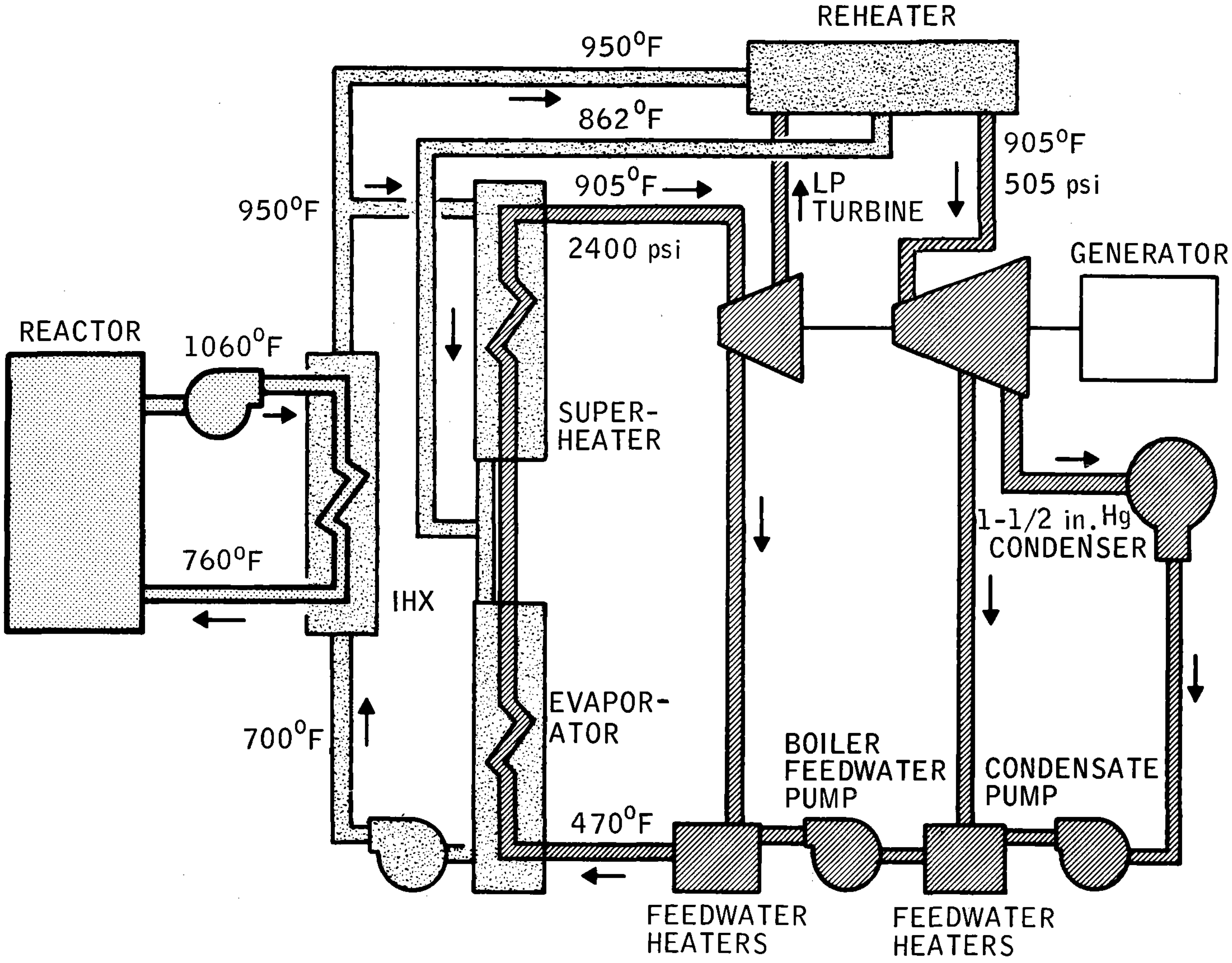

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FIGURE 2

HEAT TRANSFER SUBSYSTEM TRADE STUDIES

TYPE	TRADE STUDY	"REFERENCE" SELECTION
CONFIGURATION	● SODIUM CONTAINMENT	ELEVATED LOOP CONCEPT
	● PUMP LOCATION – HOT vs COLD LEG	HOT LEG
	● PUMP TYPE – EM vs MECHANICAL	MECHANICAL
	● PUMP SPEED CONTROL METHOD	EM COUPLING
	● VALVE TYPES	PRIMARY LOOP: THROTTLING (BUTTERFLY) CHECK (BALANCED), BLOCKING (DOUBLE WEDGE)
	● SYSTEM GAS REMOVAL	LOOP LAYOUT, GAS VENTING, DIFFUSION BARRIER DEGASSING SYSTEM AND HYDROCLONE (BACKUP)
	● EMERGENCY COOLING	CONVECTION FLOW (5%)
	● IHX TYPE	VERTICAL, HOCKEY STICK SHELL AND TUBE
DESIGN POINT	● PIPING SIZE	PRIMARY: 36 in. (SUCTION) 32-in. DISCHARGE SECONDARY: 32-in. (HOT LEG) 30 in. (COLD LEG)
	● NUMBER OF PUMPS	ONE PER LOOP
	● NUMBER OF IHX's	ONE PER LOOP

8-09-144-29

FIGURE 3.
HEAT TRANSFER SYSTEM CHARACTERISTICS

● NUMBER OF LOOPS	
■ PRIMARY	3
■ SECONDARY	3
● REACTOR THERMAL POWER (Mwt)	1250
● TOTAL REACTOR FLOW (lb/hr)	47.1 x 10^6
● REACTOR INLET TEMPERATURE (^{o}F)	760
● REACTOR OUTLET TEMPERATURE (^{o}F)	1060
● PRESSURE AT TOP OF REACTOR VESSEL (psig)	1
● PRIMARY SYSTEM SODIUM VOLUME* (ft^3)	24,750 (185,000 gal)
● PRIMARY SODIUM VOLUME/LOOP (ft^3)	3610
● SECONDARY SODIUM VOLUME/LOOP (ft^3)	10,700
● PRIMARY SODIUM PUMPS**	3 (ONE/LOOP)
■ FLOW (gpm)	38,500
■ HEAD (ft)	370 (130 psi)
■ BRAKE HORSEPOWER (Bhp)	3130
■ NPSH AVAILABLE (ft)	47

*INCLUDES THREE PRIMARY LOOPS

**FOR 100% POWER CONDITIONS

● INTERMEDIATE HEAT EXCHANGERS	3 (ONE/LOOP)
■ DUTY/IHX (Btu/hr)	1425 x 10^6
■ SURFACE AREA/IHX (ft^2)	16,000
● SECONDARY SODIUM PUMPS**	3 (ONE/LOOP)
■ FLOW (gpm)	45,000
■ HEAD (ft)	225 (81 psi)
■ BRAKE HORSEPOWER (Bhp)	2810
● STEAM GENERATOR BANKS	3 (ONE/LOOP)
■ EVAPORATOR DUTY/BANK (Btu/hr)	925 x 10^6
■ EVAPORATOR SURFACE AREA/BANK (ft^2)	14,700
■ SUPERHEATER DUTY/BANK (Btu/hr)	257 x 10^6
■ SUPERHEATER SURFACE AREA/BANK (ft^2)	5880
■ REHEATER DUTY/BANK (Btu/hr)	243 x 10^6
■ REHEATER SURFACE AREA/BANK (ft^2)	8560
■ SODIUM INLET TEMPERATURE (^{o}F)	950
■ SODIUM OUTLET TEMPERATURE (^{o}F)	700

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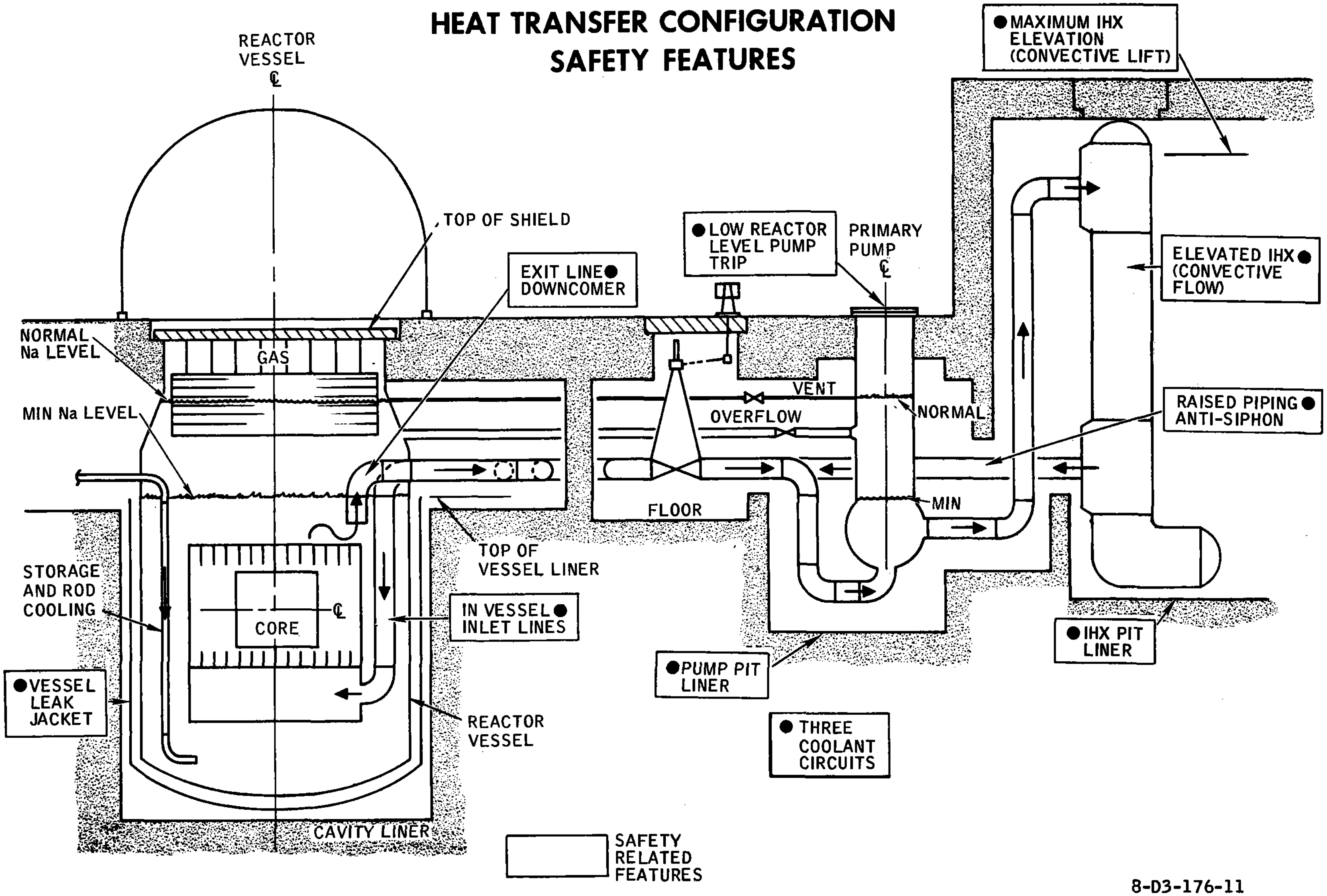
HEAT TRANSFER CONFIGURATION SAFETY FEATURES



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FUNCTIONS OF THE COVER GAS PURIFICATION SYSTEM

- MAINTAIN THE CHEMICAL PURITY OF THE COVER GAS WITHIN PRESCRIBED LIMITS
- REDUCE THE ACTIVITY OF THE COVER GAS DUE TO Xe 133 TO THE EXTENT THAT:
  - A) COVER GAS ACTIVITY NEXT TO ELASTOMER SEALS WILL NOT CAUSE PREMATURE FAILURE
  - B) POTENTIAL LEAKAGE TO THE OCCUPIED AREAS OF THE BUILDING WILL NOT RESULT IN AIRBORNE ACTIVITY IN EXCESS OF MPC
- PROVIDE THE CAPABILITY FOR CONCENTRATION AND DISPOSAL OF Kr 85, SHOULD THE REQUIREMENT BE IMPOSED AT A LATER DATE
- PROVIDE A SOURCE OF RELATIVELY PURE COVER GAS FOR PURGE FOR SODIUM FROST CONTROL OR FOR OTHER USES

COVER GAS SYSTEM

- SUPPLY PURGE GAS FOR TOP SHIELD, CONTROL RODS, PRIMARY PUMPS
  - 5 to 15 scfm
- LIMIT AIRBORNE ACTIVITY TO 0.5 MPC
  - 1% FUEL PINS OPEN
- LIMIT RADIATION LEVELS DURING OPERATION AT PUMP AND TOP SHIELD DOME
  - ~1 mr/hr FROM GAS SOURCE
- LIMIT RADIATION LEVELS DURING SHUTDOWN AT PUMP AND TOP SHIELD
  - ~1 mr/hr FROM GAS SOURCE
- LIMIT RADIATION DAMAGE TO SEALS
  - 0.1% FUEL PINS OPEN NORMALLY – 1% OCCASIONALLY
  - 10^6 to 10^7 r TID (AVERAGE 10 to 100 μc Xe^{133}/scc COVER GAS)
- CAPABILITY FOR LOW GAS RELEASE PLANT
  - Xe^{133} HOLDUP
  - FUTURE ADDITION OF Kr^{85} REMOVAL FROM COVER GAS
- CAPABILITY FOR DIRECT FUEL ASSEMBLY REMOVAL
  - LIMIT 33-kw ASSEMBLY CLADDING TO LESS THAN 1200°F
  - LIMIT 64-kw ASSEMBLY CLADDING TO ~1600°F

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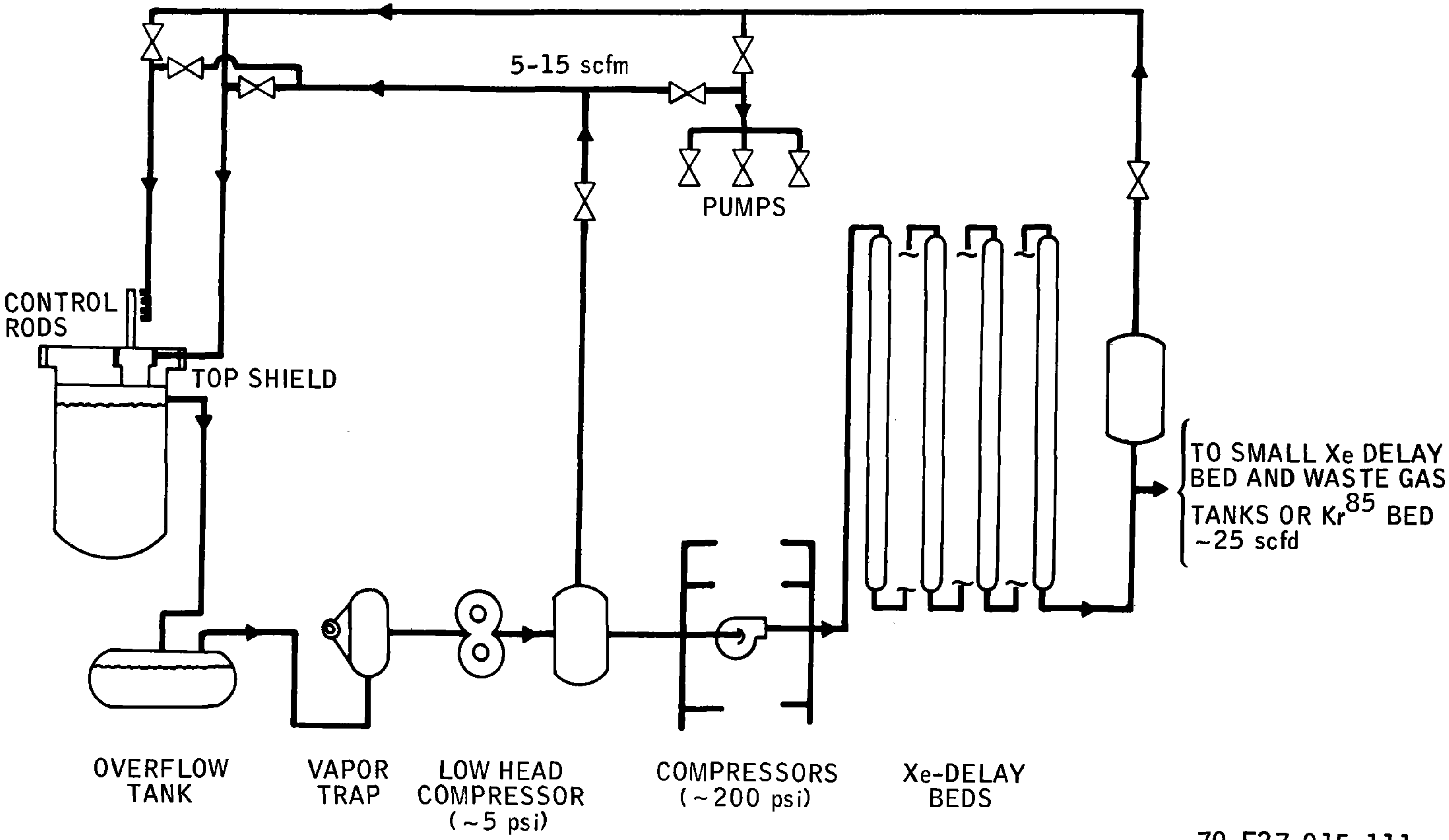
HELIUM PURIFICATION SYSTEM



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FISSION GAS RELEASE

$$A_i = X \cdot A_{io} \cdot f_i \cdot f_i' \cdot f_i''$$

A_i = ACTIVITY OF COVER GAS DUE TO ISOTOPE i

X = FRACTION OF FUEL PINS FAILED

A_{io} = TOTAL ACTIVITY OF ISOTOPE i IN CORE

f_i = FRACTION OF ISOTOPE i RELEASED FROM FUEL MATRIX

$$= \frac{1}{1.5 \times 10^5 \lambda_i} \left[1 - e^{-1.5 \times 10^5 \lambda_i} \right]$$

λ_i = DECAY CONSTANT FOR ISOTOPE i - SEC^{-1}

f_i' = FRACTION OF ISOTOPE i LEAVING THE FUEL CLADDING - ASSUME 1

f_i'' = FRACTION OF ISOTOPE i PASSING THROUGH THE SODIUM - ASSUME I

REF.: DRP/SEMTR/CAD • 68 • R • 575

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FIGURE 5.

SOURCES OF GASES IN PRIMARY SYSTEM

- FISSION GASES FROM LEAKY FUEL ELEMENTS
- GASES TRAPPED WHILE SYSTEM IS FILLED WITH SODIUM
- GAS IN-LEAKAGE FROM COMPONENTS (VALVES, PUMPS)
- GAS ENTRAINMENT AT FREE SURFACES (REACTOR VESSEL AND PUMP)
- COVER GAS ABSORPTION IN HOT SODIUM, TRANSPORTED TO LOW TEMPERATURE REGION AND RELEASED AS BUBBLES DUE TO "INVERSE SOLUBILITY."

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FIGURE 6
SOLUBILITY vs TEMPERATURE

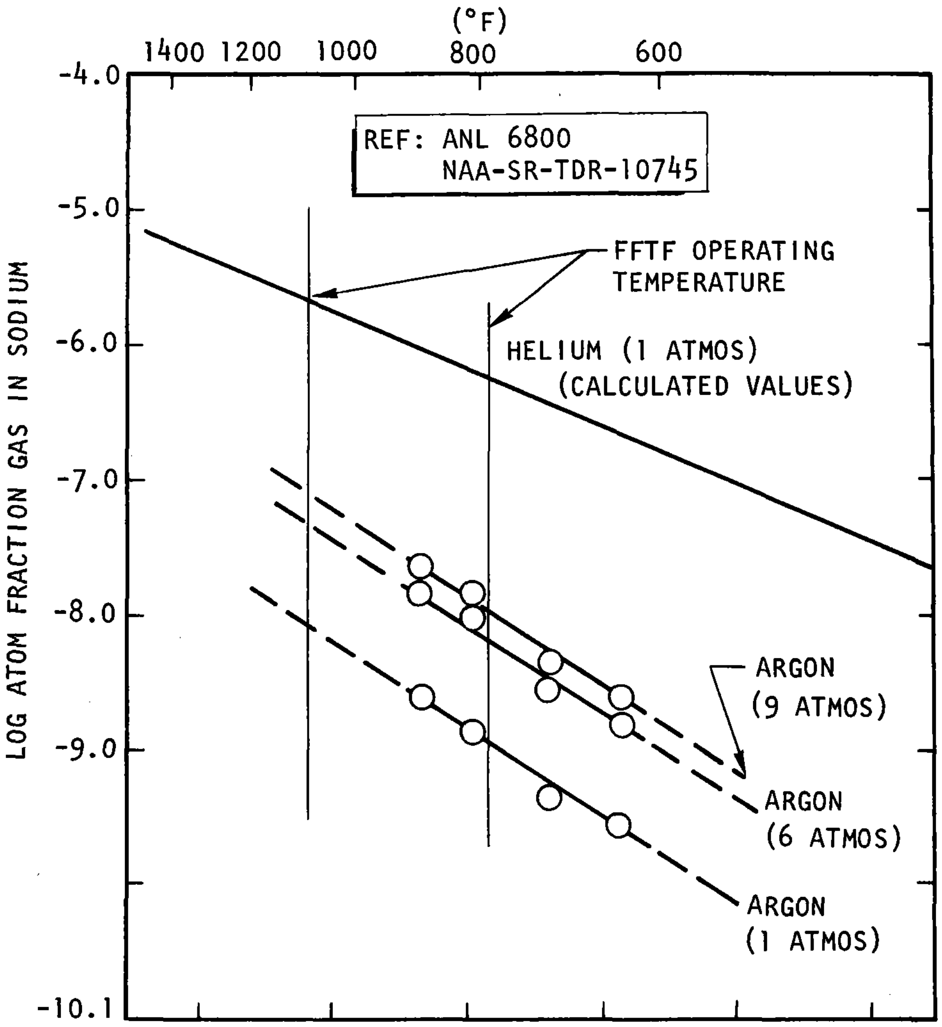

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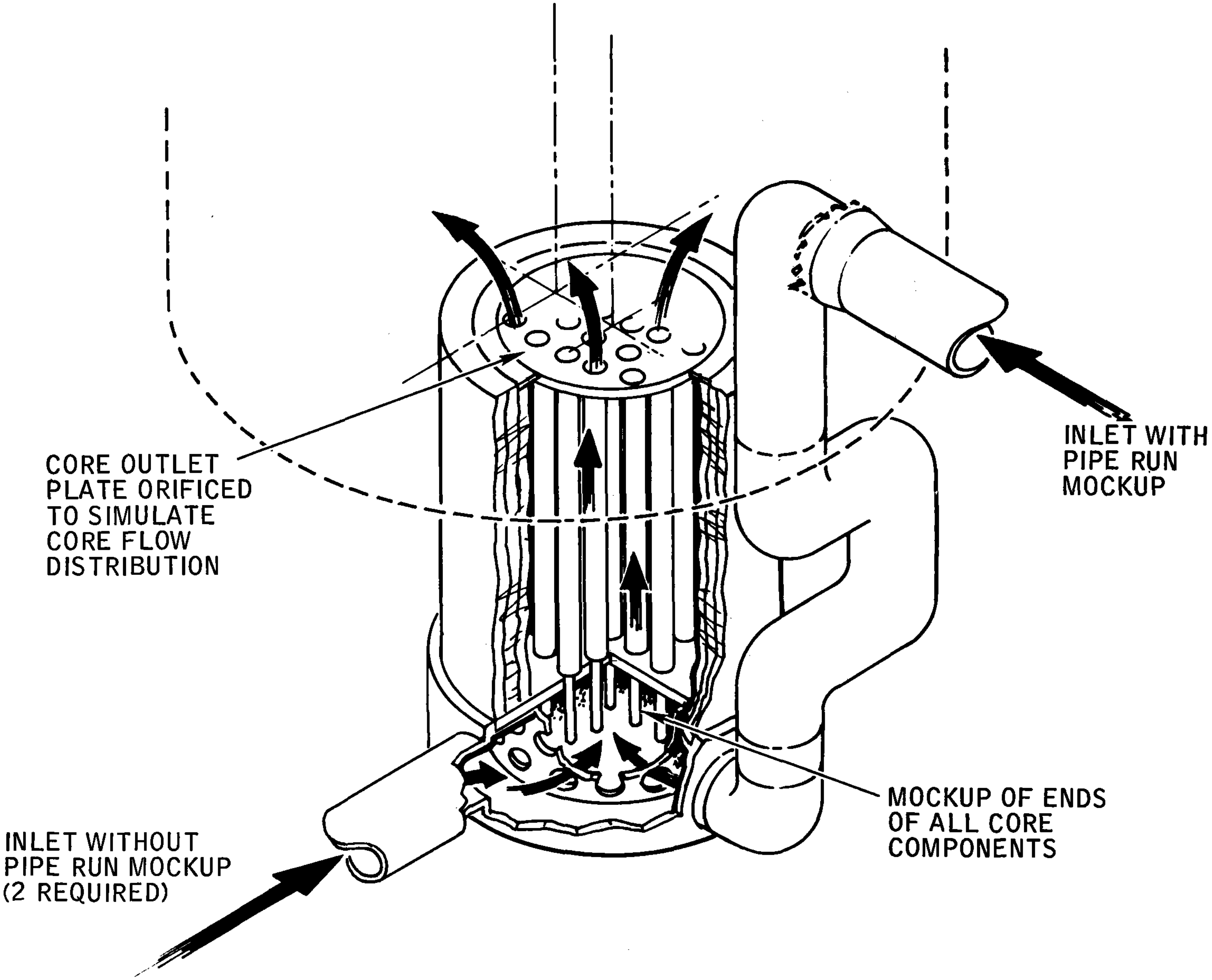
FIGURE 7.

CONCEPTUAL DESIGN — LOWER PLENUM HYDRAULIC MODEL



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PRIMARY LOOP SCHEMATIC

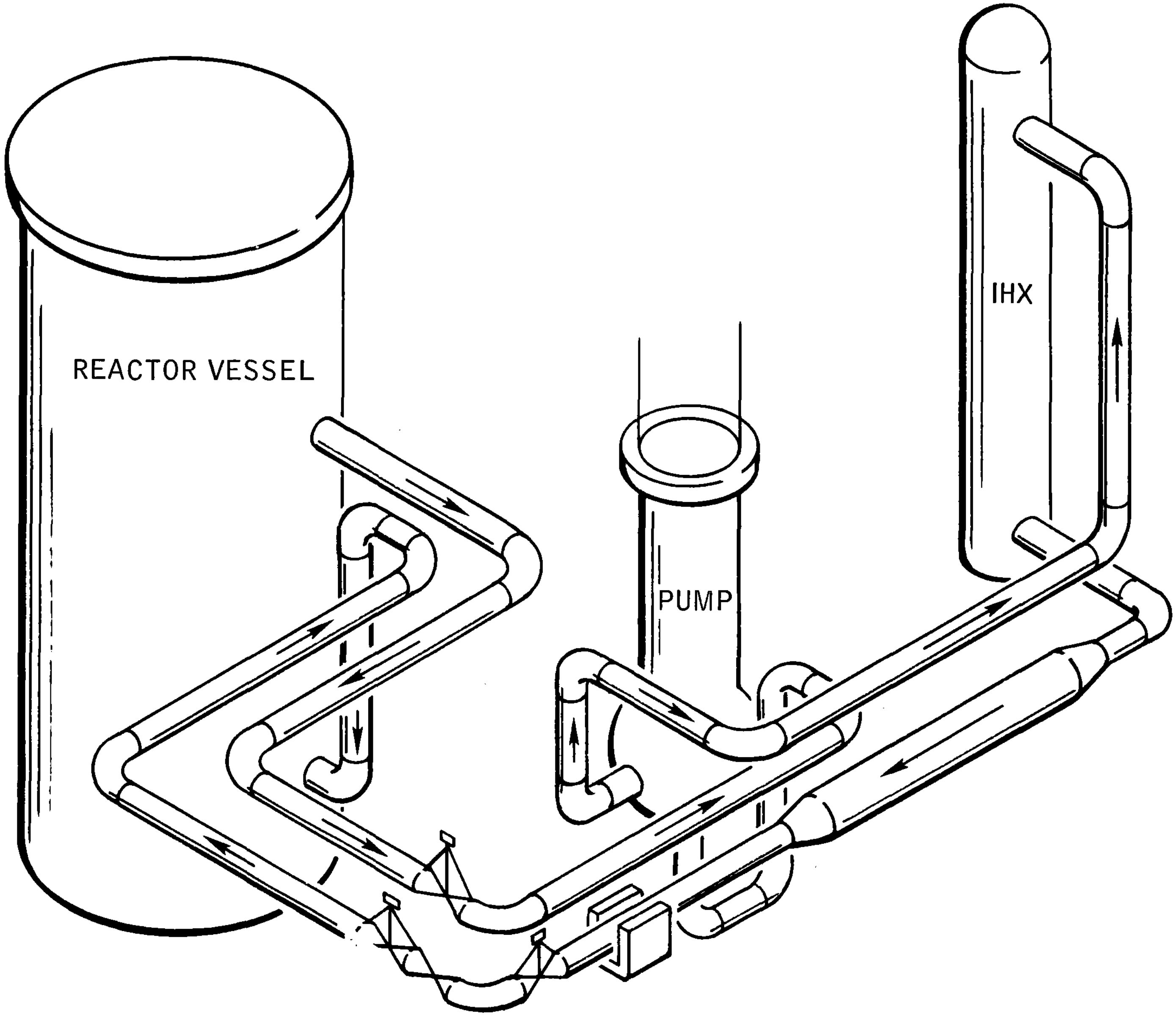

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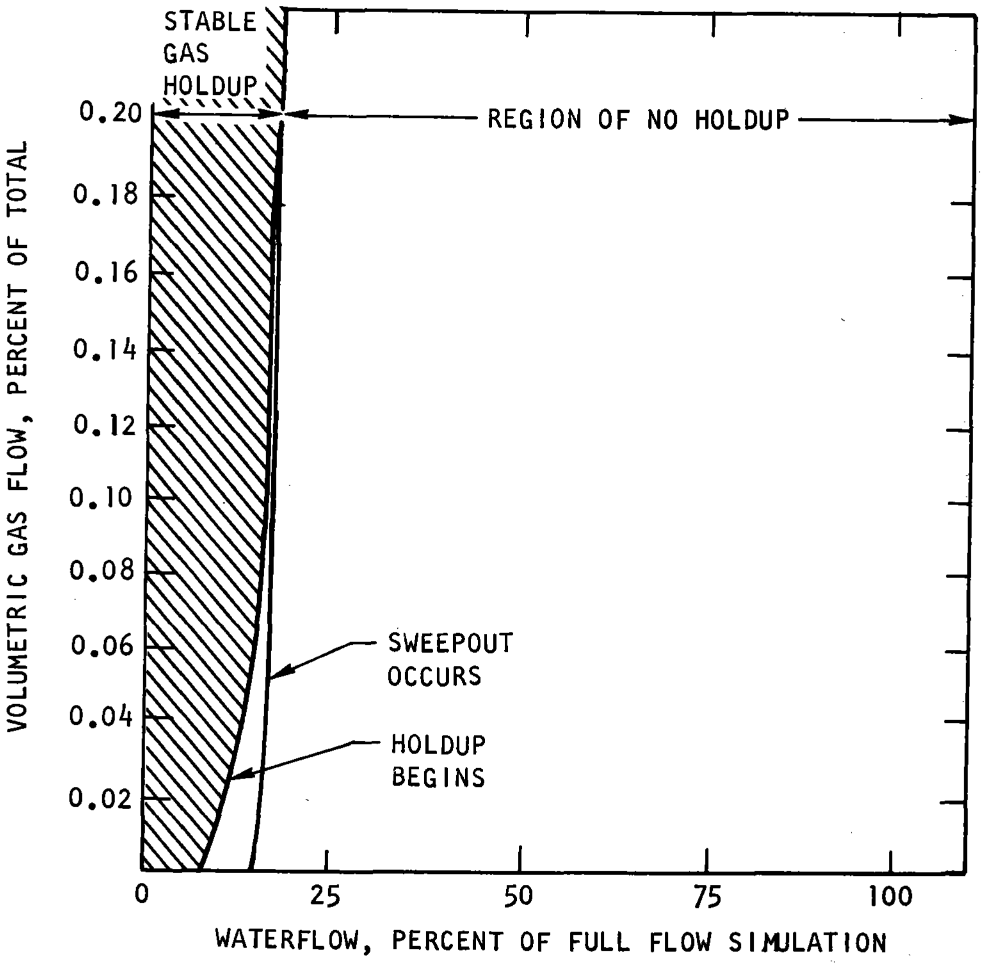
FIGURE 8

GAS HOLDUP AND SWEEP-OUT

(TOP OF HORIZONTAL TO VERTICAL PIPING DIRECTION CHANGE)



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SYSTEM DESIGN TO CONTAIN SODIUM

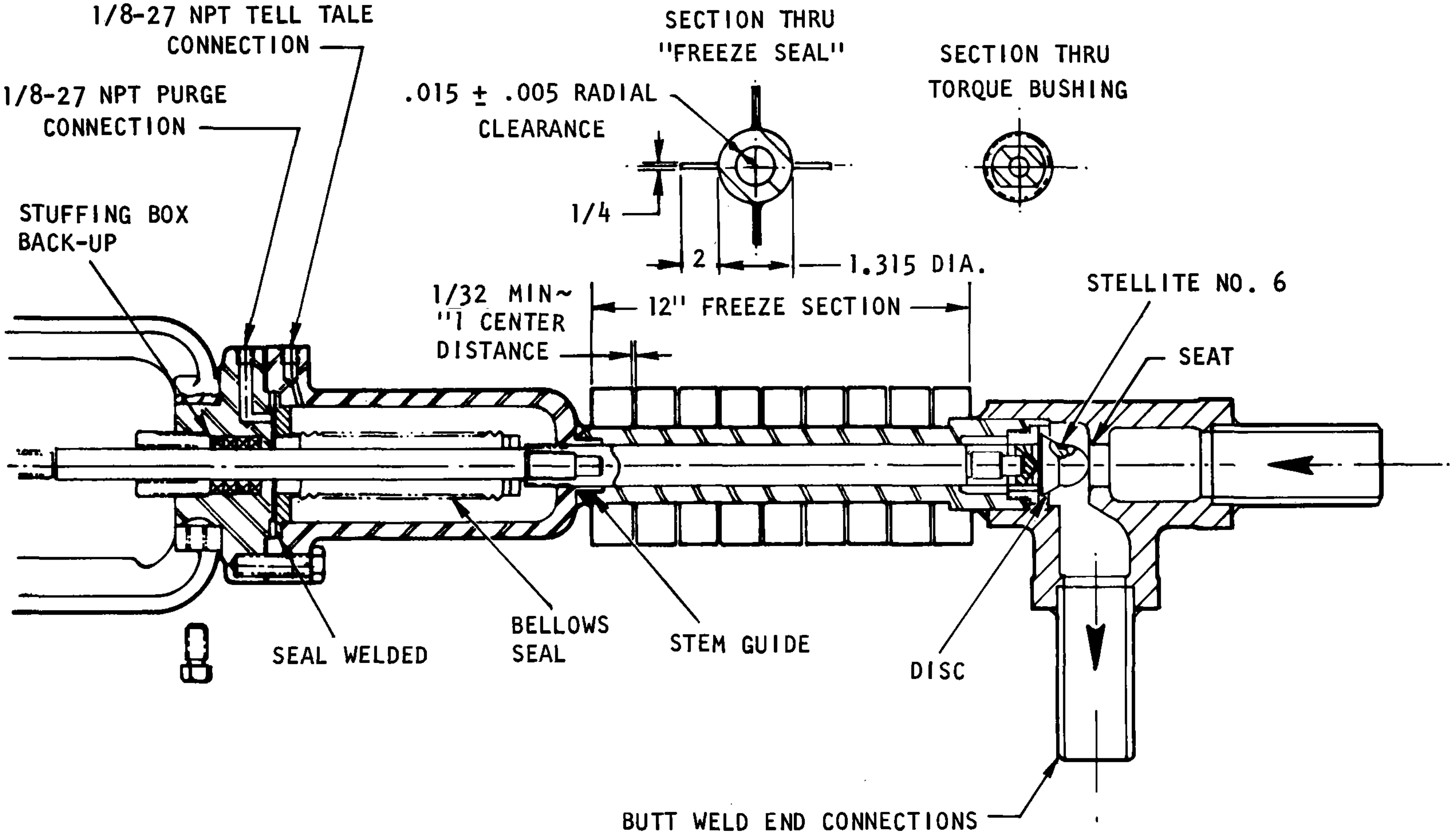
- ALL WELDED CONSTRUCTION USED IF POSSIBLE
- WELDED MANHOLES USED IF POSSIBLE
- INSTRUMENTS SPECIAL DESIGN WITH NO ENVELOPE PENETRATIONS WHERE POSSIBLE
- WHERE POSSIBLE, OPENINGS ARE IN GAS SPACE
- FREEZE SEALS USED WHERE APPLICABLE
- TANK OPENINGS ON TOP OR SIDE OF VESSEL

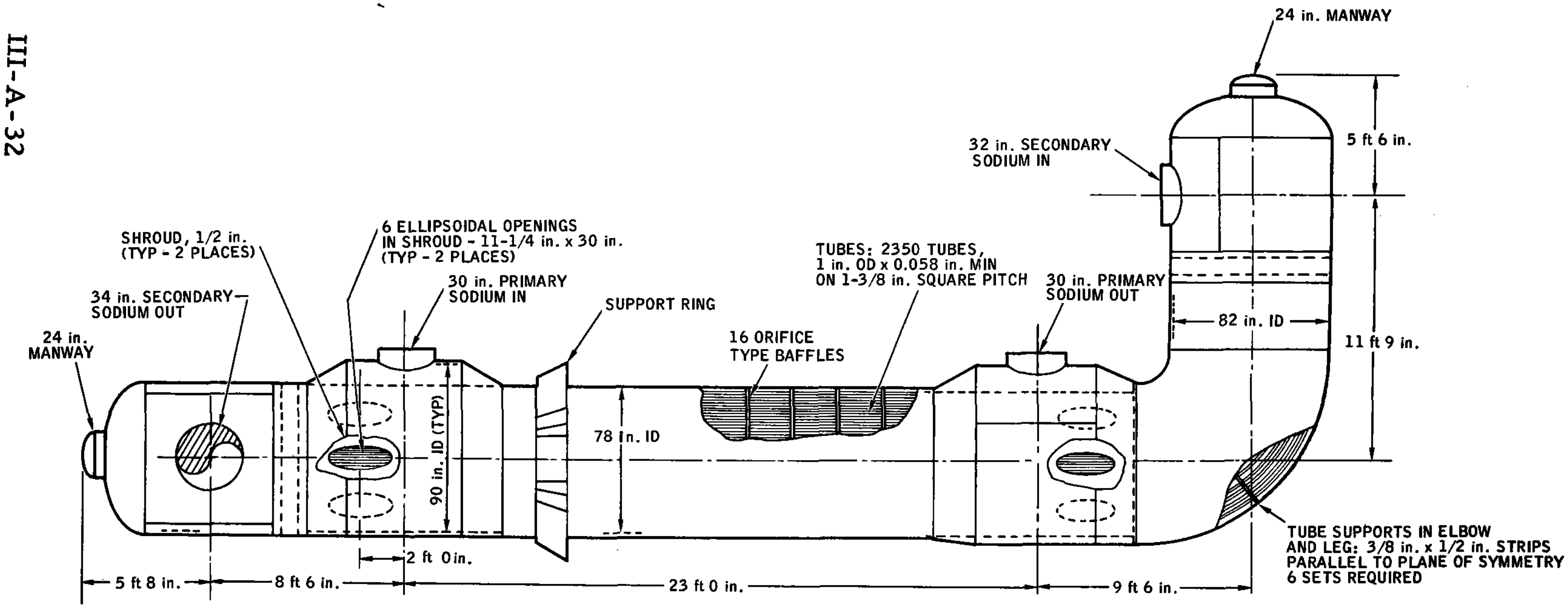
70-MA19-48-133

KEEPING OXYGEN AND MOISTURE OUT OF SYSTEM

- MAINTAIN INERT GAS COVER OVER SODIUM AT ALL TIMES
- PROVIDE DRIERS FOR COVER GAS MAKE UP IF REQUIRED
- MAINTAIN COVER GAS PRESSURE ABOVE ATMOSPHERIC
- UTILIZE SPECIAL SEALS SUCH AS BELLOWS, FREEZE SEALS, OR BACK PRESSURED SEALS WHERE POSSIBLE
- FOR SMALL SYSTEMS, USE COMPENSATORS
- PROVIDE TEMPORARY CLOSURES WHEN SYSTEMS ARE OPEN
- DO NOT PERMIT WATER OR STEAM IN SODIUM CONTAINING AREAS IF NOT ABSOLUTELY NECESSARY
- PROVIDE ADEQUATE VENTS, DRAINS, AND SLOPES
- PROVIDE COLD TRAP TO REMOVE TRACES OF OXYGEN, HYDROGEN, ETC.

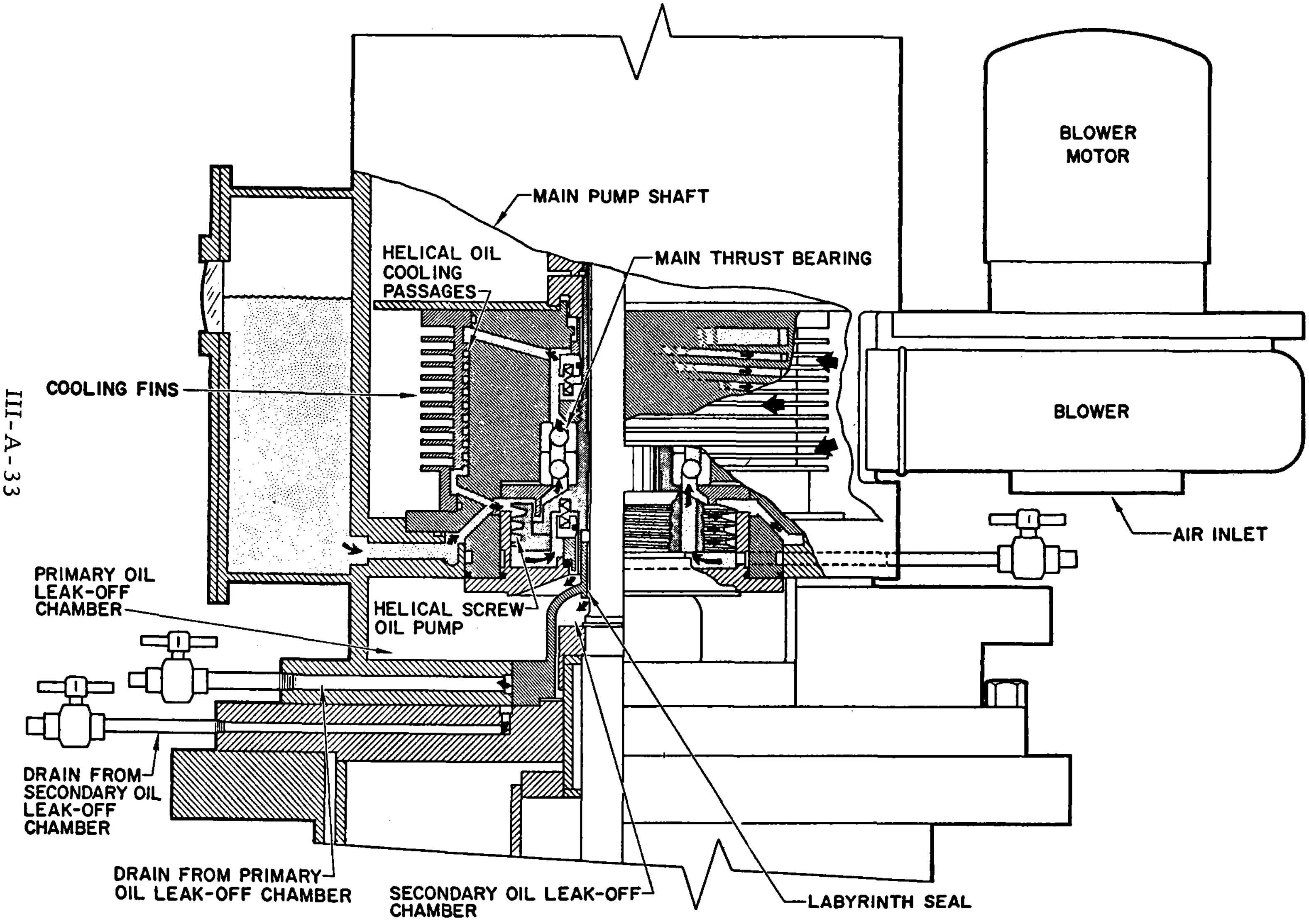
SRE PEP SERVICE SYSTEM VALVES




24 in. MANWAY
5 ft 6 in.
32 in. SECONDARY SODIUM IN
SHROUD, 1/2 in. (TYP - 2 PLACES)
6 ELLIPSOIDAL OPENINGS IN SHROUD - 11-1/4 in. x 30 in. (TYP - 2 PLACES)
TUBES: 2350 TUBES, 1 in. OD x 0.058 in. MIN ON 1-3/8 in. SQUARE PITCH
30 in. PRIMARY SODIUM OUT
34 in. SECONDARY SODIUM OUT
30 in. PRIMARY SODIUM IN
SUPPORT RING
82 in. ID
11 ft 9 in.
24 in. MANWAY
16 ORIFICE TYPE BAFFLES
90 in. ID (TYP)
78 in. ID
TUBE SUPPORTS IN ELBOW AND LEG: 3/8 in. x 1/2 in. STRIPS PARALLEL TO PLANE OF SYMMETRY 6 SETS REQUIRED
2 ft 0 in.
5 ft 8 in.
8 ft 6 in.
23 ft 0 in.
9 ft 6 in.

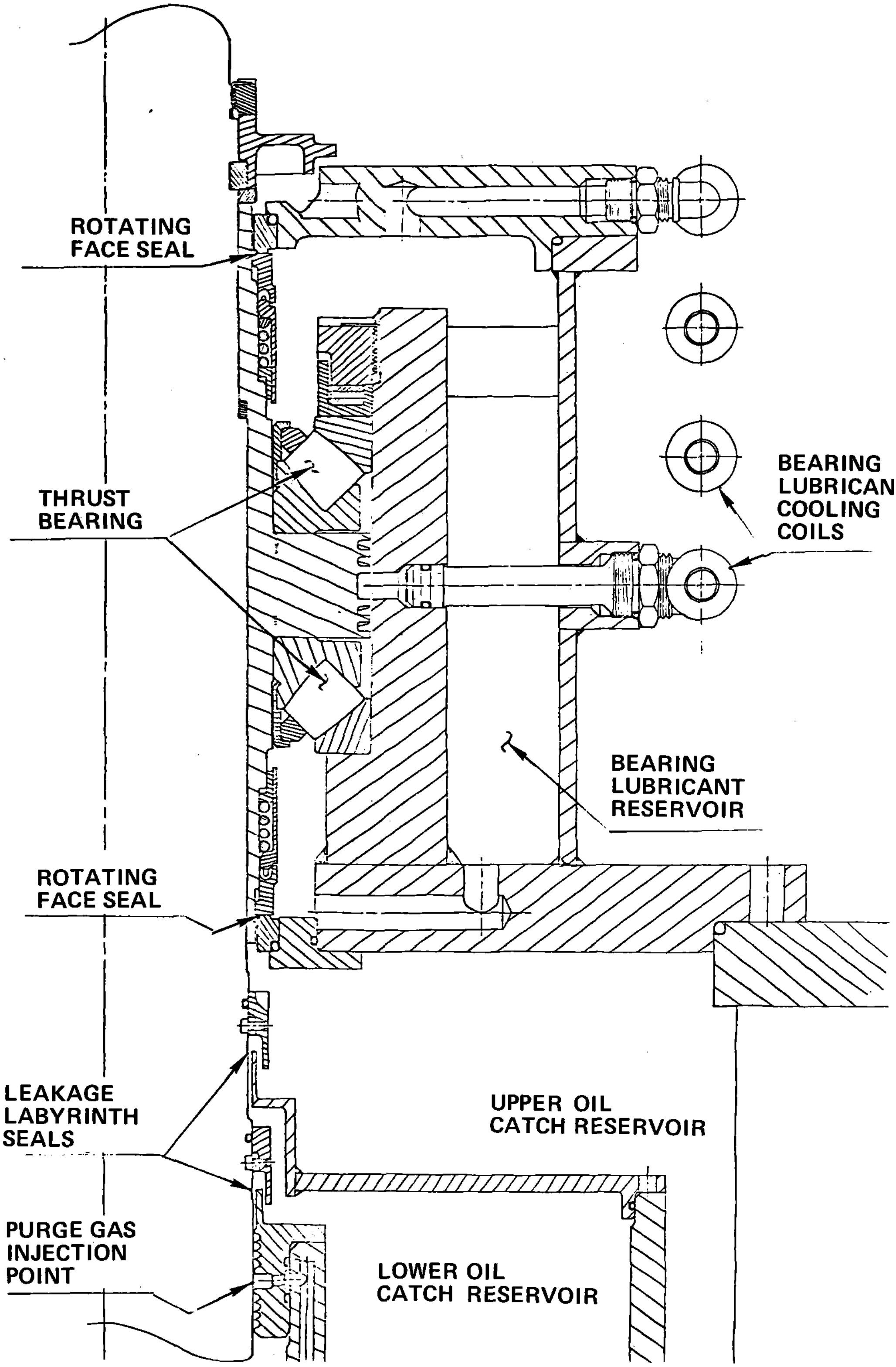
6095-1201

TYPICAL PUMP BEARING AND SEAL ASSEMBLY



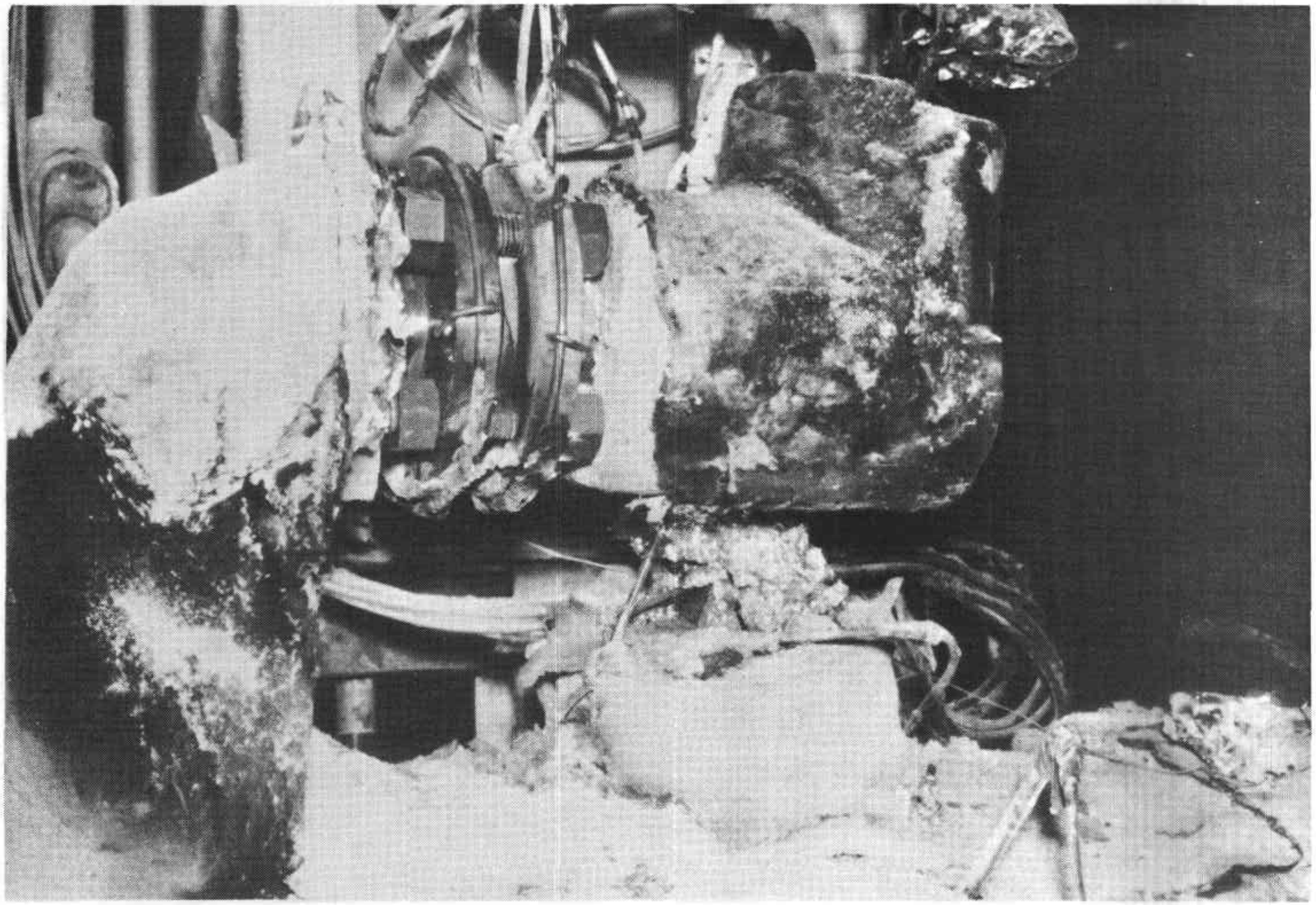
70-MA1-48-285

PROPOSED MAIN PUMP BEARING ASSEMBLY



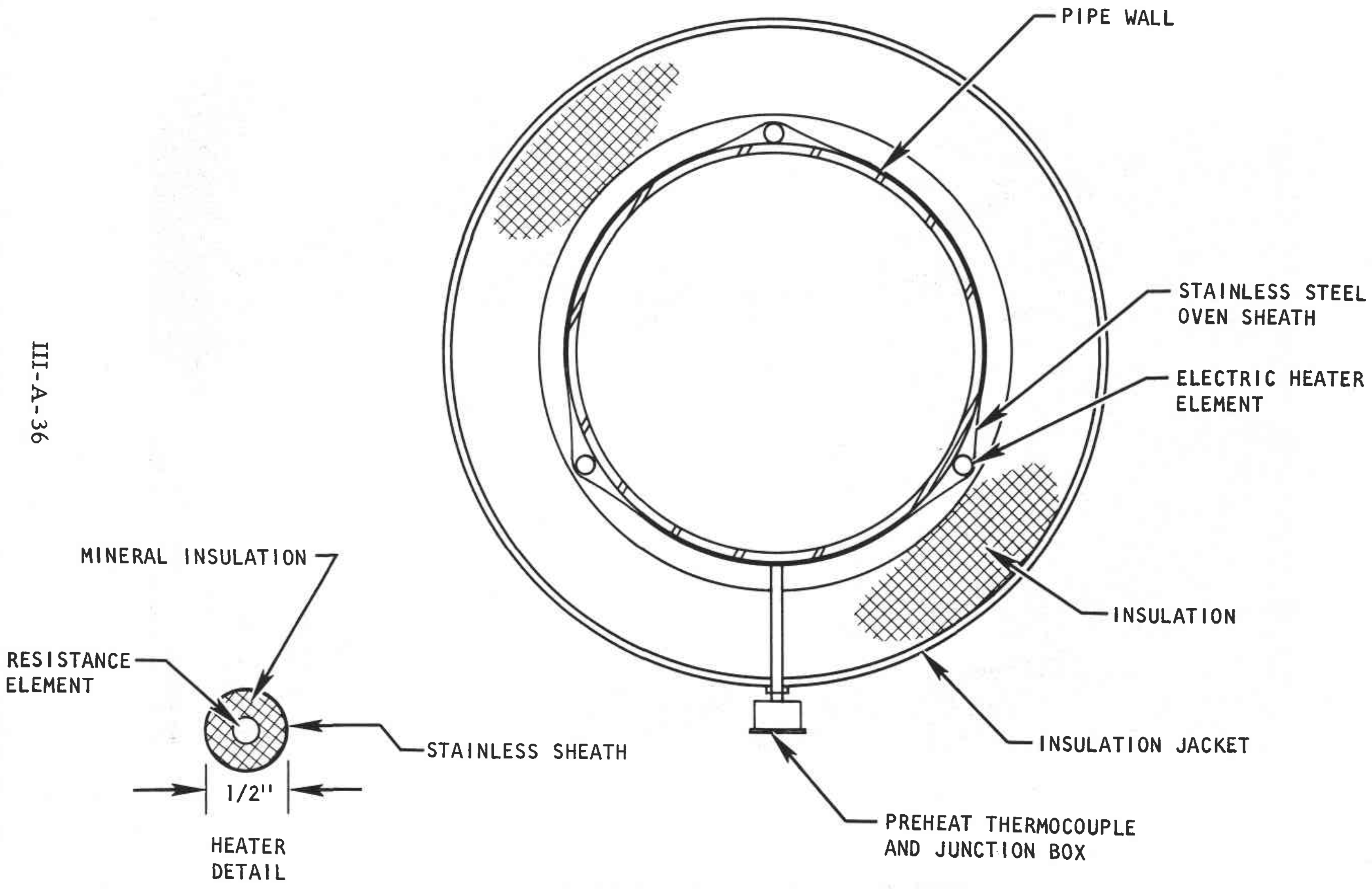
70-MA1-48-286

LEAKING FLANGED JOINT-SRE



70-MA1-48-226

PREHEAT AND INSULATION SYSTEM



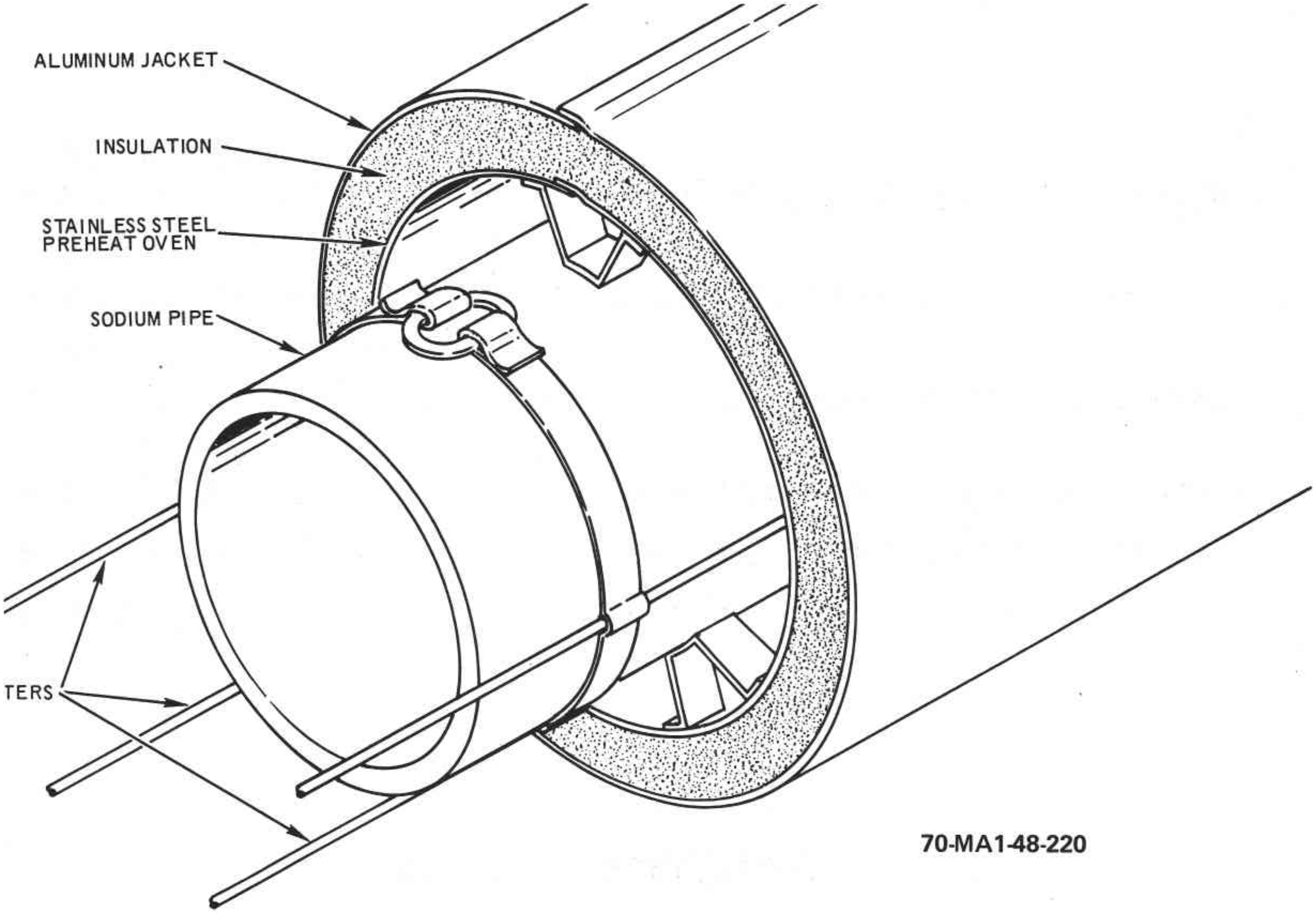
70-MA19-48-150

PREHEATING PROCEDURES

- HAVE SYSTEM OPEN TO A FREE SURFACE IF FULL OF SODIUM
- FOR EMPTY SYSTEMS, MAINTAIN ABOUT 50^0F/HR MAXIMUM HEATING RATE
- FOR LARGE EQUIPMENT (IHX) GOVERN HEATING RATE BY ALLOWABLE DELTA T EQUIPMENT IS DESIGNED FOR
- FOR STEAM GENERATORS, PREHEAT BY STEAM UNDER VACUUM CONDITIONS TO CONTROL RATE OF HEATING
- ELECTRICALLY HEATED EQUIPMENT CONTROL GOVERNED BY CHANGING SET POINTS OF CONTROLS
- FOR INITIAL SYSTEM TEMPERATURE RISE, RATE OF HEATING IS GOVERNED BY COLD TRAP CAPABILITY

70-MA19-48-125

TYPICAL PRE-HEATER AND INSULATION ASSEMBLY



70-MA1-48-220

MAINTENANCE OF SODIUM SYSTEMS, DESIGN CONSIDERATIONS

- PROVIDE FOR ACCESS AFTER SODIUM-24 DECAY
- PROVIDE FOR COMPLETE DRAINAGE
- DESIGN FOR MAINTENANCE OF MAJOR EQUIPMENT WITHOUT CUTTING THE SODIUM ENVELOPE IF POSSIBLE
- PROVIDE ADEQUATE REMOTE LEAK DETECTORS WHERE ACCESS IS RESTRICTED
- PROVIDE FOR RADIOGRAPH WHERE MAINTENANCE IS LIKELY
- PROVIDE CAPABILITY FOR REMOTE MAINTENANCE OF RADIOACTIVE SYSTEMS
- WHERE FUTURE ACCESS IS PROHIBITED, PROVIDE FOR REMOTE MAINTENANCE; PROVIDE SPARE GEAR; OR ELIMINATE MAINTENANCE REQUIREMENTS

70-MA19-48-126

TYPICAL PRIMARY COMPONENT MAINTENANCE

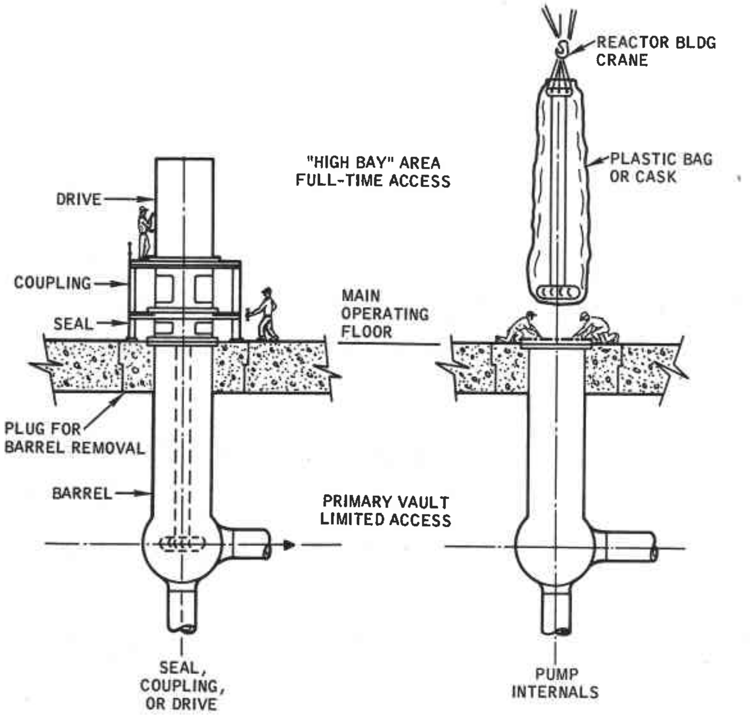


FIGURE 13. PUMP MAINTENANCE

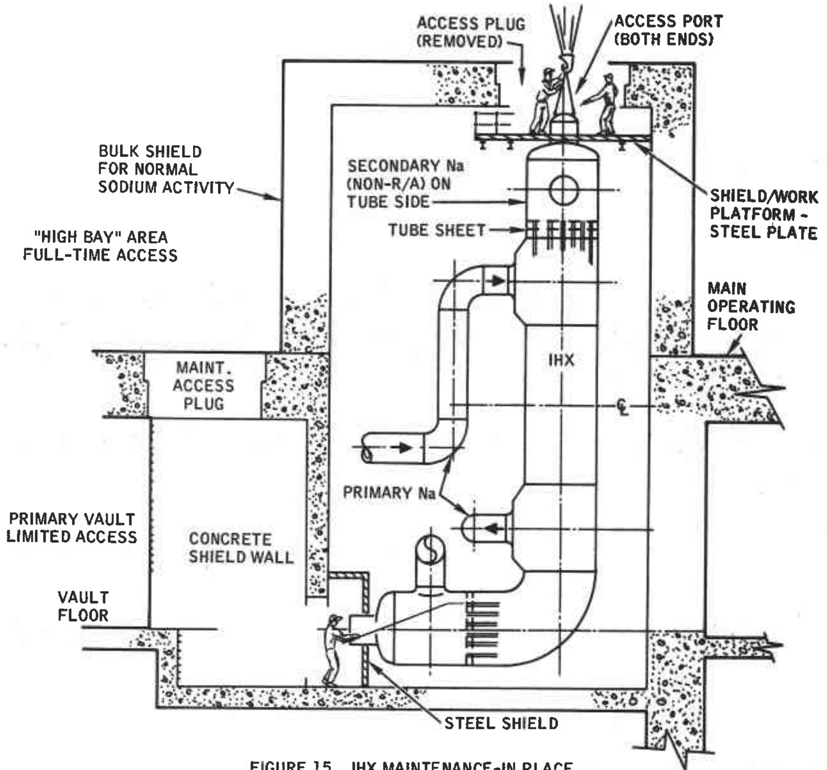


FIGURE 15. IHX MAINTENANCE-IN PLACE

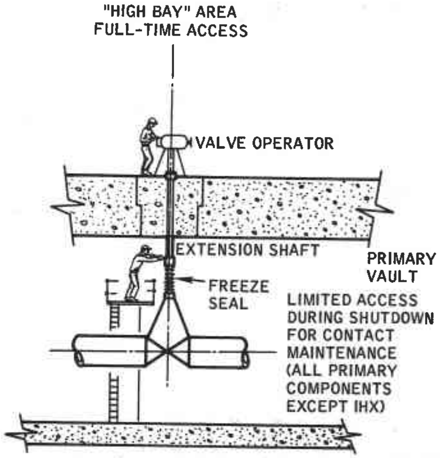


FIGURE 14. TYPICAL PRIMARY COMPONENT MAINTENANCE

9-A9-041-13

SODIUM SYSTEM MAINTENANCE

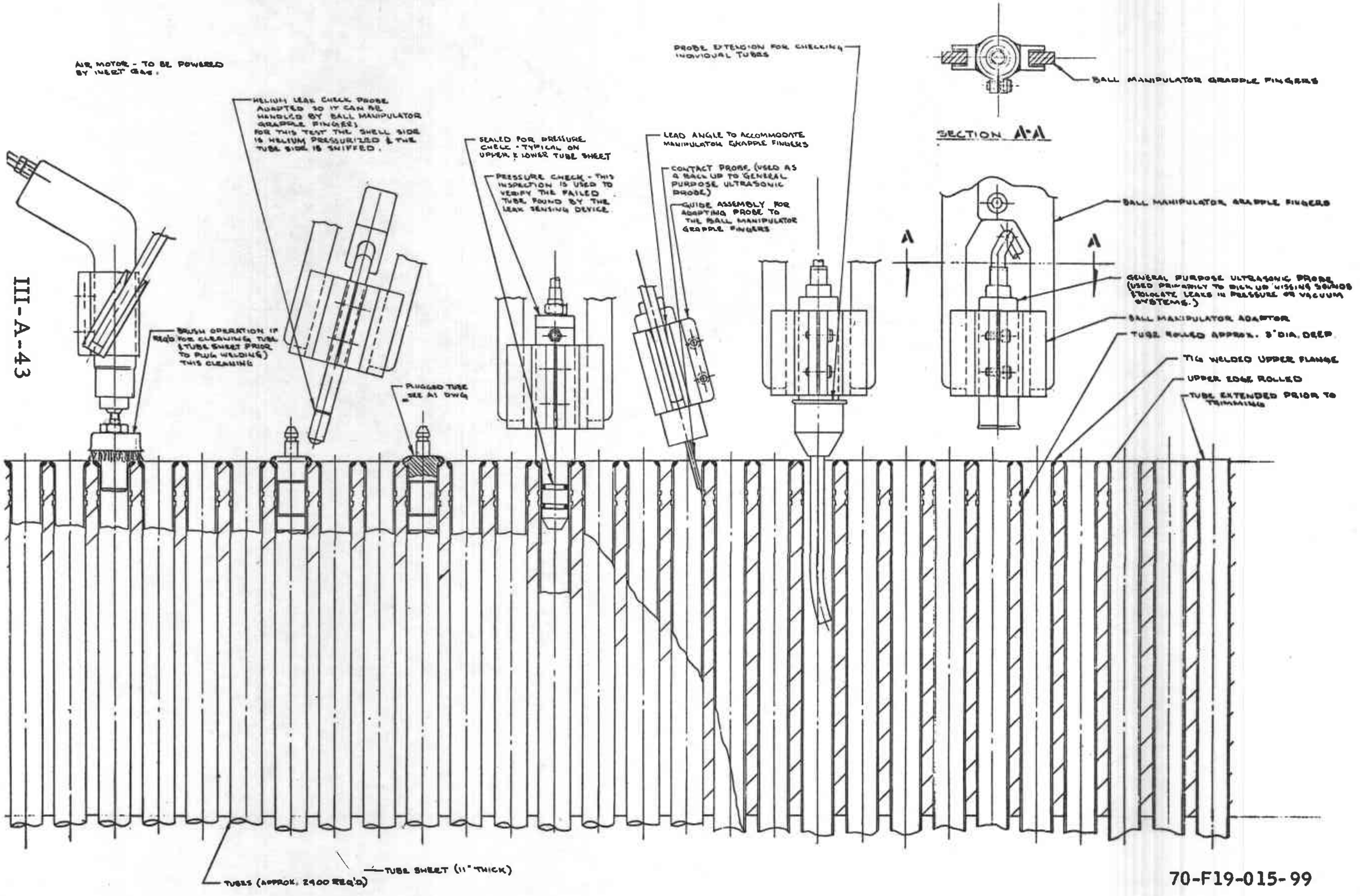
- CUTTING PIPE
- PROTECTION FROM ATMOSPHERE
- WELDING
- CLEANING COMPONENTS
- INERT GAS BLANKETING

9-010-116-42

REPAIR OF SODIUM SYSTEMS

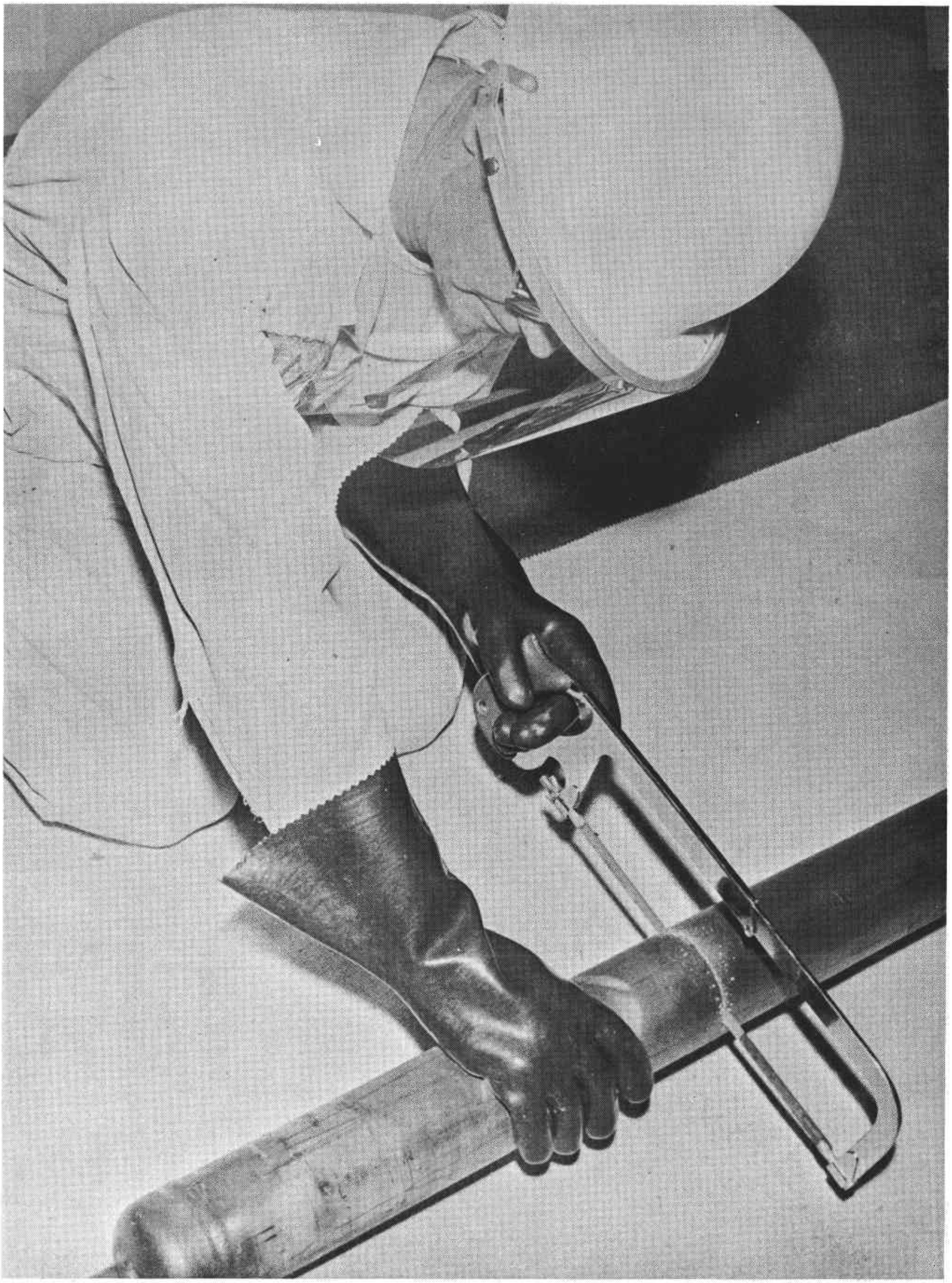
- LINES UP TO ~4 TO 6 in.
    - FREEZE LINE
    - CUT SYSTEM
- LINES ABOVE ~4 TO 6 in.
    - DRAIN AND ISOLATE
    - INERT GAS BLANKET
    - CUT SYSTEM
- PROTECT OPEN SYSTEM AND COMPONENTS BY TAPE OR PLASTIC BAG
- CLEAN REPAIR AREA
- REWELD SYSTEM

CONCEPTUAL METHODS FOR TUBE PLUGGING IHX - 500 MWe FBR



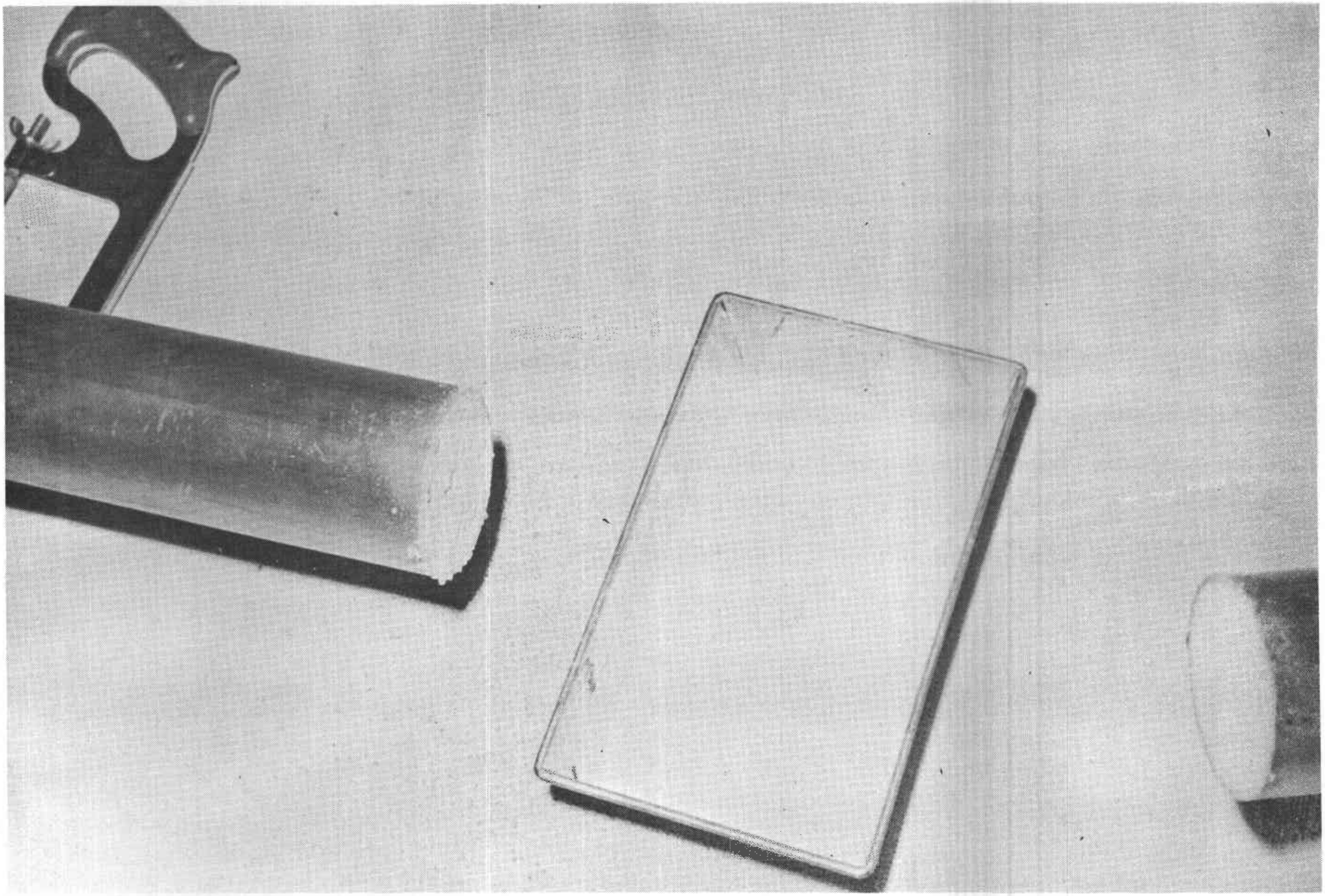
70-F19-015-99

CUTTING 4-in. PIPE FULL OF FROZEN SODIUM-SRE



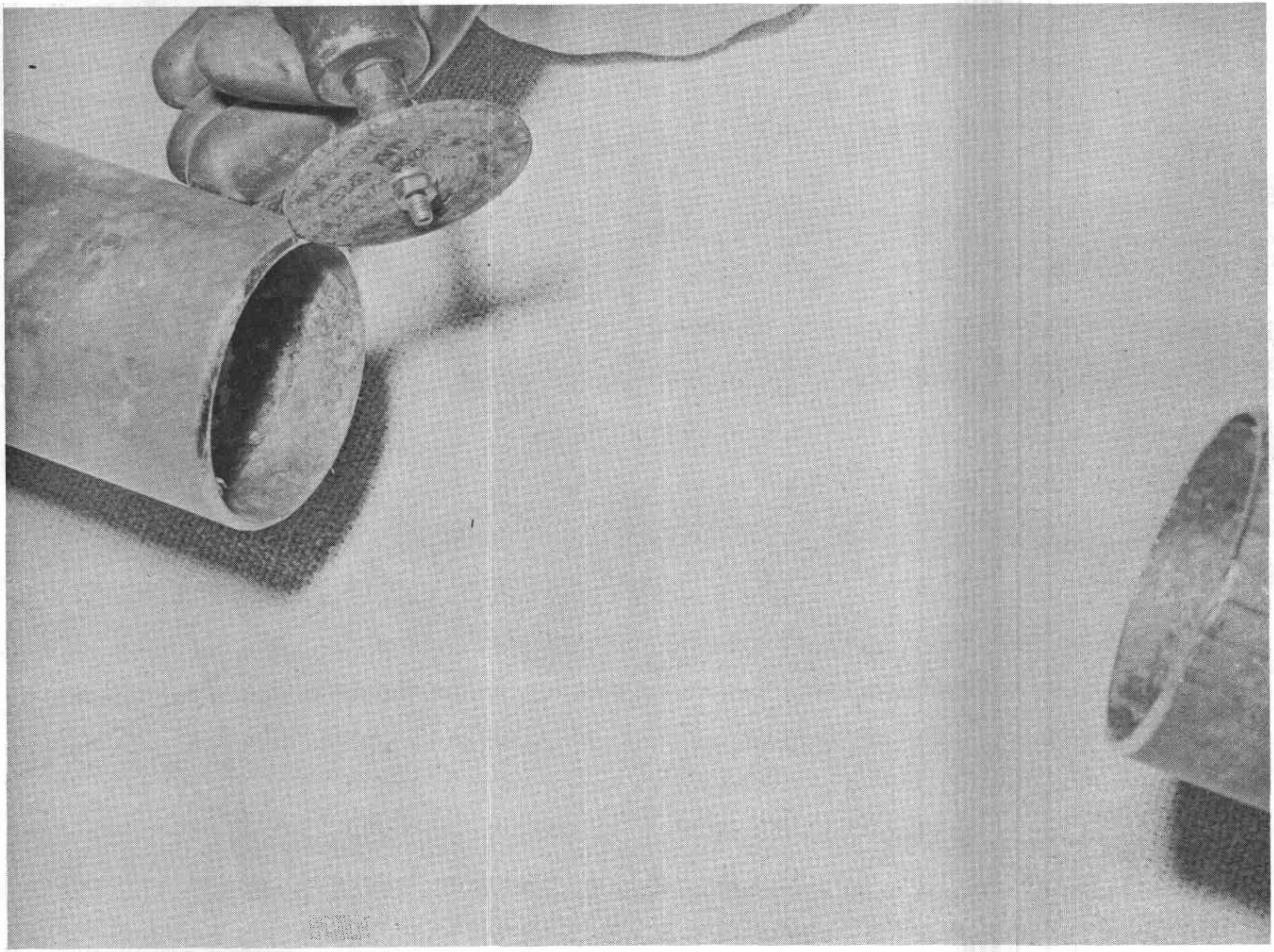
70-MA1-48-269

PIPE ENDS AFTER CUT-SRE



REMOVING SODIUM FROM PIPE ENDS PRIOR TO RE-WELDING-SRE

MAKING WELD PREPARATION PRIOR TO RE-WELDING-SRE

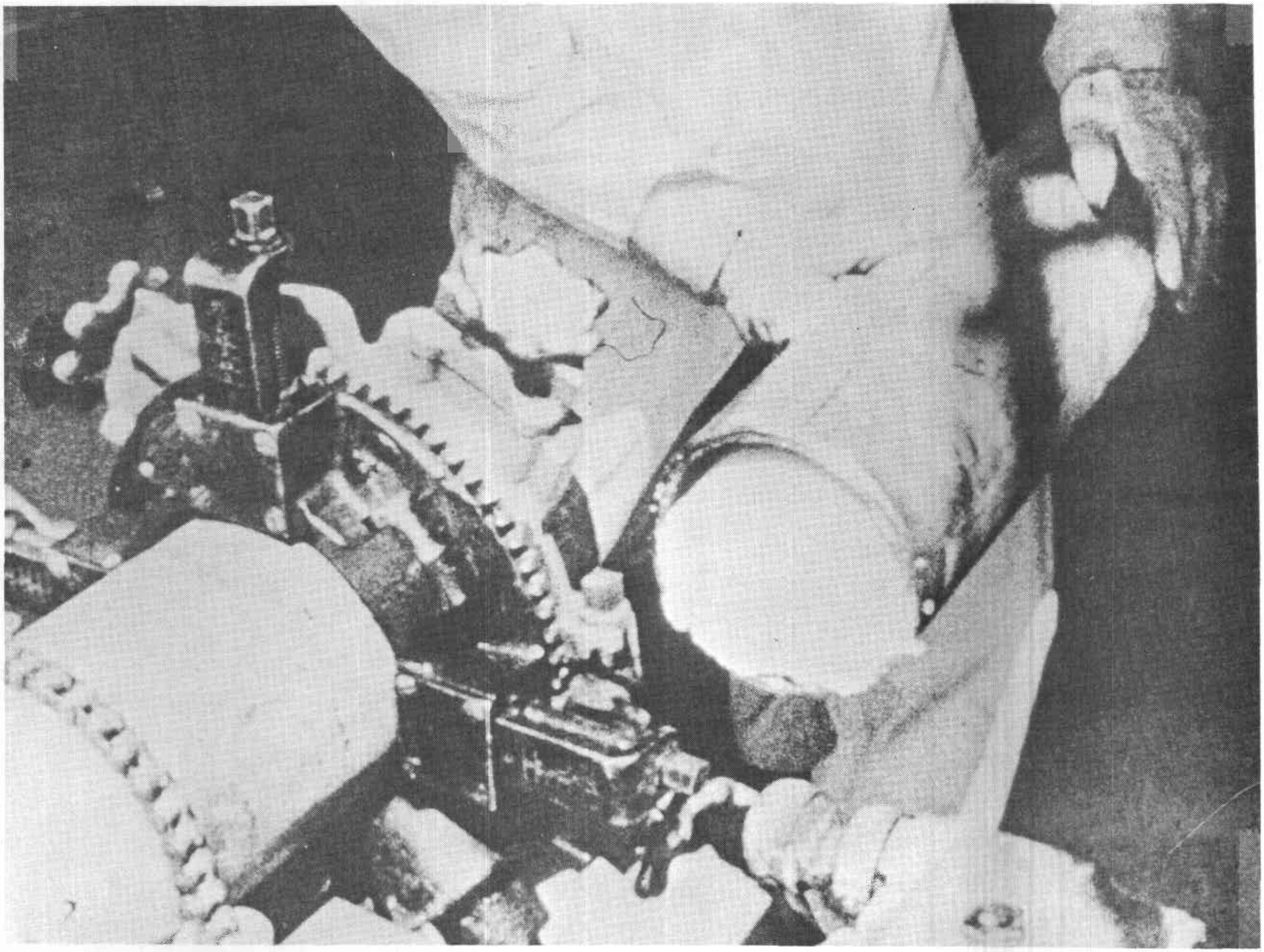


70-MA1-48-268

RE-WELDING SODIUM PIPE-SRE

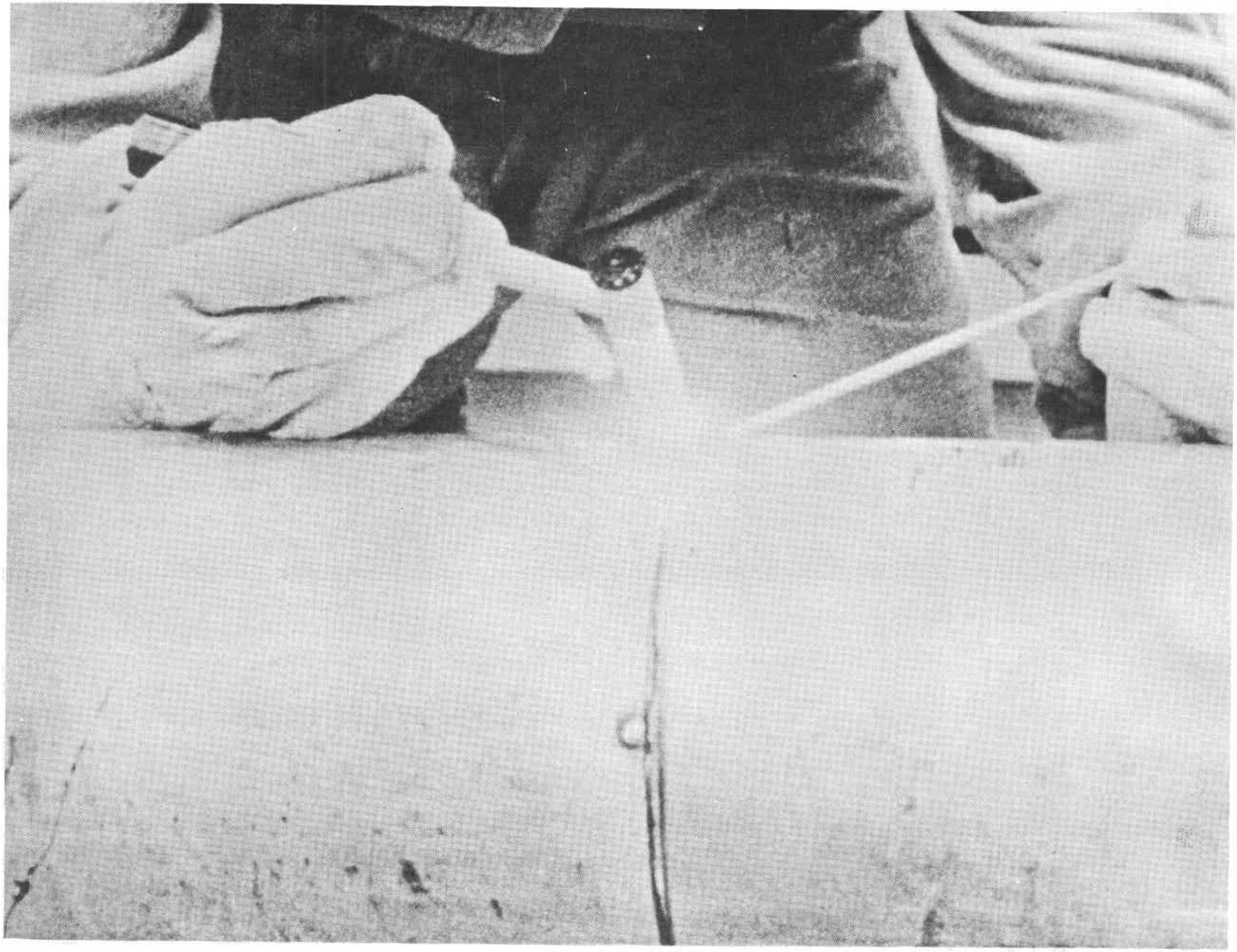
70-MA1-48-265

CUTTING 6-in. PIPE FULL OF SODIUM WITH AIR CUTTER



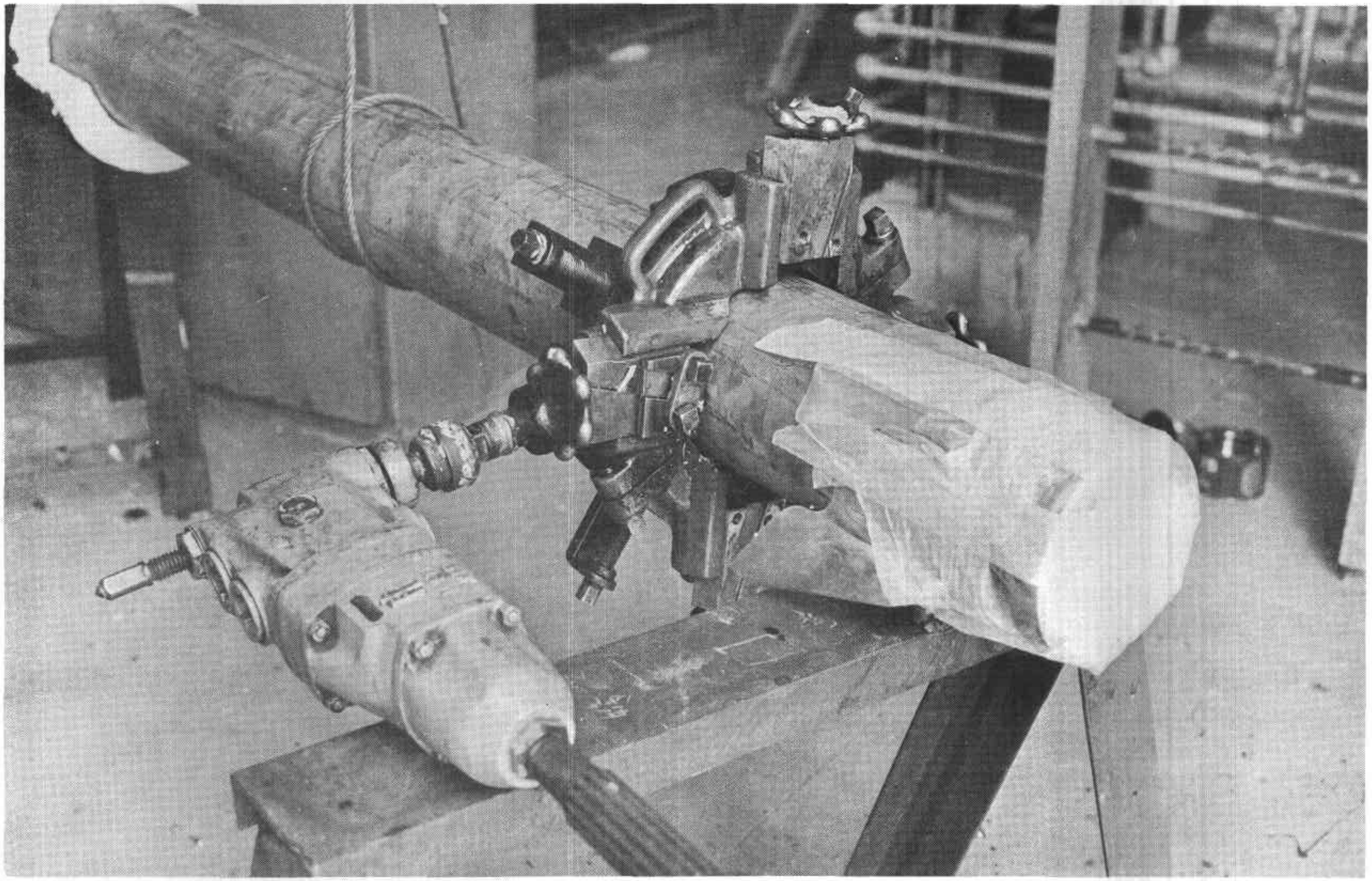
70-MA1-48-271

RE-WELDING 6-in. PIPE USING HELIARC WELD



70-MA1-48-270

6-in. PIPE SET UP FOR CUTTING WITH PNEUMATIC DRIVEN PIPE CUTTER-SRE

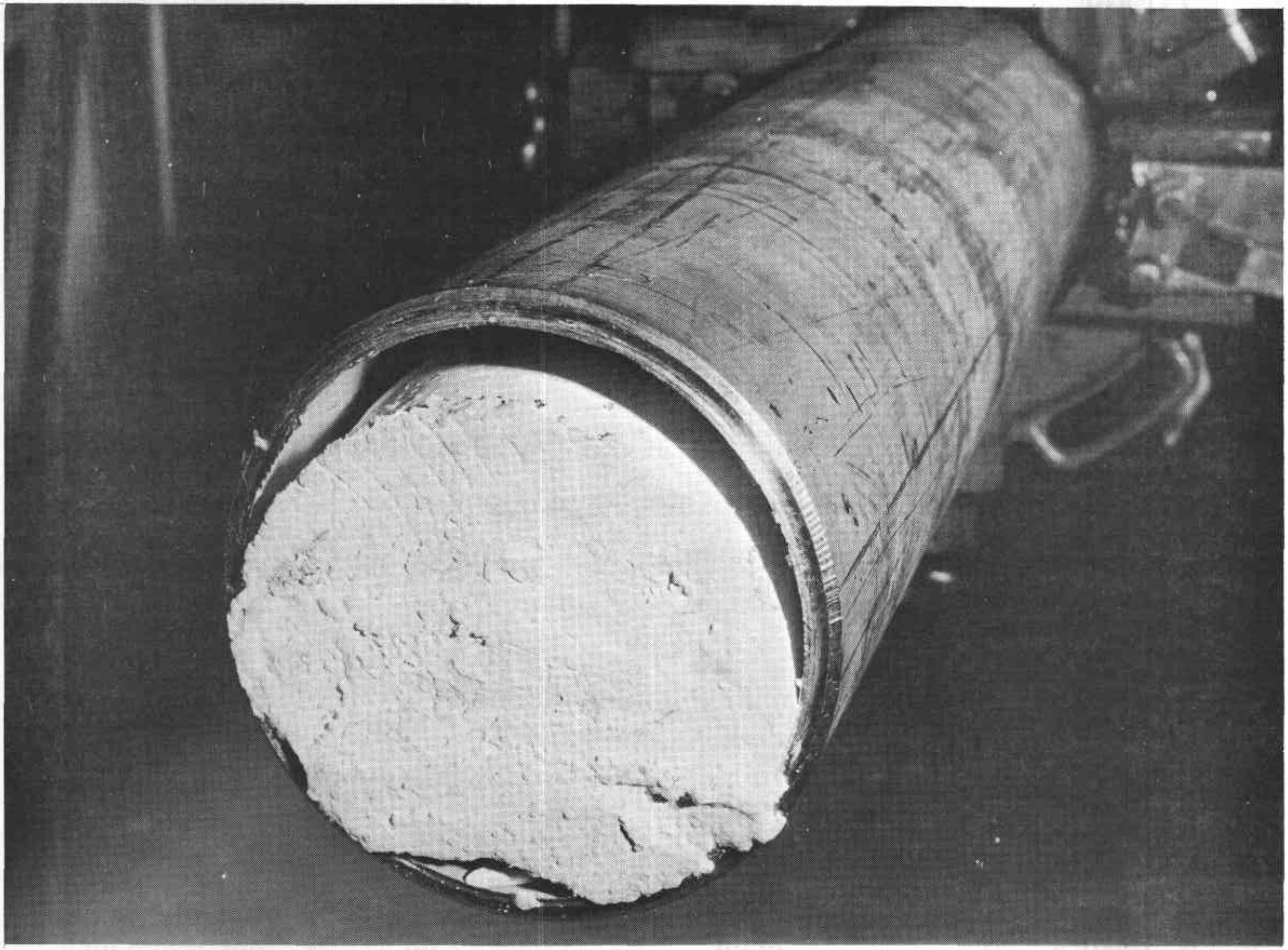


70-MA1-48-225

4-in. PIPE FULL OF FROZEN SODIUM AFTER CUTTING WITH HACK SAW-SRE

70-MA1-48-222

6-in. PIPE FULL OF SODIUM AFTER MACHINE CUTTING-SRE



70-MA1-48-224

CLEANING

METHODS

- CHEMICAL REACTION
  - DOWANOL – SLOW REACTION
  - ALCOHOL – FASTER REACTION
  - STEAM – CONTROLLED BY QUANTITY
  - WATER – FAST REACTION
- AMMONIA DISSOLUTION
- VACUUM
- MELTING AND DRAINING
- HOT OIL

PROCEDURE

- REMOVE EXCESS BY HAND OR MELT AND DRAIN
- SMALL COMPONENTS – DOWANOL OR ALCOHOL
- LARGE COMPONENTS – STEAM
- LIGHT SODIUM REMOVAL – WATER
- FINAL RINSE – WATER
- DISPOSAL OF WASTE SODIUM BY WATER REACTION

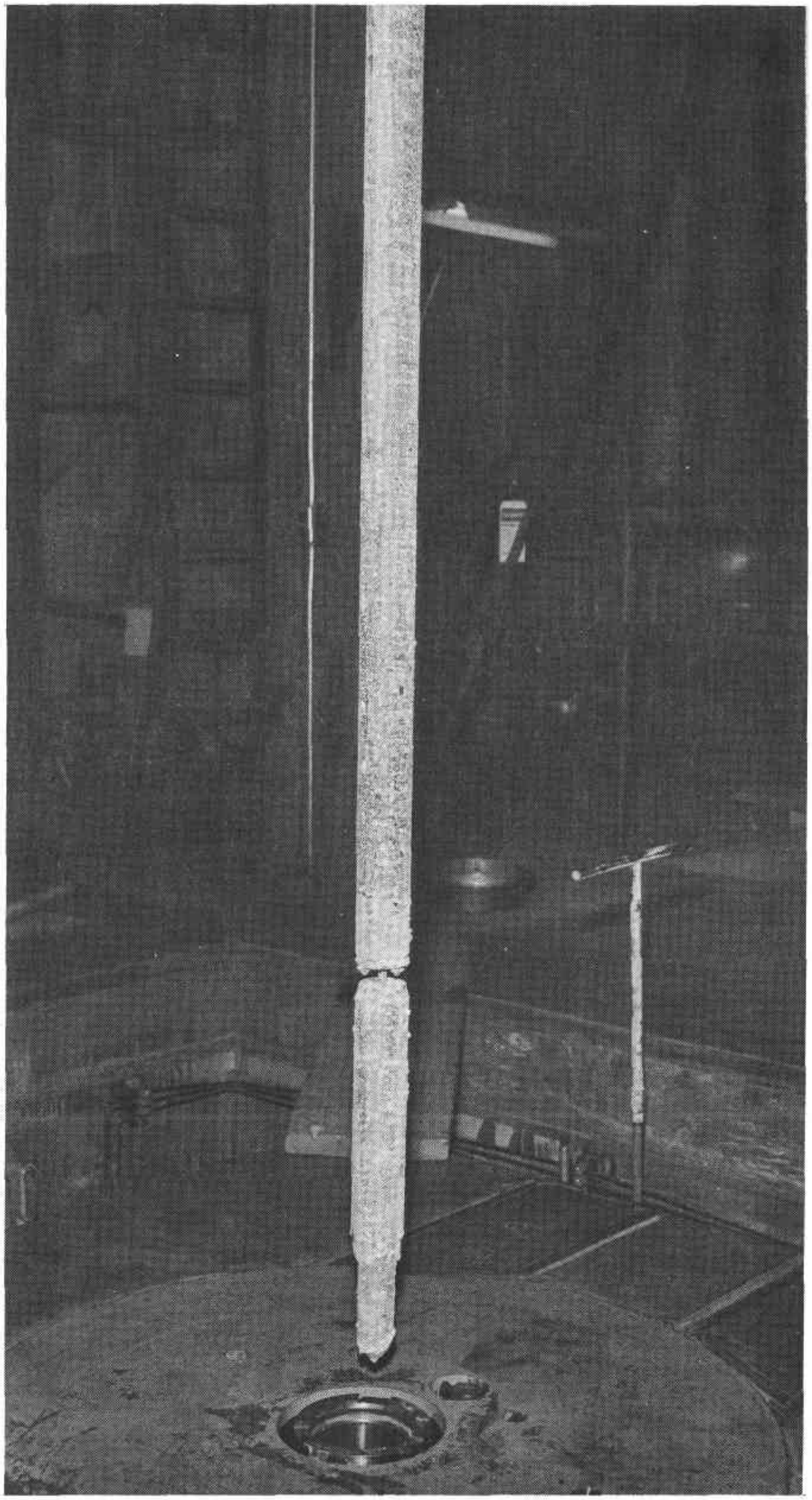
9-010-116-126

BR 5 CLEANING PROCEDURES

- DRAIN PRIMARY SODIUM (REMOVED NA 22 AND Cs 137)
- PREHEAT TO ABOUT 150°C (USING INSTALLED PREHEATERS)
- REACT RESIDUAL SODIUM WITH STEAM (REMOVED Cs 137 AND Zr 95)
- FILL WITH DISTILLED WATER FOR "A FEW DAYS" (REMOVED Cs 137, Zr 95, Fe 59, Co 58, AND Co 60)
- FILL WITH DISTILLED WATER FOR SIX DAYS
- ACID WASH WITH 5% HNO_3 FOR 6 HOURS AT 70°C
- ACID WASH WITH 5% HNO_3 FOR 12 HOURS AT 70°C
- ACID WASH WITH 5% HNO_3 FOR 16 HOURS AT 70°C
- FIVE CYCLES OF THE FOLLOWING TREATMENT:
  - a) 5% $KMnO_4$ FOR 24 HOURS AT 70°C
  - b) 5% HNO_3 AND 1% OXALIC ACID 3 TO 4 HOURS AT 70°C
  - c) DISTILLED WATER FOR ONE HOUR AT 60 TO 80°C
- DRY UNDER VACUUM AT 150°C

70-MA19-48-153

CORE COMPONENT SHOWING ADHERING SODIUM-SRE

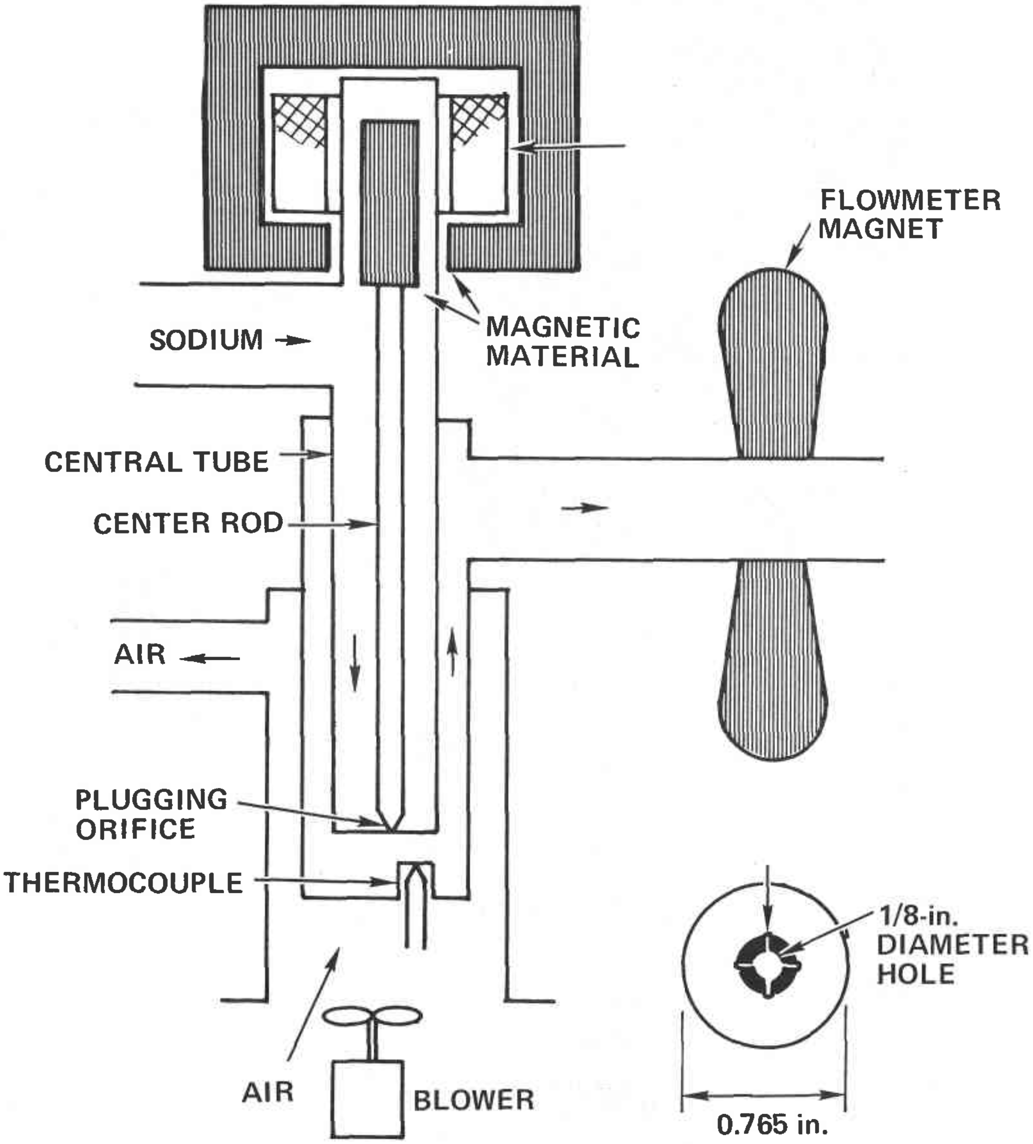


70-MA1-48-228

SRE PUMP AFTER FLOODING AND FREEZING

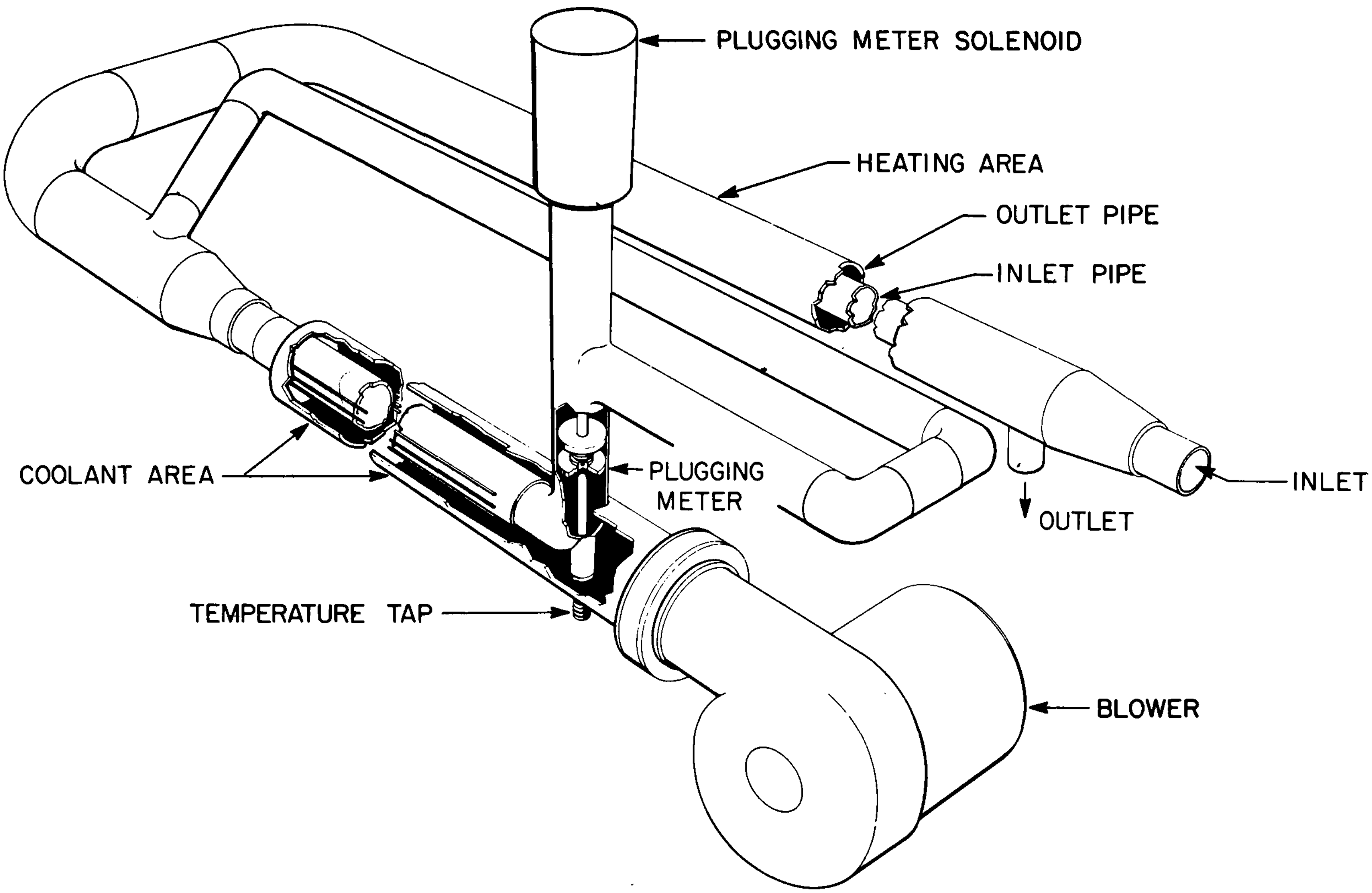
70-MA1-48-227

PLUGGING METER SCHEMATIC



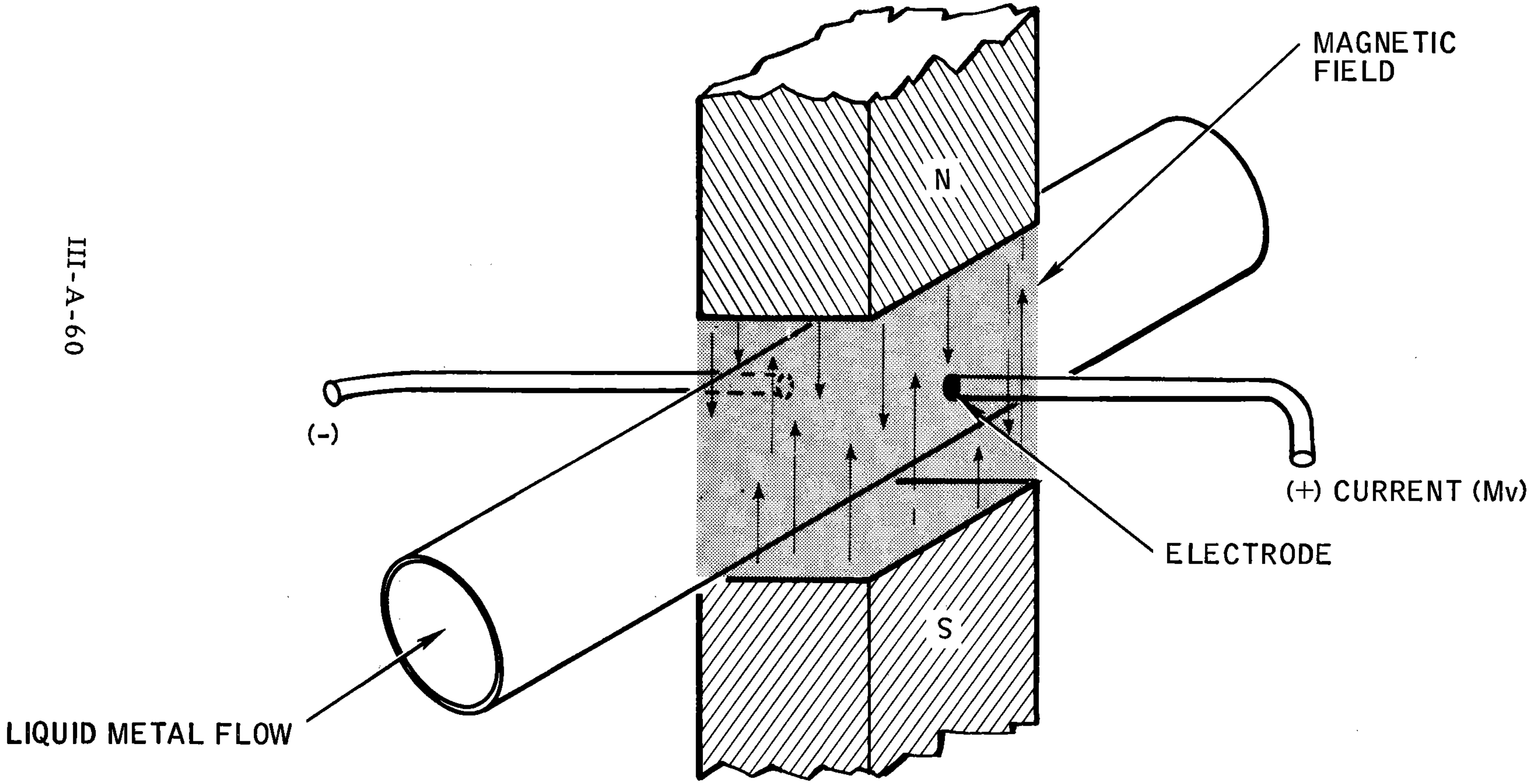
70-MA1-48-289

PLUGGING METER



66-00-83-41

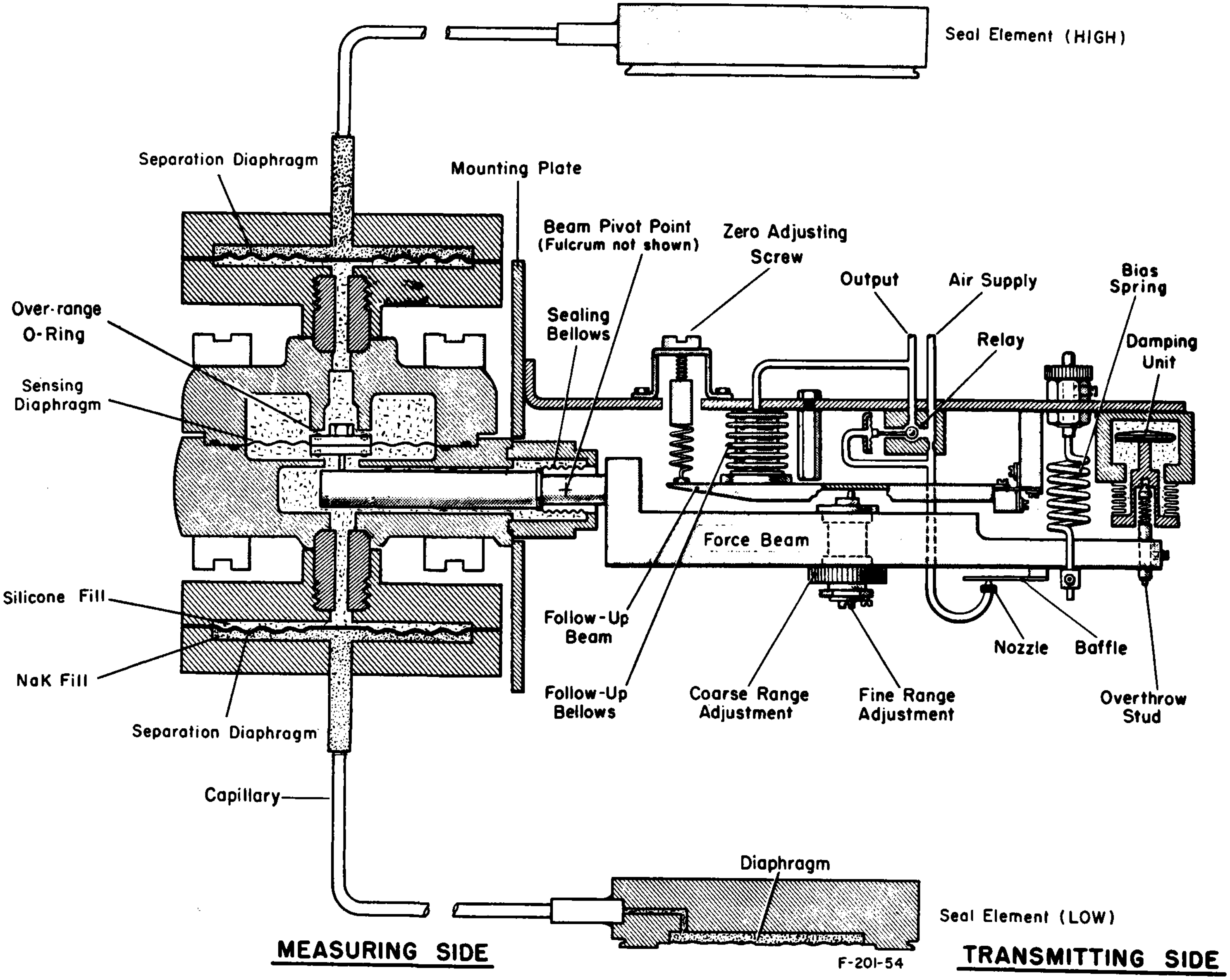
MAGNETIC FLOW METER SCHEMATIC



FLOW OF LIQUID METAL CUTS LINES
OF FORCE PRODUCING EMF

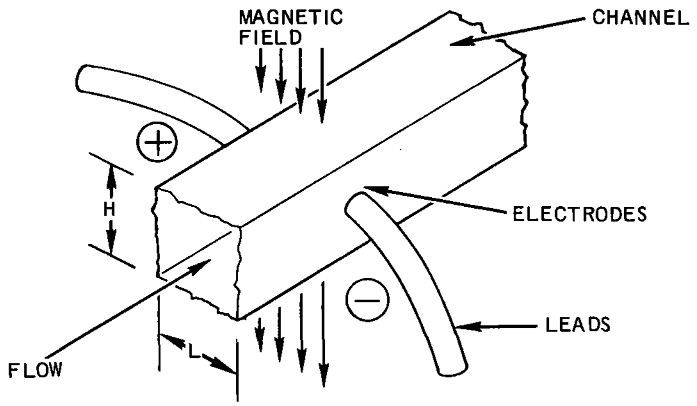
9-010-116-41

NaK FILLED DIAPHRAGM TYPE PRESSURE TRANSMITTER

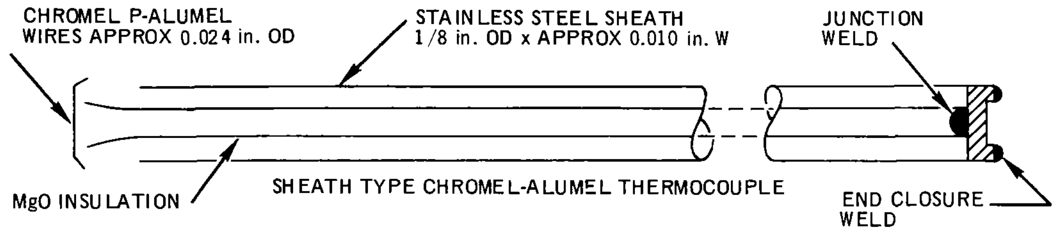


70-MA1-48-287

TYPICAL SODIUM SYSTEM INSTRUMENTATION

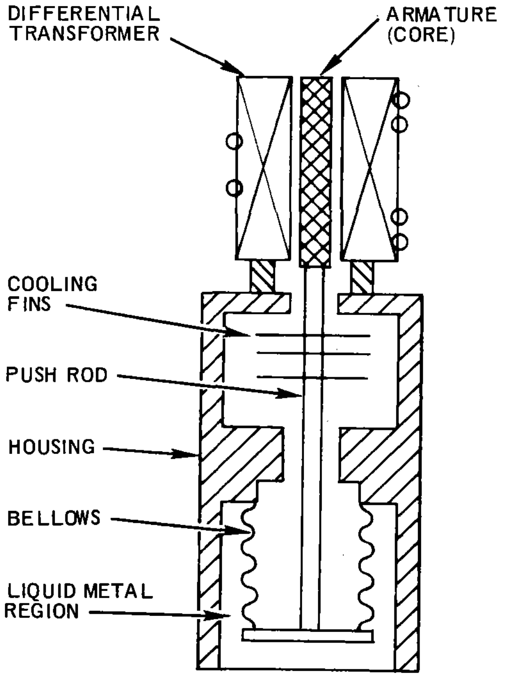


ELECTROMAGNETIC FLOWMETER

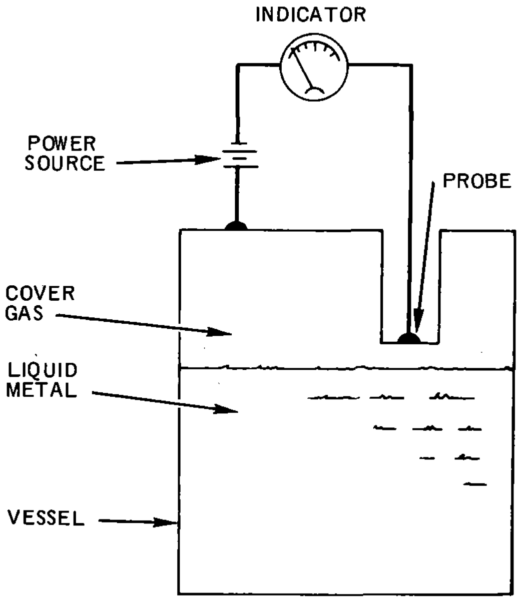


SHEATH TYPE CHROMEL-ALUMEL THERMOCOUPLE

TEMPERATURE MEASUREMENT



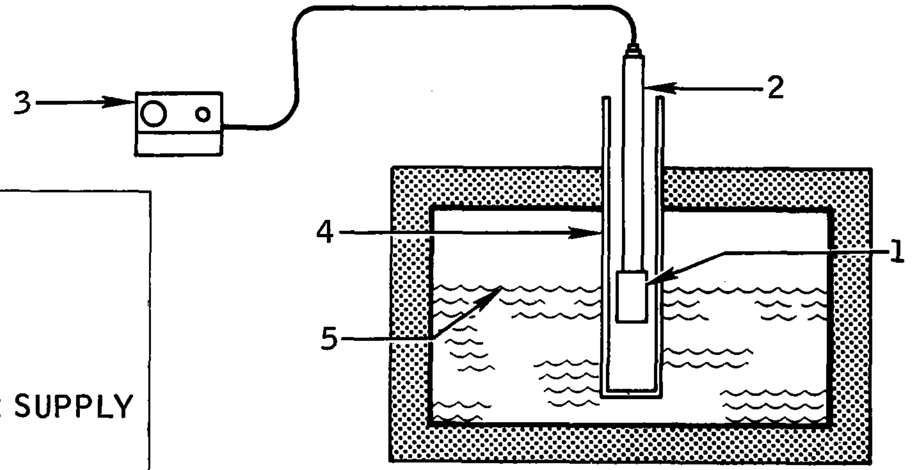
BELLOWS TYPE PRESSURE GAGE WITH LINEAR VARIABLE DIFFERENTIAL TRANSDUCER



LEVEL PROBE, THIMBLE TYPE

6095-1213

LIQUID METAL LEVEL SENSOR SCHEMATIC

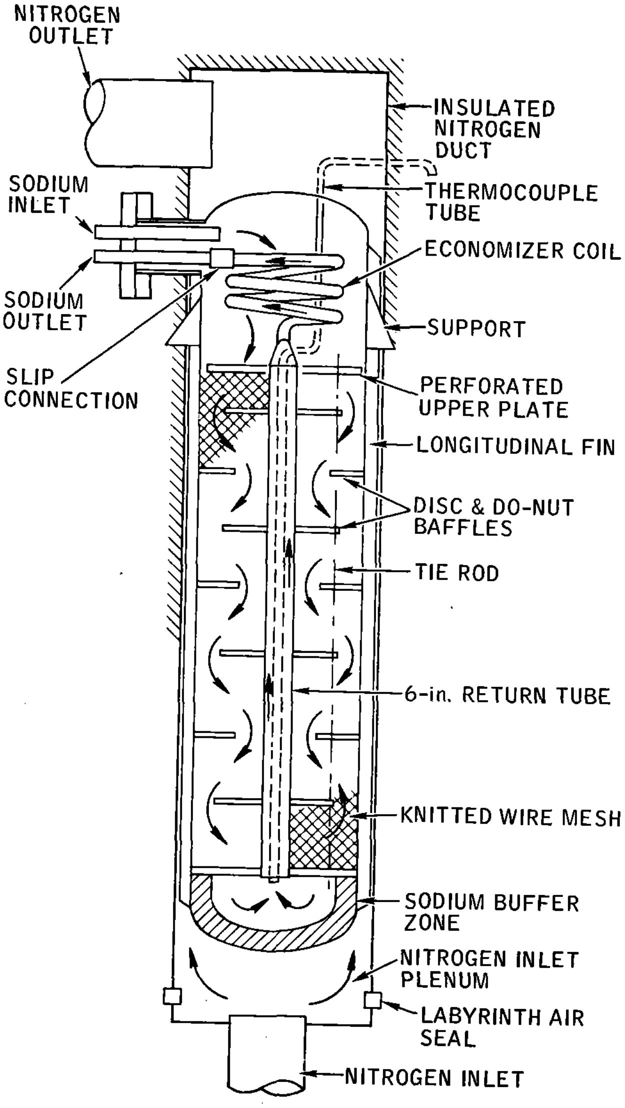


LEGEND

1. COIL
2. PROBE
3. INDICATOR, OSCILLATOR AND POWER SUPPLY
4. STAINLESS STEEL THIMBLE
5. LIQUID METAL LEVEL

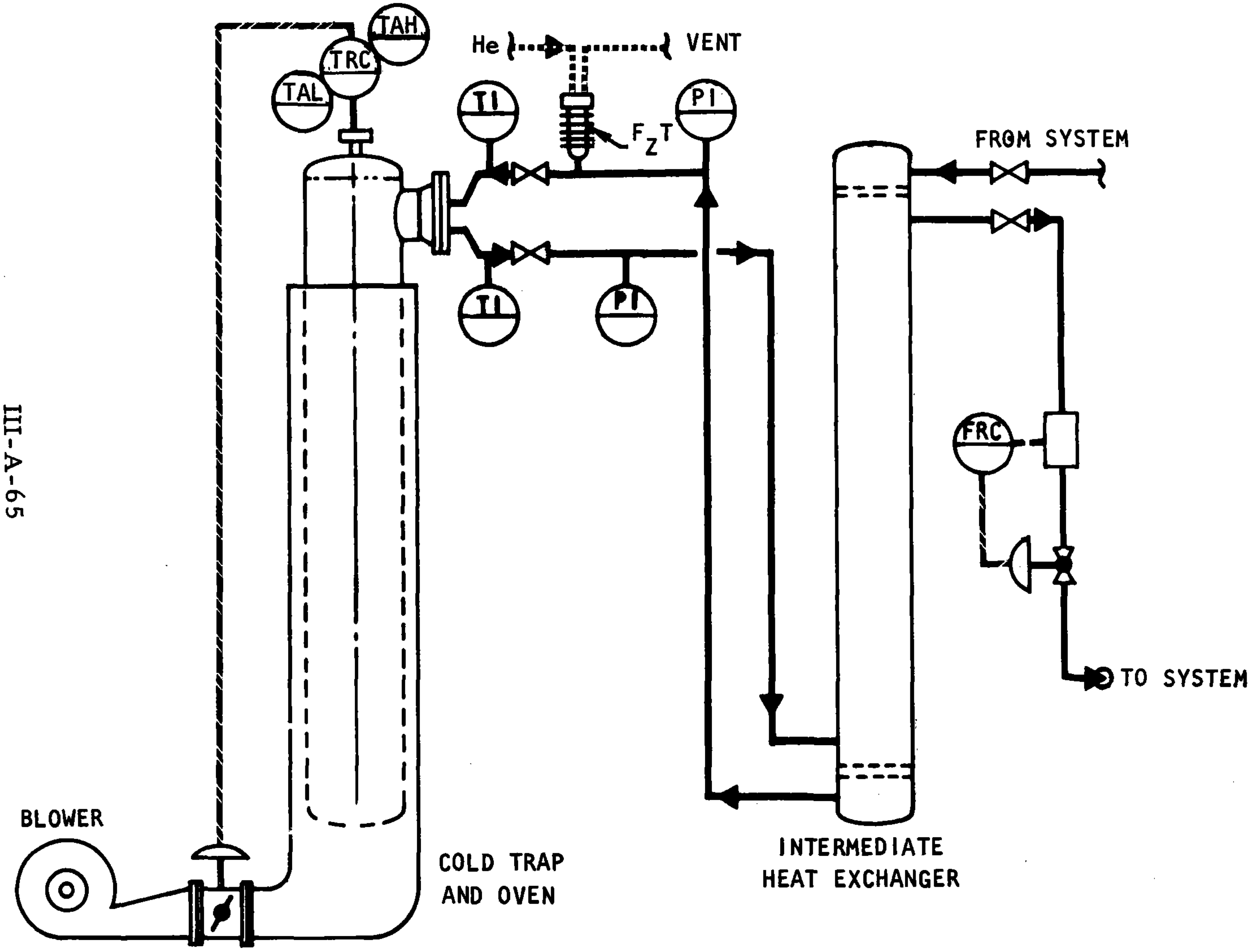
METHOD OF OPERATION

CYCLIC VOLTAGE APPLIED TO CENTER COIL INDUCES EQUAL AND OPPOSITE VOLTAGES IN 2 OUTSIDE COILS WHEN THEY ARE IN A HOMOGENEOUS MEDIUM. WHEN PROBE IS INSERTED INTO THE THIMBLE TO THE POINT WHERE THE LOWER COIL IS BELOW LEVEL OF THE LIQUID METAL, THE IMPEDANCE CHANGE PERMITS CURRENT TO FLOW. MAXIMUM READING IS OBTAINED WHEN ONLY THE LOWER COIL IS COMPLETELY BELOW THE LEVEL OF THE LIQUID METAL.


NITROGEN OUTLET
INSULATED NITROGEN DUCT
SODIUM INLET
THERMOCOUPLE TUBE
ECONOMIZER COIL
SODIUM OUTLET
SUPPORT
SLIP CONNECTION
PERFORATED UPPER PLATE
LONGITUDINAL FIN
DISC & DO-NUT BAFFLES
TIE ROD
6-in. RETURN TUBE
KNITTED WIRE MESH
SODIUM BUFFER ZONE
NITROGEN INLET PLENUM
LABYRINTH AIR SEAL
NITROGEN INLET

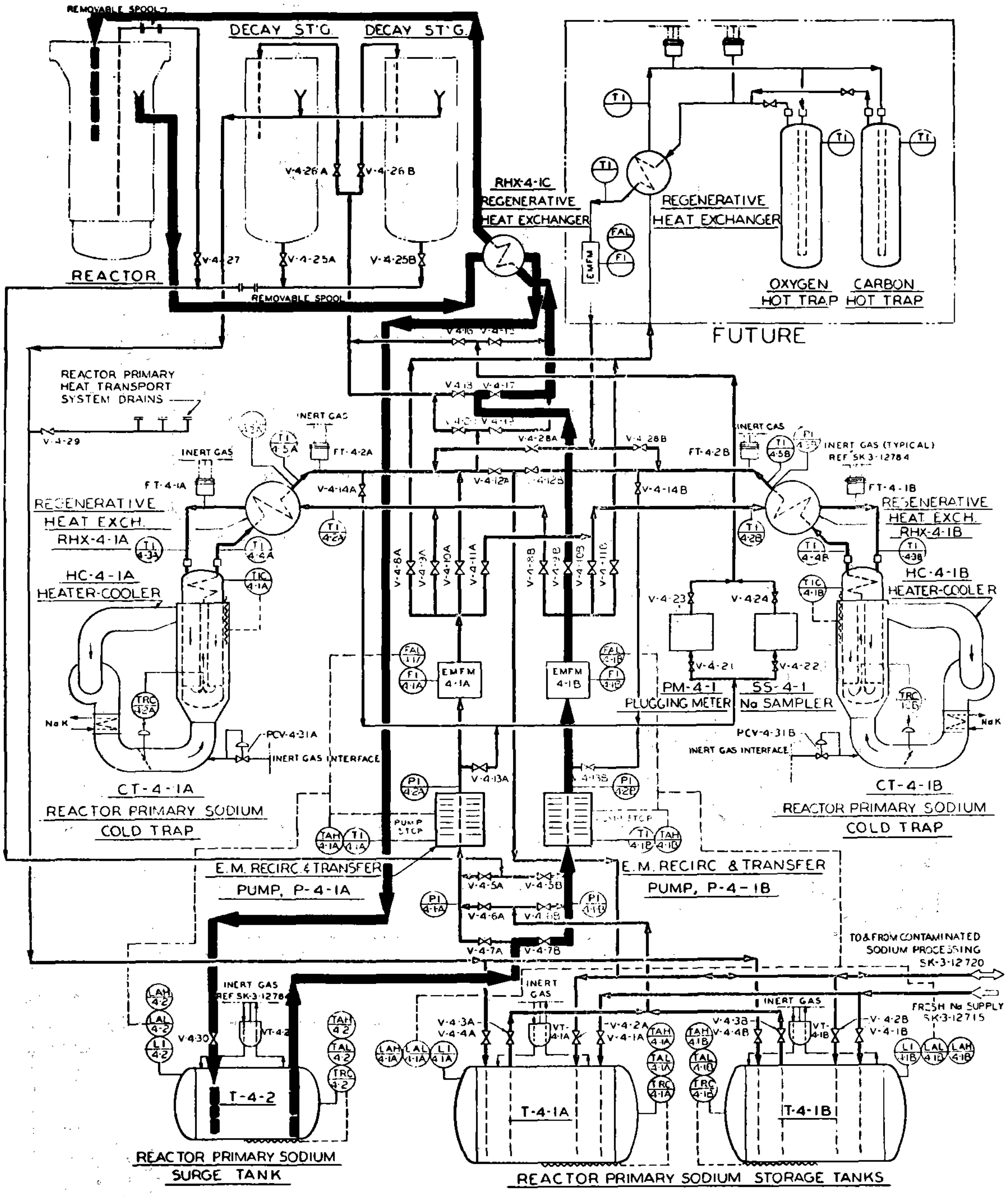
7-7694-206-10

TYPICAL COLD TRAP INSTALLATION



70-MA19-48-142

TYPICAL SODIUM SERVICE SYSTEM



70-MA1-48-280

CODES AND STANDARDS

I. NUCLEAR POWER SYSTEMS

1. ASME BOILER AND PRESSURE VESSEL CODE, SECTION III, NUCLEAR VESSELS SUPPLEMENTED BY CODE INTERPRETATION CASE NO. 1331 FOR HIGH TEMPERATURE SERVICE
2. USA STANDARD CODE FOR PRESSURE PIPING USAS B31.7 NUCLEAR POWER PIPING SUPPLEMENTED BY CODE INTERPRETATION CASE NO. 67 FOR HIGH TEMPERATURE SERVICE
3. ASME CODE FOR PUMPS AND VALVES FOR NUCLEAR POWER (TENTATIVE ISSUE)* (HIGH TEMPERATURE SERVICE IS NOT COVERED)
4. ASME CODE FOR IN-SERVICE INSPECTION OF NUCLEAR SYSTEMS (TENTATIVE ISSUE)*

II. NON-NUCLEAR SYSTEMS

1. ASME BOILER AND PRESSURE VESSEL CODE – SECTION I – POWER BOILERS
2. ASME BOILER AND PRESSURE VESSEL CODE – SECTION VIII – PRESSURE VESSELS
    a) DIVISION 1 – PRESSURE VESSELS
    b) DIVISION 2 – ALTERNATIVE RULES FOR PRESSURE VESSELS
3. USA STANDARD CODE FOR PRESSURE PIPING – USAS B31.1.0 – 1967 POWER PIPING

III. OTHER STANDARDS

ASTM MATERIAL SPECIFICATIONS
USA STANDARDS (PIPE, FITTINGS, ETC.)
MSS STANDARD PRACTICES
ANS STANDARDS
RDT STANDARDS

*THESE TENTATIVE STANDARDS ARE FOR WATER-COOLED REACTORS. WE EXPECT SIMILAR CODES FOR SODIUM COOLANT SERVICE IN THE NEAR FUTURE.

9-N11-129-62

INSPECTIONS AND TESTS — MATERIALS

I. PLATE

(1) CHEMICAL ANALYSIS

(2) MECHANICAL TESTS
TENSILE STRENGTH (LONGITUDINAL AND TRANSVERSE)
BEND PROPERTIES**
ELONGATION
HARDNESS

(3) DIMENSIONAL INSPECTION AND SURFACE FINISH

(4) SPECIAL TESTS
ULTRASONIC INSPECTION
RADIOGRAPHIC EXAMINATION
IMPACT TESTING*
CLEANLINESS

II. PIPE AND TUBES

(1) CHEMICAL ANALYSIS

(2) MECHANICAL TESTS
TENSILE STRENGTH (LONGITUDINAL AND TRANSVERSE)
FLATTENING
ELONGATION
HARDNESS

(3) DIMENSIONAL INSPECTION AND SURFACE FINISH

(4) SPECIAL TESTS
RADIOGRAPHIC EXAMINATION OF WELDS
ULTRASONIC EXAMINATION
HYDROSTATIC TEST (REQUIRED)
IMPACT TEST*
CLEANLINESS

*REQUIRED FOR SECTION III
**REQUIRED FOR 400 SERIES STEELS

INSPECTIONS AND TESTS OF VESSELS

*†ℓ1. HYDROSTATIC (OR PNEUMATIC OR PROOF TEST SUBSTITUTE)
*†ℓ2. CHECK OF WELDING PROCEDURE WITH CERTIFICATION
*†ℓ3. CHECK OF WELDOR QUALIFICATIONS WITH CERTIFICATION
*†4. CHECK OF INSPECTION QUALIFICATION
*†5. 100% RADIOGRAPH OF WELD SEAMS
ℓ(2)6. SPOT RADIOGRAPH OR SECTION PROCEDURES
7. DYE PENETRANT EXAMINATION OF EDGES
8. DYE PENETRANT EXAMINATION OF WELDS
*(1)9. ULTRASONIC INSPECTION OF WELDS
*(1)10. MAGNETIC PARTICLE EXAMINATION
11. HAMMER TEST
12. IMPACT TESTS OF WELD COUPONS
13. BEND TESTS OF WELD COUPONS
14. CONFORMANCE TO DIMENSIONS
15. CLEANLINESS AND DRYNESS
16. HELIUM LEAK TEST

NOTES:

*REQUIRED IN SECTION III, CLASS A VESSELS
†REQUIRED IN SECTION VIII, DIVISION 2
ℓREQUIRED IN SECTION VIII, DIVISION 1
(1)ONE OF THESE TWO TESTS REQUIRED AFTER HYDROSTATIC
(2)FULL RADIOGRAPH MAY BE USED WITH INCREASED LIGAMENT EFFICIENCY

FACTORS INVOLVED IN ESTABLISHING PRIMARY AND SECONDARY Na PIPE WALL THICKNESS

- DESIGN BASIS
  - USAS CODE FOR PRESSURE PIPING
  - USAS B31.7 NUCLEAR PIPING
- ALLOWABLE STRESS
  - BASED ON 250,000 DESIGN LIFE
- CORROSION ALLOWANCE
  - DETERMINED BY VELOCITY AND OXYGEN CONTENT OF SODIUM
- DECARBURIZATION
  - FERRITIC STEEL – RECOMMENDED 20% REDUCTION IN ALLOWABLE STRESS
- EXTERNAL PRESSURE
  - MUST WITHSTAND EXTERNAL PRESSURE WHICH COULD BE IMPOSED DURING
  - PRESSURIZED LEAK TESTING OF INNER CONTAINMENT BARRIER (PRIMARY VAULTS)

70-F16-015-24

DESIGN APPROACH

- CONCEPTUAL DESIGN
    - PRESSURE DESIGN AND STRESS ANALYSIS FOR THERMAL EXPANSION ACCORDING TO USAS B31.1.0 – 1967
- PRELIMINARY DESIGN
    - TRANSITION FROM USAS B31.1.0 – 1967 TO USAS B31.7 – 1969
    - ESTABLISH ALLOWABLE STRESS INTENSITIES
    - PRESSURE DESIGN FOR WALL THICKNESSES
    - FLEXIBILITY ANALYSIS TO OBTAIN FORCES AND MOMENTS
    - THERMAL AND STRESS ANALYSIS FOR THERMAL GRADIENTS
    - FOLLOW-UP OF PRESENTLY CONDUCTED RESEARCH PROGRAMS COVERING UNCERTAINTIES AND NEW ANALYTICAL TECHNIQUES
    - SUPPORTING SUPPLEMENTAL RESEARCH PROGRAMS TO OBTAIN INFORMATION FOR PERFORMING B31.7 ANALYSIS WHEN DATA FROM OTHER SOURCES ARE NOT AVAILABLE, e.g., STRESS INDICES AND H. T. DESIGN CRITERIA
    - EARTHQUAKE ANALYSIS
    - SIMPLIFIED B31.7 STRESS ANALYSIS AND ITS EVALUATION
        - ▶STRESSES ARE ACCEPTABLE (BASED ON PRESENTLY AVAILABLE TECHNIQUES AND DATA)
        - ▶CALCULATED STRESSES EXCEED ALLOWABLE VALUES AT CERTAIN POINTS. ALTERNATE PROCEDURES:
            - APPLY DETAILED APPENDIX F ANALYSIS OR SIMPLIFIED ELASTIC PLASTIC ANALYSIS
            - REDESIGN COMPONENTS
            - REDESIGN PIPING CONFIGURATIONS
- FINAL DESIGN
    - COMPLIANCE WITH B31.7 REQUIREMENTS CONCURRENT WITH RESULTS OF THE RESEARCH PROGRAMS
    - PREPARATION OF B31.7 STRESS REPORT

70-F16-015-16

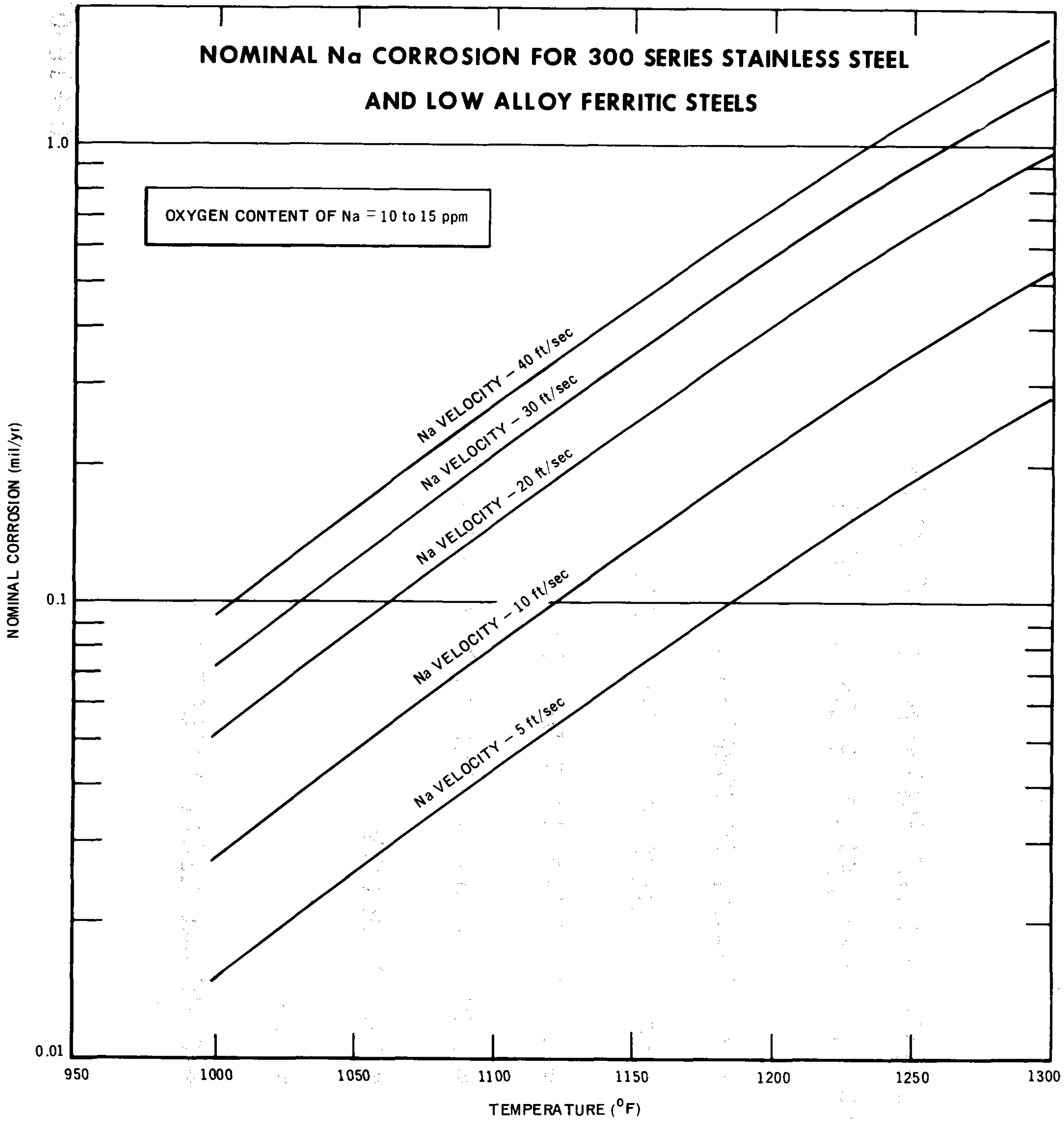
EARTHQUAKE ANALYSIS

- USAS B31.7 – 1969 NUCLEAR POWER PIPING CODE INCLUDING CODE INTERPRETATION CASES
  - NO. 67 – CLASS I PIPING FOR HIGH TEMPERATURES WITH REVISIONS PRESENTLY IN PREPARATION
  - NO. 70 – CRITERIA FOR NUCLEAR POWER PIPING UNDER ABNORMAL CONDITIONS
- BNWL-1236 SUGGESTED DESIGN CRITERIA FOR FTR PIPING SYSTEMS
  - WILL BE COVERED BY LMFBR PIPING DESIGN GUIDE NOW BEING PREPARED BY C. F. BRAUN & CO. AND UNITED NUCLEAR CORP. UNDER AEC CONTRACT
- EARTHQUAKE ANALYSIS OF NUCLEAR POWER PIPING
  - CODE CASE UNDER PREPARATION
  - UCLA "QUAKE" STUDIES
  - LITERATURE REVIEW

70-F16-015-15

GUIDELINES FOR PRIMARY SODIUM PIPING MATERIALS SELECTION

- RESISTANCE TO CORROSION
- COMPATIBILITY WITH THE SYSTEM
- STABILITY UNDER RADIATION
- PHYSICAL AND METALLURGICAL PROPERTIES
- FABRICABILITY
- COST
- CODE AND LEGAL ACCEPTANCE



NOMINAL Na CORROSION FOR 300 SERIES STAINLESS STEEL AND LOW ALLOY FERRITIC STEELS

SHOP FABRICATION

ENVIRONMENT	EFFECT	POSSIBLE COUNTERMEASURES
● FABRICATION – WELDING		
CONTAMINATION	MATERIAL CONTAMINATION C, Pb, S HALOGENS	ESTABLISH REQUIREMENTS
OIL, DUST, ETC.	RESIDUAL STRESS	APPROVE PROCEDURES
MOISTURE	CORROSION	IN-PROCESS CONTROL
METAL CHIPS	STRESS CORROSION	PROPER CLEANING
MARKING PENCILS, ETC.	WELD POROSITY	CONTROL MATERIALS
WELDING MATERIAL	WELD CRACKS	ANNEAL IF POSSIBLE
FLUXES	MECHANICAL PROPERTIES	STRESS RELIEF IF POSSIBLE
TEMPERATURE	LOW TEMPERATURE EMBRITTLEMENT	TAG SENSITIZED COMPONENTS
NDT FLUIDS		CONTROL ENVIRONMENT
COUPLANTS		
DYES		
● STORAGE AND SHIPMENT		
CONTAMINATION	OXIDATION	SPECIFIC REQUIREMENTS
NATURE	CORROSION	APPROVE PROCEDURES
BLOOD, SWEAT, AND TEARS	STRESS CORROSION	CONTROL ENVIRONMENT
DUNNAGE AND CRATING	SCRATCHES AND DINGS	
	DEFORMATION	

ENVIRONMENTAL ANALYSIS

- FABRICATION, SHIPPING, AND STORAGE
- INSTALLATION AND ERECTION AND STORAGE
- OPERATION AND MAINTENANCE
- ABNORMAL OPERATION AND MAINTENANCE
- SHUTDOWN AND RETIREMENT

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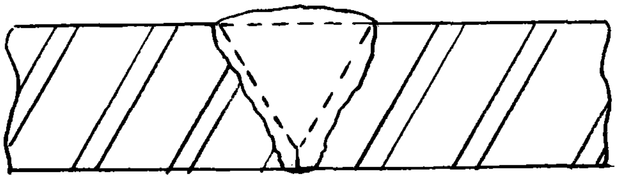
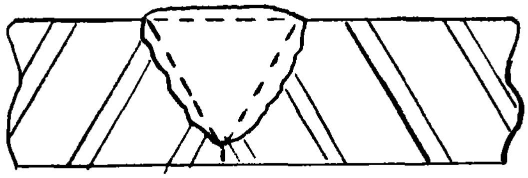
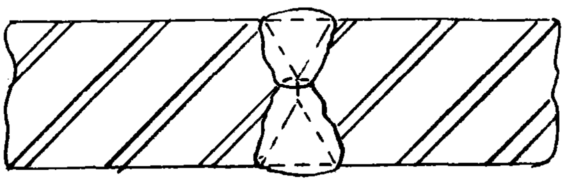
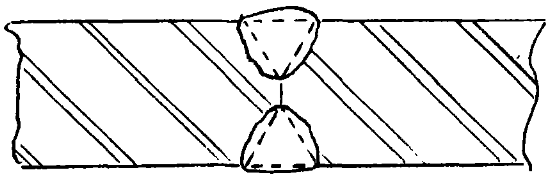
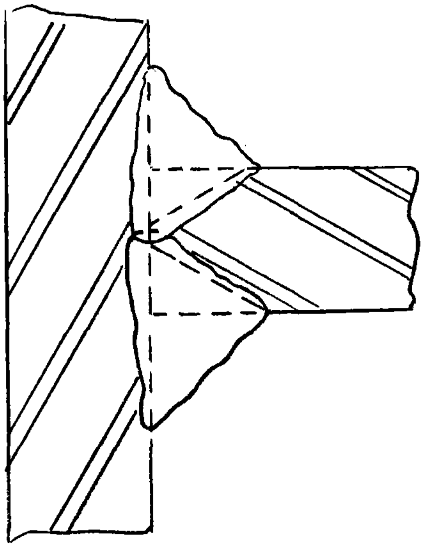
TYPICAL WELD DETAILS

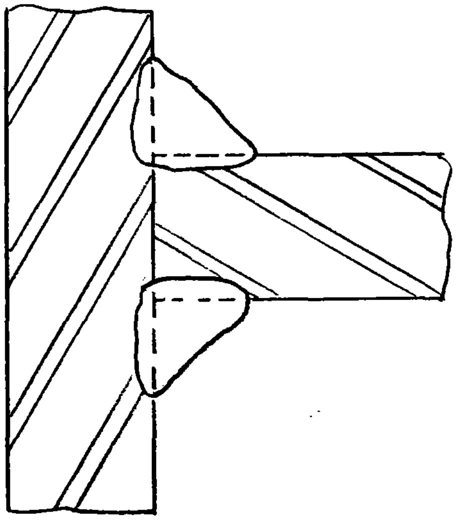


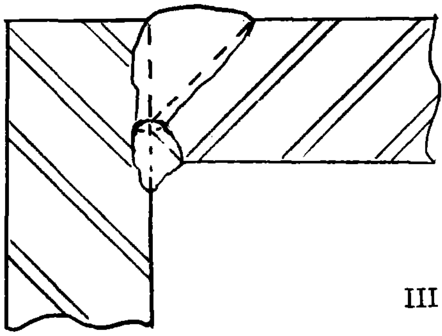


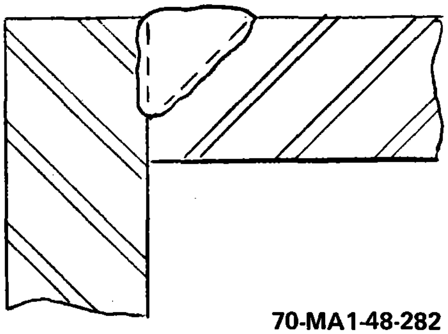




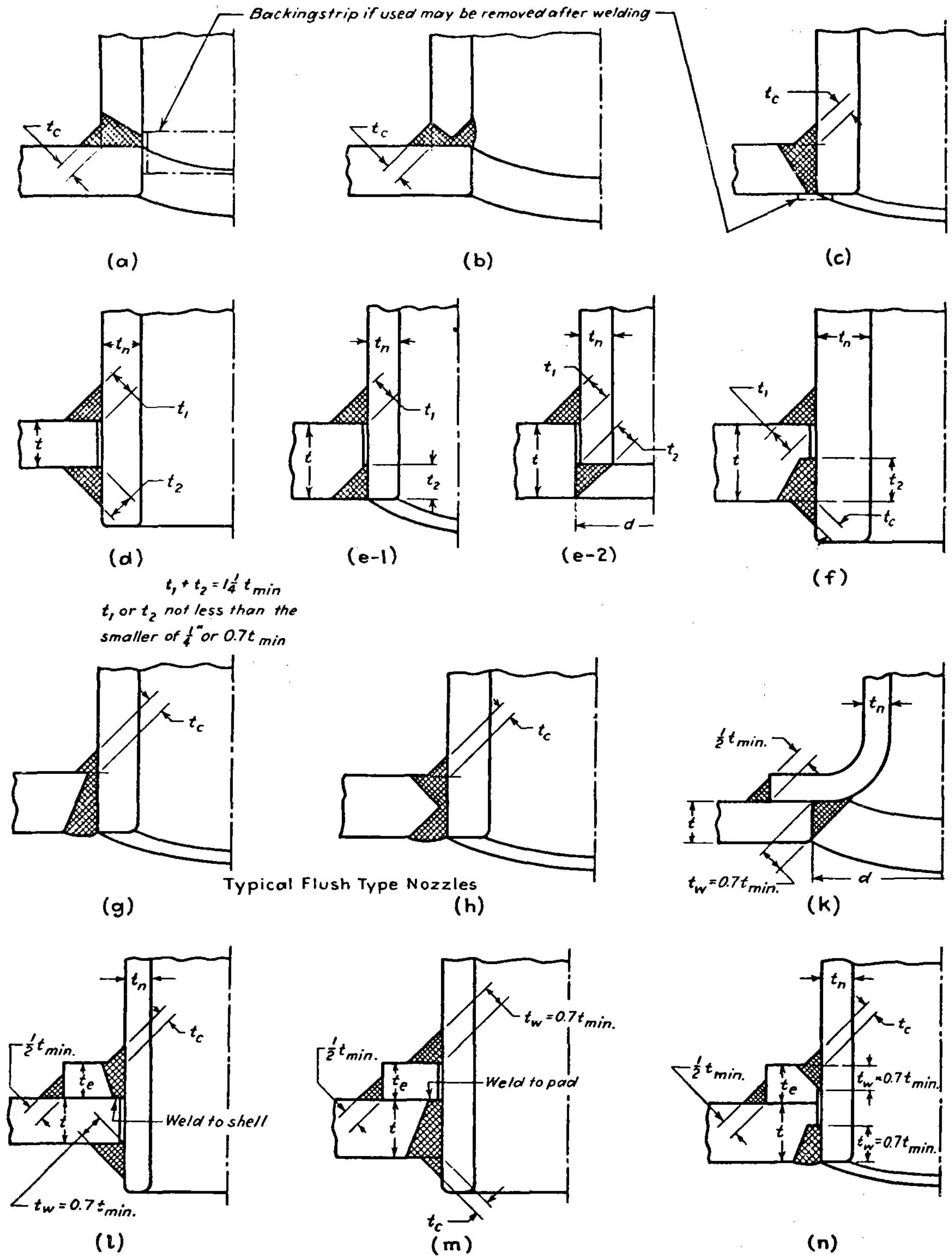








SOME ACCEPTABLE TYPES OF WELDED NOZZLES & OTHER CONNECTIONS TO SHELLS, DRUMS, & HEADERS

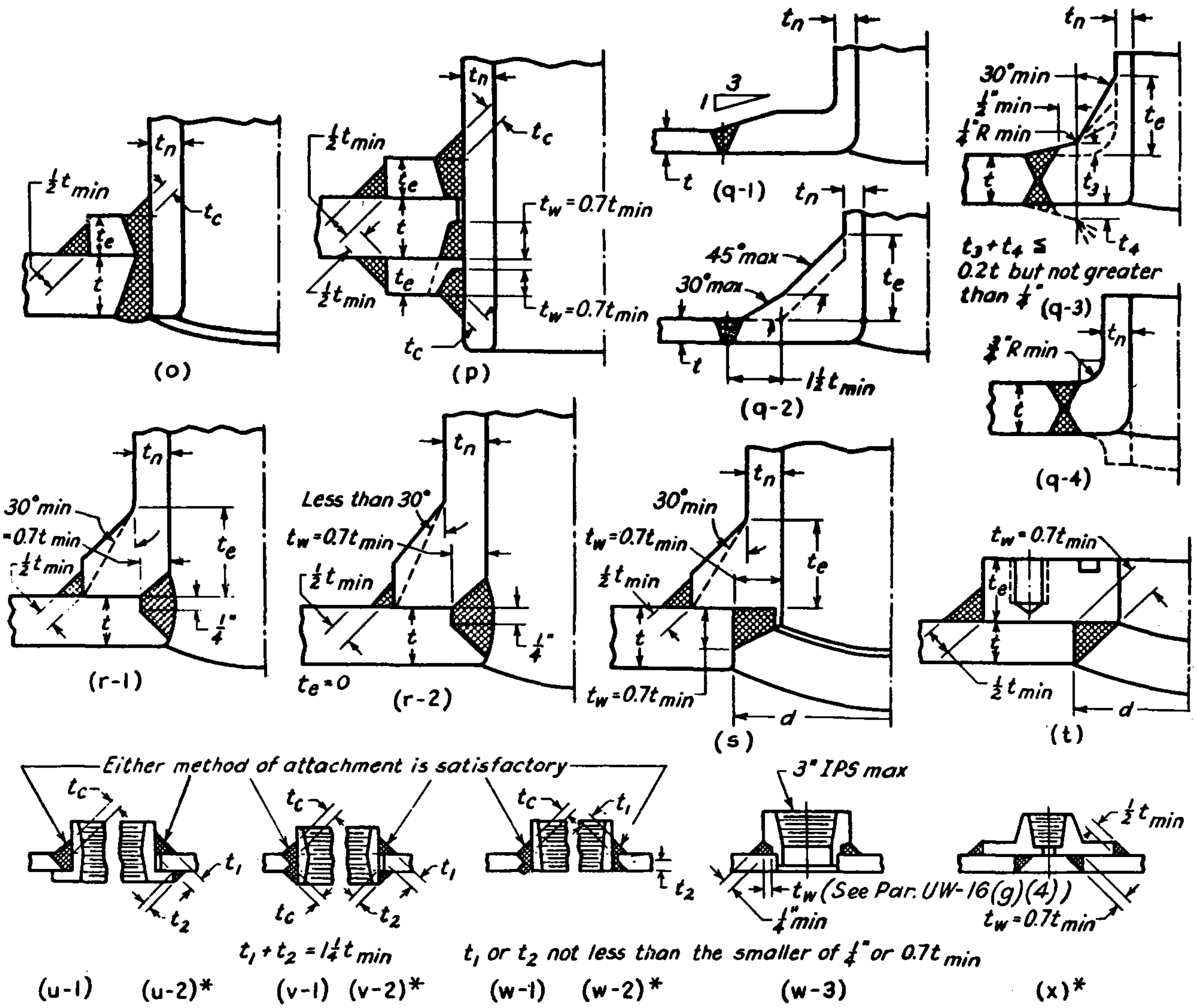


$t_1 + t_2 = 1\frac{1}{4}\, t_{min}$

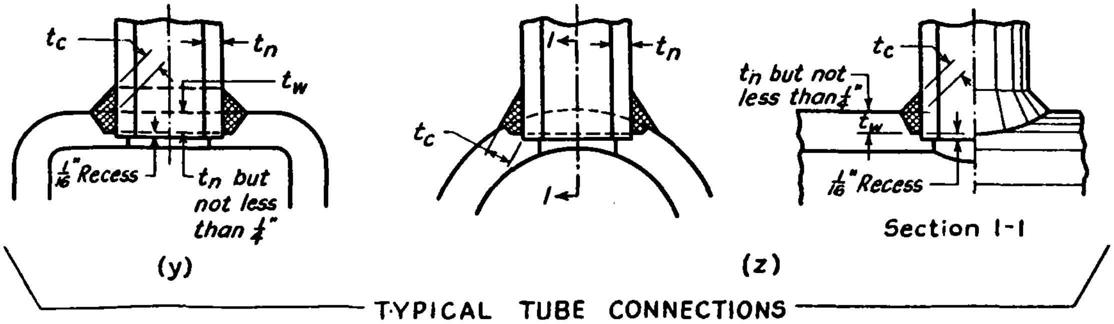
t_1 or t_2 not less than the smaller of $\frac{1}{4}''$ or $0.7 t_{min}$

Typical Flush Type Nozzles

SOME ACCEPTABLE TYPES OF WELDED NOZZLES & OTHER CONNECTIONS TO SHELLS, DRUMS, & HEADERS



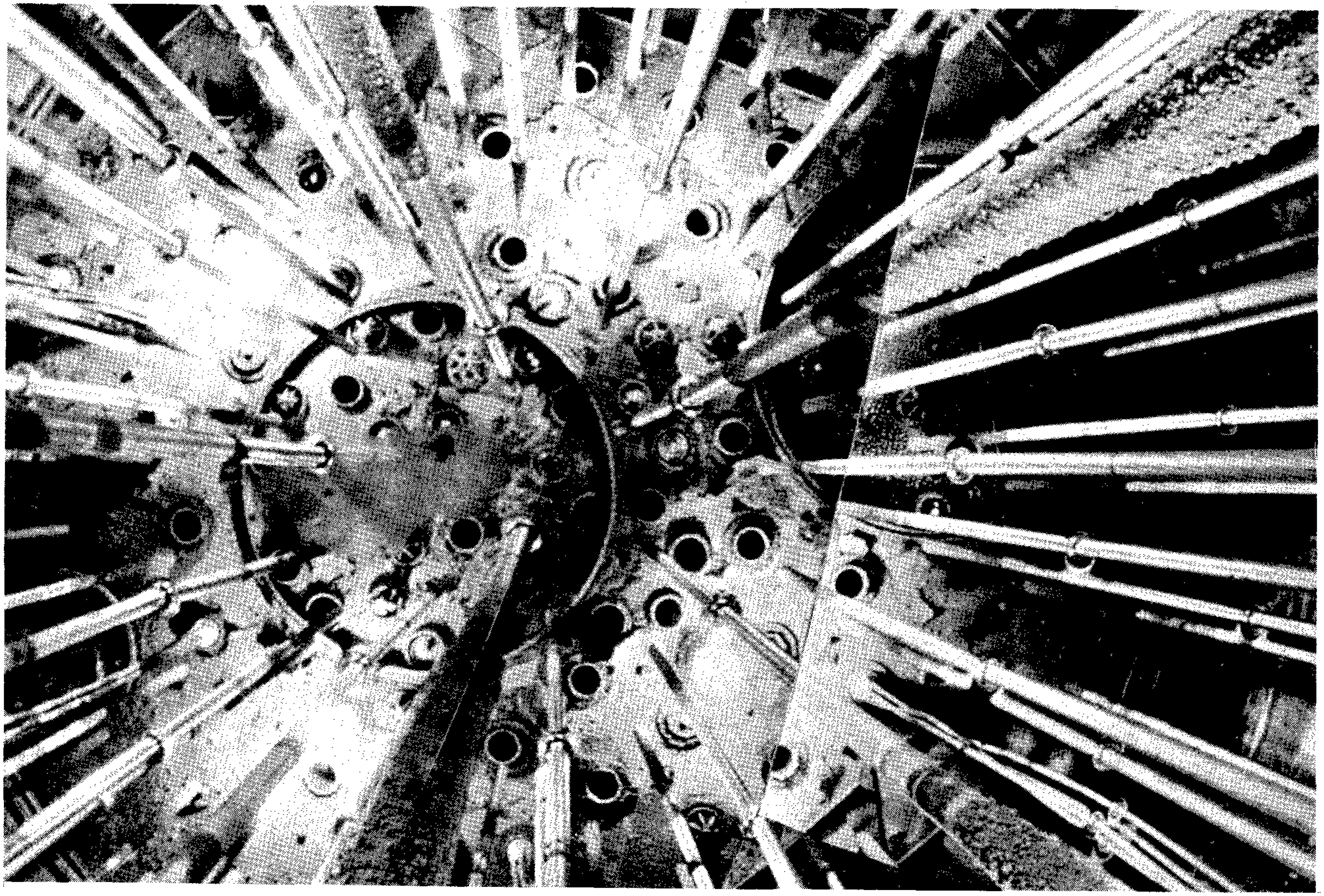
* For 3" pipe size and smaller, see exemptions in Par. UW-16(g)(2)



TYPICAL TUBE CONNECTIONS

(When used for other than square, round, or oval headers, round off corners)

VIEW OF SODIUM FROST FORMATION IN SRE



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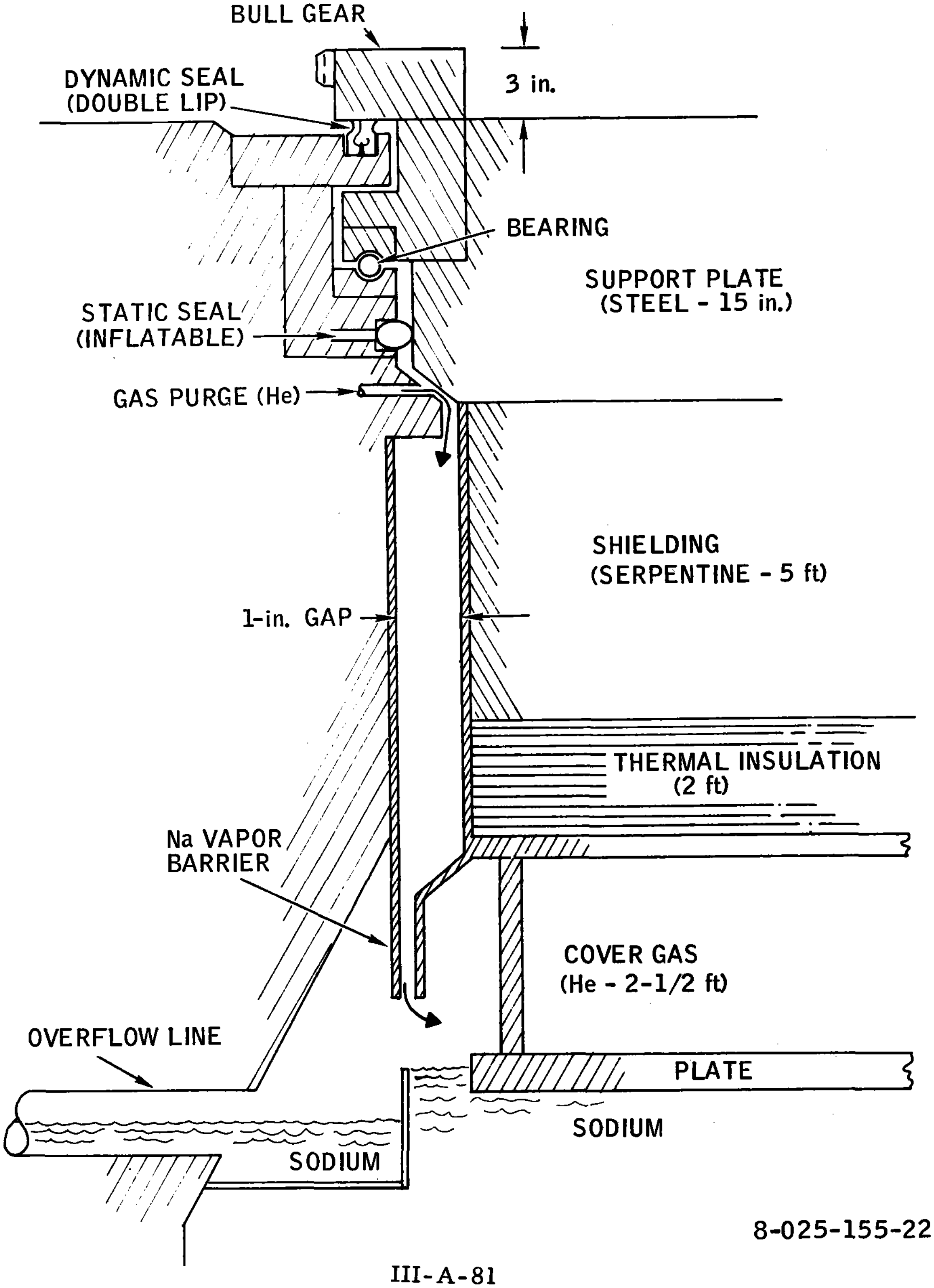
TOP SHIELD SEAL AND Na FROST CONTROL



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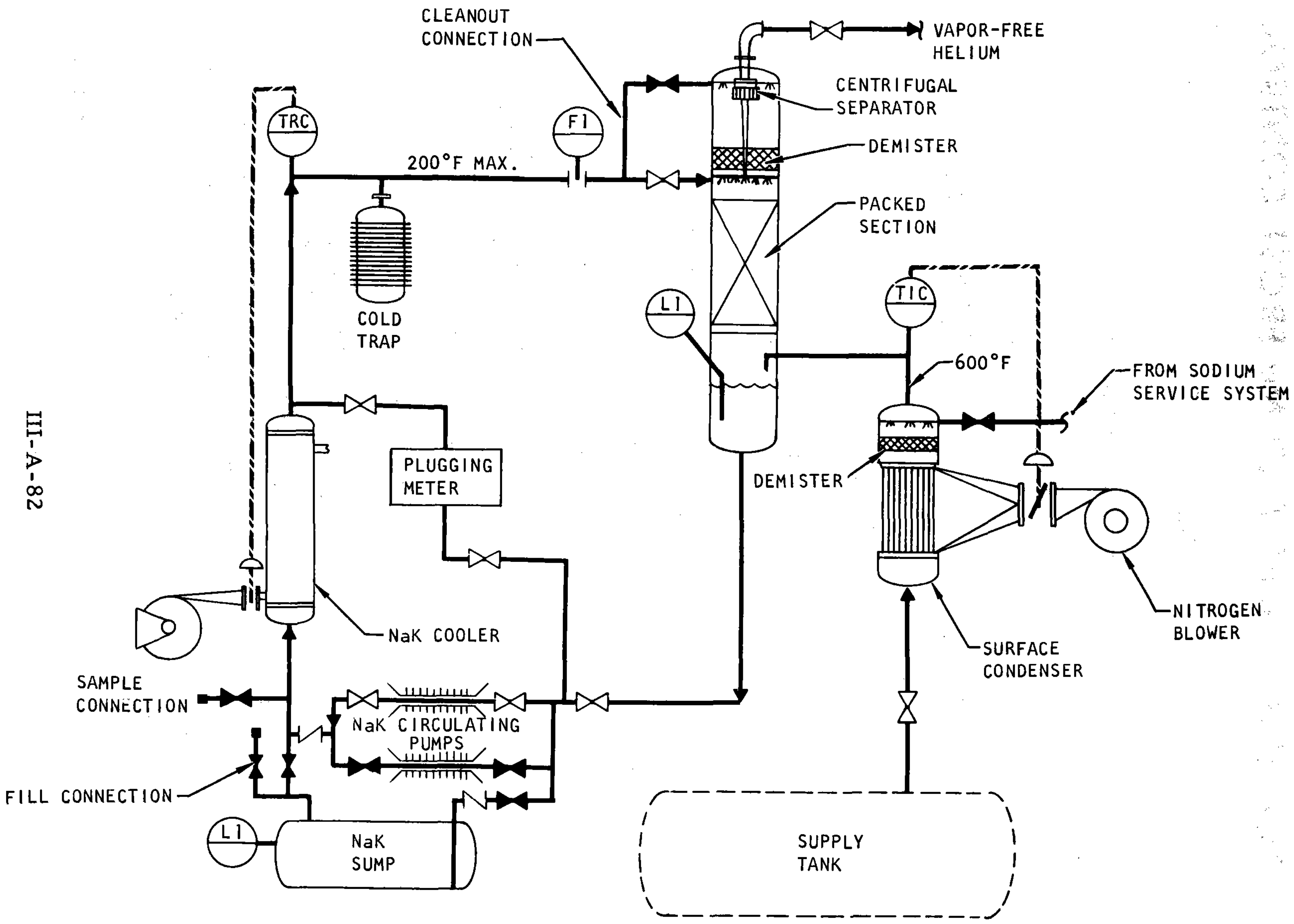
HIGH VOLUME VAPOR TRAP CONCEPT 5-SUGGESTED REFERENCE DESIGN



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SPECIAL PROBLEMS

- SELF-WELDING

  THE TENDENCY OF TWO PIECES OF METAL TO WELD TOGETHER WHEN PRESSED TOGETHER FOR A LONG PERIOD OF TIME AT ELEVATED TEMPERATURE IN A REDUCING ATMOSPHERE

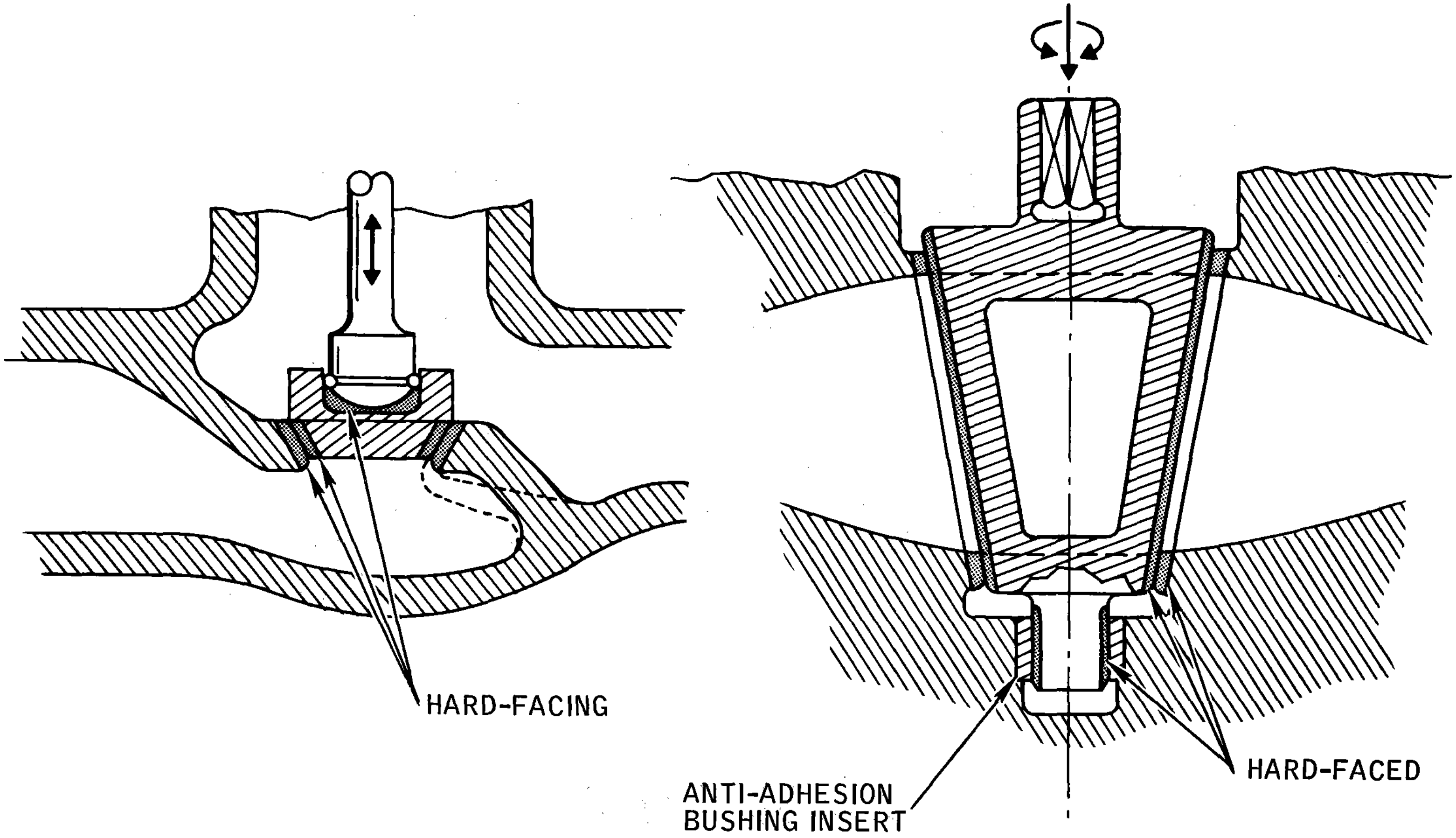
- SEIZING

  THE TENDENCY OF TWO METALS IN SLIDING CONTACT TO BECOME WELDED TO ONE ANOTHER AT THE POINT OF CONTACT

- GALLING

  THE TENDENCY OF TWO METALS IN SLIDING CONTACT TO DAMAGE THE SURFACE OF ONE OF THE METALS AT THE POINT OF CONTACT, RESULTING IN GOUGING OF THE ONE SURFACE, AND THE BUILDUP OF THE METAL ON THE OTHER SURFACE

FIGURE 10
HARD-FACE APPLICATIONS

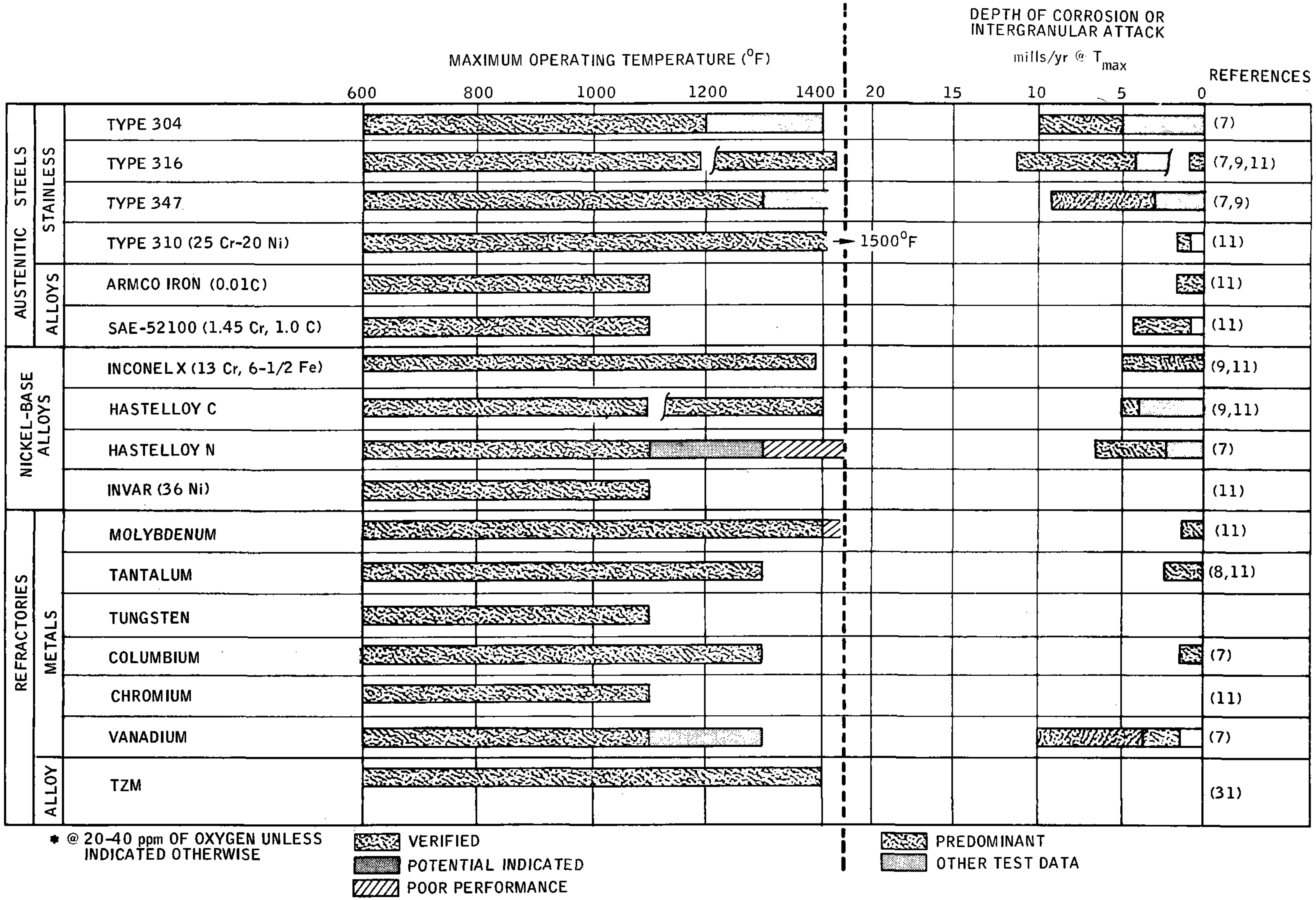


a. GLOBE VALVE SEAT

b. PLUG VALVE SEAT

FIGURE 3(a)

POTENTIAL MATERIALS, INCLUDING CORROSION RATES, FOR USE IN HIGH TEMPERATURE SODIUM ENVIRONMENT *



* @ 20-40 ppm OF OXYGEN UNLESS INDICATED OTHERWISE

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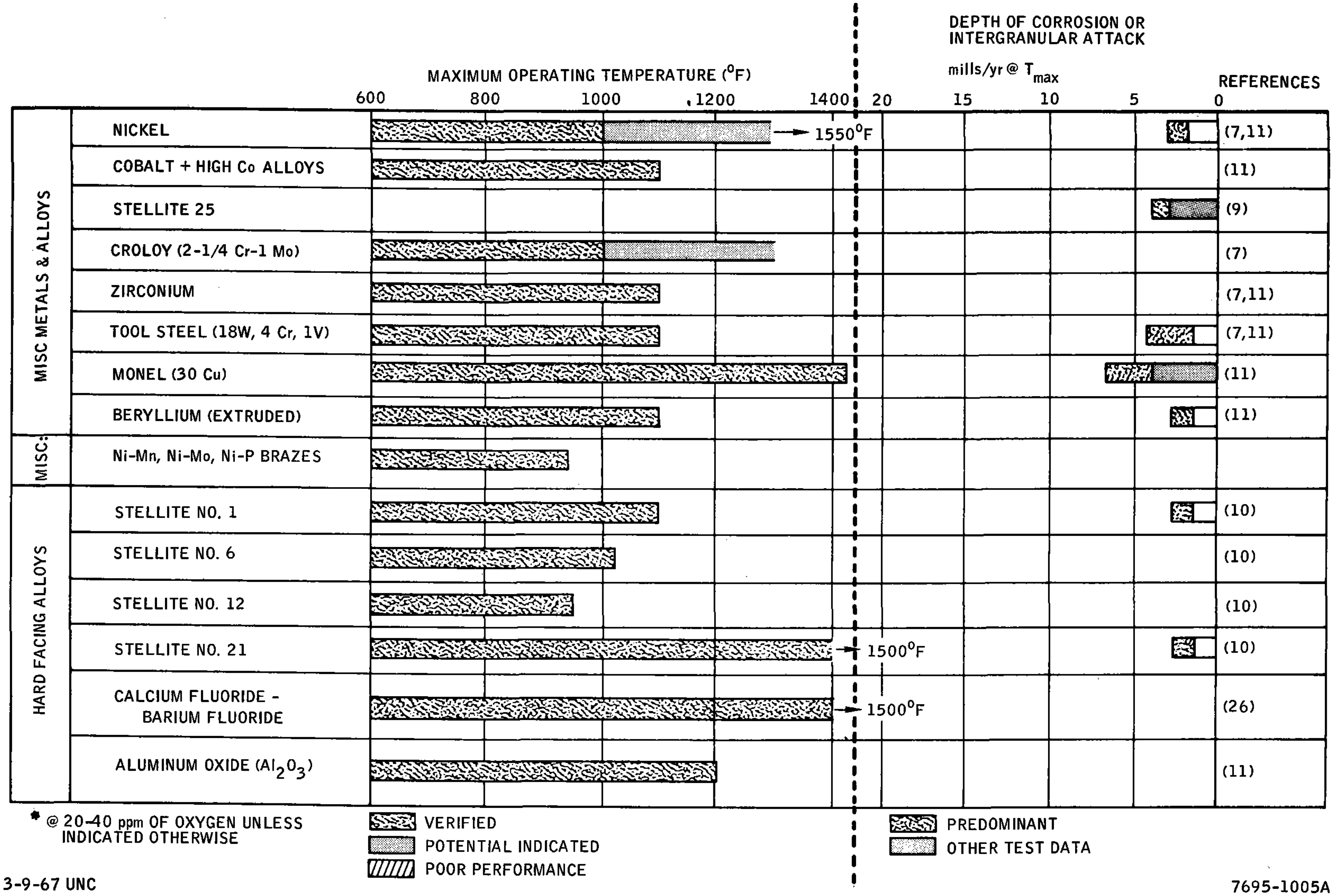
FIGURE 3(b)

POTENTIAL MATERIALS, INCLUDING CORROSION RATES, FOR USE IN HIGH TEMPERATURE SODIUM ENVIRONMENT *



* @ 20-40 ppm OF OXYGEN UNLESS INDICATED OTHERWISE

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FIGURE 4

WEAR RATE - TEMPERATURE RANGES FOR VARIOUS MATERIALS IN HIGH TEMPERATURE SODIUM ENVIRONMENT

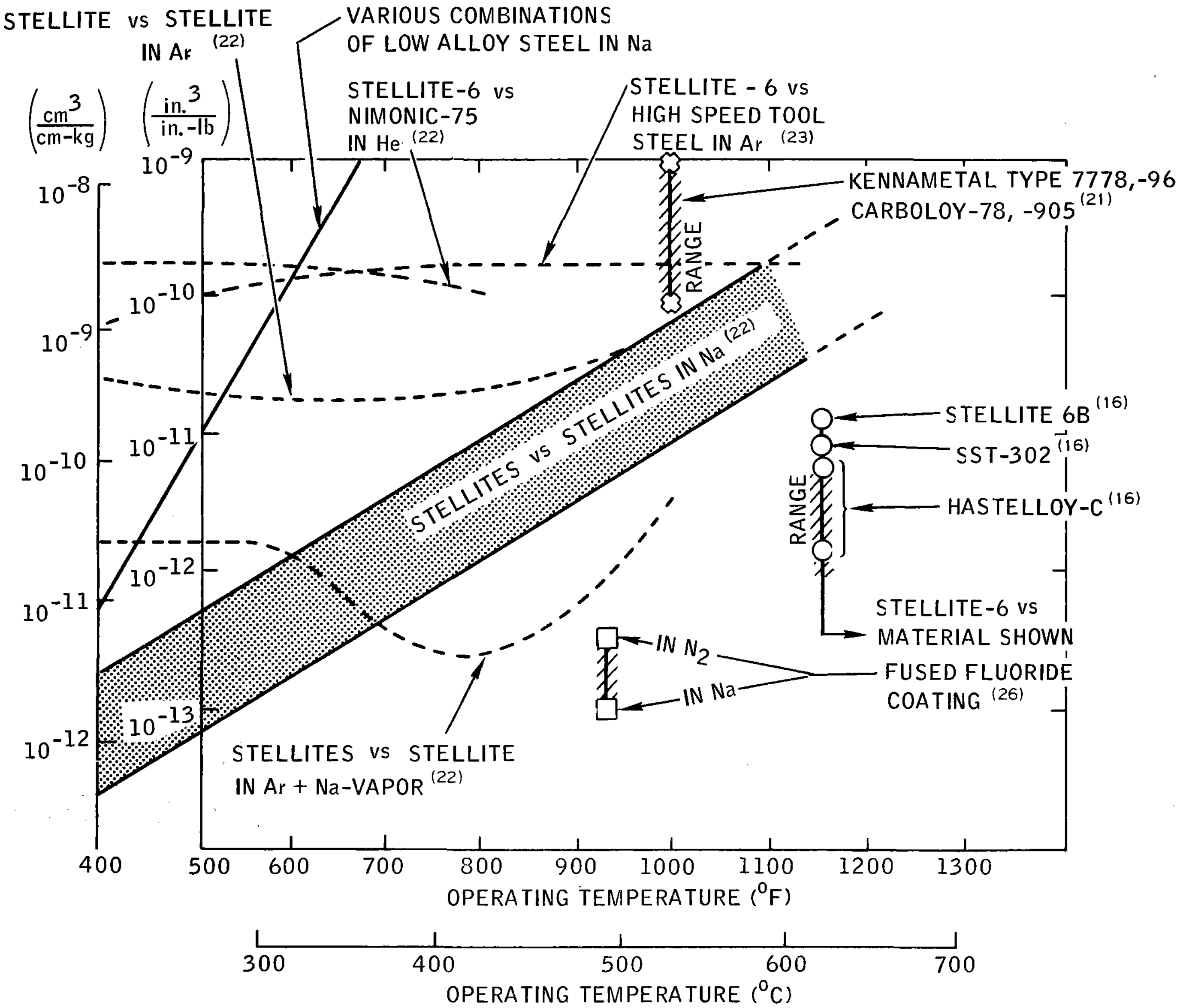

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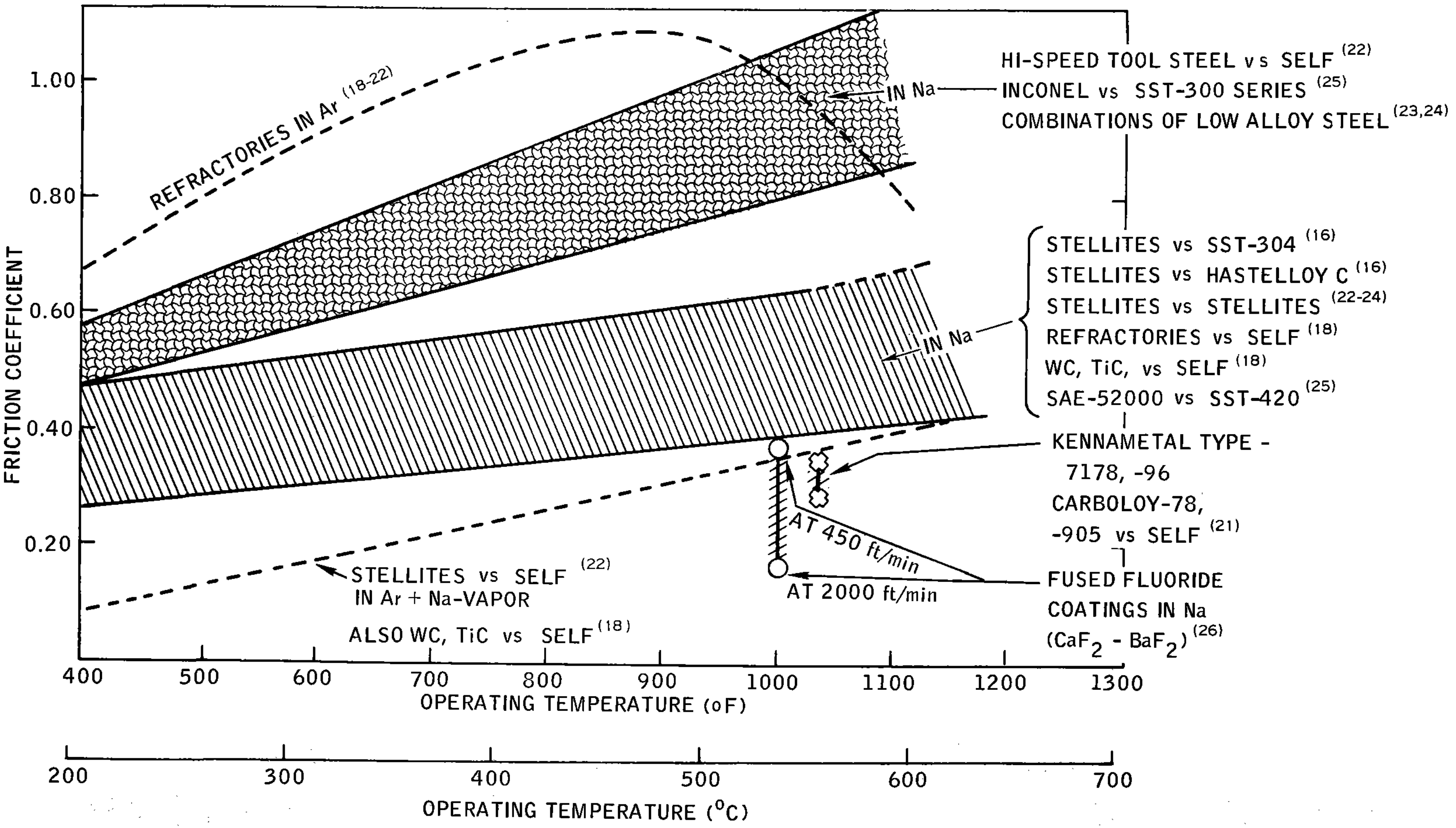
FIGURE 5

FRICTION COEFFICIENT - TEMPERATURE RANGES FOR VARIOUS MATERIALS COUPLES IN HIGH TEMPERATURE SODIUM ENVIRONMENT



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ANTI-ADHESION COMPATIBILITIES OF ALLOYS AND METALS IN HIGH TEMPERATURE SODIUM (1200°< T < 1500)

Material		Couple Combinations																																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Kennametal-8	1																																			
Kennametal-3H	2		★																																	
Kennametal-21	3			★																																
Kennametal-151	4				X																															
Kennametal-138A	5	□																																		
Kennametal-150A	6																																			
Kennametal-151A	7						X	X																												
Kennametal-152B	8	X					X	X	X																											
Kennametal-161B	9									★																										
Kennametal-162B	10	X									X																									
Inconel-X	11											X																								
Hastelloy-X	12												X																							
Hastelloy-D	13																																			
Hastelloy-B	14																																			
SST-347	15	X																																		
SST-316	16														X		★																			
Hastelloy-C	17													X			★																			
Inconel	18					X											★		X																	
Stellite-6	19	X										X							X	★																
Stellite-12	20					X					X										★															
Stellite-40	21																		X																	
Kennametal-91	22																																			
Kennametal-94	23					★		X				X							X					□												
Kennametal-96	24										X														□											
Molybdenum	25	★	★	X	X	X	X		X	X	X	X				X			X	X	★	★	□	*	★	*										
Tantalum	26															□										★	X									
Tungsten	27	X	★	★						X						□								★	★	*		*								
Zirconium	28											X														X		□								
Columbium	29																										□	□								
WC	30																				X					★		★			X					
WC-12 wt % Ni	31					X			X	X									X			X		X	□	★										
TiC	32																			X																
Silver	33											X														X		X								
Chromium	34																			X						X										
Multimet-N155	35														X																					X

SYMBOLS:

- * Primary Choice (T = 1500°F x > 100 hr)
- □ Secondary Choice (T = 1500°F x > 100 hr)
- ★ Limited Performance (T = 1500°F x < 100 hr)
- X Breakdown (T = 1200°F x ≤ 24 hr)

Array of More Promising Material Combinations

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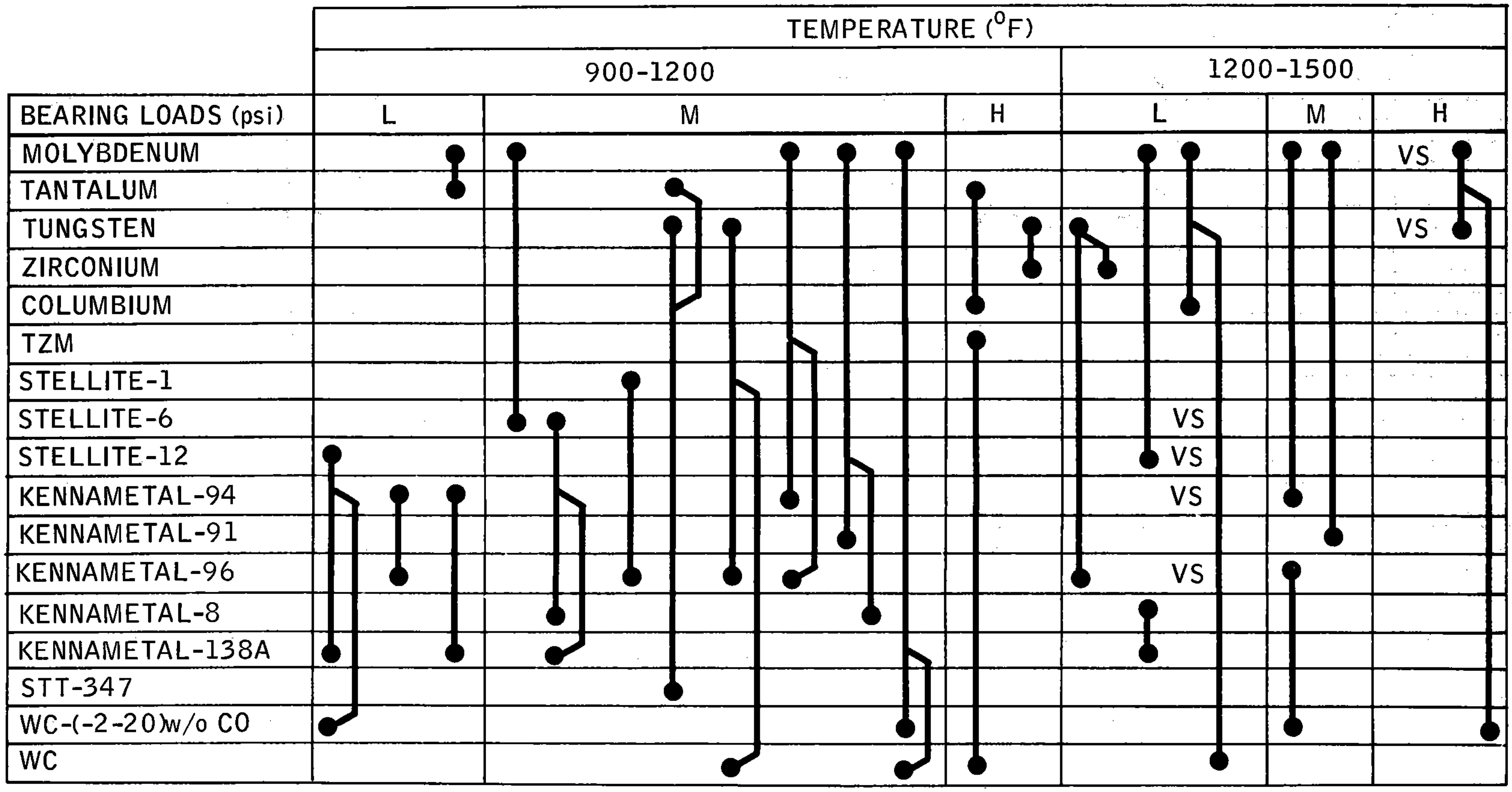
TABLE V

MATERIAL COUPLES FOR JOURNAL BEARINGS AT VARIOUS LOAD LEVELS AND TEMPERATURE RANGES IN SODIUM



NOMENCLATURE:

DESIGNATES A WITH B AND

A WITH C BUT

NOT B WITH C

REF. (6) (8) (15)

LOAD RANGE:	PRESSURE DISTRIBUTION UNIFORM	PRESSURE DISTRIBUTION HERTZIAN LINE CONTACT
L ≜ LIGHT	< 500 psi	TO ~ 4,000 psi
M ≜ MEDIUM	< 1,000 psi	TO ~ 10,000 psi
H ≜ HIGH	< 4,000 psi	TO ~ 35,000 psi

VS = DESIGNATES MATERIAL SHOWN VERSUS ITSELF

RADIOLOGICAL IMPLICATIONS ON DESIGN

- NUCLEAR REACTIONS OF SODIUM

	HALF LIFE	DECAY ENERGY (Mev)
$Na^{23} + n \longrightarrow Na^{24} + \gamma$	15 hr	1.38γ 2.76γ β
$Na^{23} + n \longrightarrow Na^{22} + 2n$	2.6 yr	1.28γ β^+

- ACTIVITY DURING NORMAL OPERATION

SPECIES	SPECIFIC ACTIVITY (c/cc)	DOSE RATE NEAR OPERATING IHX (R/hr)
Na^{24}	4.56×10^{-2}*	5×10^{5}
Na^{22}	1.47×10^{-6}	3
CORROSION PRODUCTS		210
FISSION PRODUCTS		10

*IF 10 cc's OF THIS MATERIAL WERE BURNED IN THE REACTOR BUILDING (AFTER A SPILL), MPC WOULD BE EXCEEDED.

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RADIOLOGICAL IMPLICATIONS ON DESIGN

- ACTIVITY AFTER SHUTDOWN

SPECIES	DOSE RATE NEAR DRAINED IHX	MAINTENANCE TIME/3 mo	DOSE RATE NEAR IHX AFTER 2 weeks DELAY	MAINTENANCE TIME/3 mo
Na^{24}	2×10^3 R/hr	2 sec	0.2 MR/hr	∞
Na^{22}	4×10^{-2} R/hr	30 hr	4×10^{-2} R/hr	30 hr
● CORROSION PRODUCTS	210 R/hr	20 sec	210 R/hr	20 sec
● FISSION PRODUCTS	10 R/hr	7 min	8.5 R/hr	8 min

COMPARISON OF SOME HEAT TRANSFER MEDIA

PARAMETER	SODIUM	WATER	HELIUM
PRESSURE (atm)	3.5×10^{-6}	46.2	17*
TEMPERATURE (°F)	500	600	500
SPECIFIC HEAT (Btu/lb-°F)	0.316	1.19	1.242
DENSITY (lb/ft^3)	55.53	48.95	0.097
VISCOSITY (lb_m/ft-hr)	0.9235	0.257	0.0710
THERMAL CONDUCTIVITY (Btu/hr-ft-°F)	37.61	0.3510	0.1222
PRANDTL NUMBER	0.004331	0.861	0.72
COMPARATIVE h (Btu/hr-ft^3-°F)	8050	4640	199
PRESSURE DROP (psi/100 ft)	16.0	12.35	9.9
ASSUMED VELOCITY FOR 8 AND 9 (ft/sec)	8	8	150
BOILING POINT AT ONE ATMOSPHERE (°F)	1619	212	-452.1

*HELIUM IS A GAS AT ALL TEMPERATURES CONSIDERED. A PRESSURE OF 250 psia WAS SELECTED FOR COMPARISON.

COMPARISON OF SOME HEAT TRANSFER MEDIA

PARAMETER	SODIUM	WATER	HELIUM
PRESSURE (atm)	0.0108	245†	17*
TEMPERATURE (°F)	1000	1000	1000
SPECIFIC HEAT (Btu/lb-°F)	0.3006	0.723	1.242
DENSITY (lb/ft^3)	51.39	5.02	0.0638
VISCOSITY (lb$_m$/ft-hr)	0.5419	0.786	0.0925
THERMAL CONDUCTIVITY (Btu/hr-ft-°F)	45.43	0.060	0.159
PRANDTL NUMBER	0.006394	1.0	0.72
COMPARATIVE h (Btu/hr-ft^3-°F)	10,300	352	196
PRESSURE DROP (psi/100 ft)	12.6	195	8.2
ASSUMED VELOCITY FOR 8 AND 9 (ft/sec)	8	100	150
BOILING POINT AT ONE ATMOSPHERE (°F)	1619	212	-452.1

*HELIUM IS A GAS AT ALL TEMPERATURES CONSIDERED. A PRESSURE OF 250-psia WAS SELECTED FOR COMPARISON.

†WATER IS A GAS ABOVE 710°F.

SYSTEMS

1. SODIUM HEAT TRANSFER SYSTEM
2. SODIUM STORAGE AND PURIFICATION SYSTEMS
3. HELIUM SUPPLY SYSTEM
4. R/A VENT SYSTEM
5. SECONDARY SODIUM VENT SYSTEM
6. ELECTRICAL PREHEAT SYSTEM
7. STEAM SYSTEM
   - A) MAIN STEAM SYSTEM
   - B) STEAM PREHEAT AND STARTUP SYSTEM
8. FEEDWATER SUPPLY SYSTEM
9. ELECTRICAL SUPPLY SYSTEM
10. NITROGEN SUPPLY SYSTEM
11. VAULT COOLING SYSTEM
12. STEAM GENERATOR RUPTURE RELIEF AND RECOVERY SYSTEM
13. INSTRUMENTATION AND CONTROL SYSTEM

9-N18-129-67

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C. Valves IV-30
D. Steam Generators IV-40
E. Air Cooled Heat Exchangers IV-44
F. Freeze Traps IV-47
G. Cold Traps IV-49
H. Vapor Traps IV-52
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J. Piping Specialties IV-57

PROJECTIONS

Pages IV-A-1 through IV-A-113

SODIUM TECHNOLOGY COURSE, SESSION IV
SODIUM SYSTEMS COMPONENTS
H. O. Charnock and H. B. Holz

The last discussion covered the various process systems which go to make up an operating plant, utilizing sodium or other liquid metal heat transfer media as the working fluid. In the discussion today, we will cover some of the specialized equipment, or configurations which have been adapted for use with liquid metals. In general, the discussion will cover the following basic components:

Sodium Pumps
Intermediate Heat Exchangers
Valves
Steam Generators
Air Cooled Heat Dump Exchangers
Freeze Traps
Cold Traps
Vapor Traps
Plugging Meters, and
Other Specialties

A. PUMPS

Probably the most distinctive feature which distinguishes a liquid metal pump from pumps used for other fluids is the method of sealing. In general, two basic methods of sealing pumps have been developed. For the larger pumps, centrifugal pumps have been adopted as the preferred type. In this pump, the free surface seal has been developed and is used almost universally today. Other developments have been tried, including the freeze shaft seal, and a slinger type seal. However, these have been discarded. For smaller pumps, some companies are still favoring hermetically sealed pumps. However, I do not believe these are being seriously considered for large pumps at present.

Another type of seal is used in the EM pump, where there is no penetration into the sodium envelope, and consequently, no seal problem.

A-1

In recent months, two very good reports have been submitted to the AEC, one by Westinghouse, the other by Byron Jackson, recommending the type of pump for the next generation of plant. This view shows the recommendation of Byron Jackson. I understand the recommendation of Westinghouse was similar.

Byron Jackson recommends a free surface pump with a wound rotor motor, a water box type speed control, and a pony motor for low flow operation under emergency power operating conditions. The pump case serves as a suction tank, and the discharge is into a volute and out the bottom of the pump. It is a single-stage pump, and may be installed either in the hot leg or the cold leg of the system. However, there appear to be rather strong reasons for installing the pump in the hot leg.

A-2

There are two generalized types of centrifugal pumps, which I will categorize as the HNPF type pump, and the EFFBR type pump. This view shows a schematic of the EFFBR type pump. This pump was used at the Fermi plant with the sodium entering the pump barrel from the side and discharging out the bottom of the pump. The entire pump can be removed from the top, separated by a set of labyrinth seals at the high pressure side. The EFFBR was unique because a built-in checkvalve is underneath the pump. This configuration permits the check valve to be pulled out with the pump barrel for maintenance, and does not present the problems that the Hallam pump had with maintaining level in the upper barrel. However, it does have an analogous problem. Sodium will rise in the barrel of this pump to a level which is equal to the reactor level minus the friction drop through the pump suction line between the reactor and the pump. Thus, there is a draw down of this level from a maximum level at zero pump speed to a minimum level at maximum operating pump speed. It is readily seen that the pump must be designed with sufficient barrel length to accommodate these level changes.

Both pump types have shield plugs at the top of the barrel when used as primary pumps. These plugs are designed to serve the dual purpose of shielding and thermal insulation to protect the main thrust bearing from the heat and radiation intensity developed by the sodium.

A-3

This chart shows a schematic of the Hallam pump. There are a number of interesting points in this pump which I'd like to describe to you; first, the method of assembly of the pump. The pump itself is assembled in an inner-barrel assembly by which the entire pump, diffuser, and impeller can be pulled from the pump body for maintenance without affecting the piping connections in the sodium system. The discharge or high head portion of the system begins at the diffuser and includes the entire bottom portion of the pump barrel. You will note small ports from the high pressure area into the hydrostatic bearing from where flow can go either downward through the back side of the impeller to cool the lower portion of the hydrostatic bearing, or upward into the upper barrel. In turn, the flow upward goes out the overflow of the pump.

Again, there is a labyrinth seal at the bottom of the pump which seals the high pressure bowl area; from the low pressure suction area, however, leakage from around the seal results in inefficiency in the pump. This is a rather small quantity in the overall picture. There are also leakages to the upper portion of the pump barrel. One of the problems presented with this pump is the disposition of the leakage to the upper portion of the pump barrel.

A-4

This viewgraph shows the basic differences from a systems standpoint, between the HNPF type pump and the EFFBR type pump. On the left, we see a schematic of the HNPF type pump, in which there is leakage from the high pressure bowl of the pump to the low pressure area above the radial bearing assembly. This leakage is made up of leakage around the labyrinth case seal, and leakage through the hydrostatic radial bearing. In some pumps there may be other minor leakage paths, such as instrument thimbles. In the HNPF pump, there were passages through the hydrostatic radial bearing from top to bottom, as well as holes in the backside of the pump impeller. These passages allowed the sodium from the upper pump barrel to pass downward through the bearing and the pump impeller shroud, into the low pressure eye of the impeller. However, a delicate balance was necessary. If the upflow of the sodium exceeded the downflow, then the level in the upper barrel increased until sufficient head was developed to equal the upflow. Conversely, if downflow through the bearing and impeller exceeded upflow, then the level in the upper barrel was drawn down, and gas could be drawn into the pump. This necessary balance is accomplished by proper sizing of the holes in the impeller barrel, coupled with proper design of the overflow system.

On the right, we see the schematic design of the Fermi pump. This pump presents no such problem as has the HNPF pump. However, since the upper barrel of the Fermi pump is actually the suction side of the pump, care must be taken in design to avoid vortexing in the upper barrel, resulting in gas being drawn into the pump. Further, there will be a draw-down of the level in the upper barrel equal to the pressure drop on the suction side of the system. This results in one of several choices. Either the suction side of the system must be designed for very low pressure drop, in which case the cost of the system is increased, or a level control system is required. A third alternate is to make an excessively long pump barrel, in which case additional bearings may be required. Here again are both a technical and a cost problem. In particular, if the pump is in the cold leg, it is necessary to design for a very low pressure drop through the IHX, which is an expensive IHX design.

A-5

Here is another sketch of the HNPF pump showing the problem of level control in more detail. The bypass at the bottom of the pump is relatively insignificant. However, you can see where the case labyrinth seal and the hydrostatic bearing allow sodium to flow to the upper barrel of the pump. In general, the pumps are adjusted to permit a small overflow at all times, say on the order of 500 to 1000 gpm, to assure that there is always upflow, and there will never be a set of operating conditions resulting in gas being drawn into the pump. Note the vortex breakers in the suction plenum. The hydrostatic bearings are standard with all free surface centrifugal pumps. Note that the diffuser and suction cone are attached to the inner barrel and are removed from the top with the pump. Also, note the hollow shaft with reflective insulation inside. This standard construction minimizes heat conduction along the pump shaft and the vortex breakers above the bearing minimize the swirl of the sodium in the upper plenum due to the rotation of the shaft.

A-6

Centrifugal pumps are generally classified according to the type of impeller as radial flow, mixed flow, or axial flow. In general, the radial flow pumps are for higher heads, whereas the mixed flow or axial flow pumps are used more for higher flows and lower heads. This graph shows how the existing pumps in sodium service fall within these classifications. As you can see, most of the pumps have been radial flow, and fall within the heads and flow normally calling for this type of pump. However, there is one set of pumps which seem to deviate. The pumps for the British PFR are mixed flow pumps. The reason for this is unknown. In general, the pumps for the larger FBR's will fall above this chart at the higher heads.

A-7

At AI we have developed a number of rules of thumb for use in systems design of sodium systems. This figure shows one of these empirical design approaches. From an assumed suction specific speed of ~8000, we derive a speed for the pump at maximum capacity. From these rules, we can also scale pump costs for estimating purposes.

A-8

In the pump report by Byron Jackson for the AEC, a series of nomographs were prepared which give the designer a very good approximation of what a pump might look like. From such data, we can proceed with preliminary layouts, power requirements, cost estimates, and other plant parameters. In this figure, we use head and NPSH to arrive at a suitable specific speed. We then use head and NPSH to determine pump speed.

A-9

The next chart utilizes the flow, TDH, temperature, and suction specific speed to derive horsepower requirements.

A-10

Figure 3 in the rough sizing charts is used to derive the required shaft diameter from the horsepower and speed of the shaft at full power.

A-11

Rough Sizing Chart 4 is used to arrive at the maximum case diameter estimate. This information is used to make rough layouts.

A-12

In this nomograph, the flow rate, the NPSH, and the previously determined pump case minimum diameter are used to determine the diameter of the pump outer barrel.

A-13

Finally, from the TDH, the NPSH, and the flow rate, an estimate of the inlet and discharge nozzle diameter are derived. These charts, then give the layout designer the main dimensions required for preliminary layout of the plant with respect to the pump.

A-14

Location of the pump is one of the classical decisions to be made in laying out the primary heat transfer system. It may be located either in the hot leg, between the reactor and the IHX; or in the cold leg, between the IHX and the reactor inlet nozzle. Here are some of the pros and cons of this matter. Since the surface of the reactor is maintained at approximately atmospheric pressure (to minimize leakage through the various seals) the suction pressure will be maximum at this point, dropping with the resistance to flow in the suction line. If the unit is placed in the cold leg, then the pump must be designed for the pressure drop through the IHX on the suction side of the pump. This results in a larger and more expensive pump. By placing the pump as near the reactor as possible, the bulk of the piping is on the high pressure side of the pump, and the size of the piping and building can be reduced.

With the hot leg primary pump, the IHX can be designed for higher velocities, resulting in a smaller IHX shell and lower heat exchanger cost. Where-ever possible, the primary system is maintained at a slight positive pressure to minimize air inleakage. When the pump is on the downstream side of the IHX, the IHX is at a slight negative pressure, with additional risk of air inleakage.

A-15

AI's studies have shown it is preferable in power reactors to place the primary coolant pump on the hot leg, based on economics, and on practical considerations of maintaining levels within tolerable bounds. Any additional cost of the pump, due to temperature considerations, is quite negligible as we saw from the estimating charts a few minutes ago. However, in most of the plants built to date, the pumps have been installed in the cold leg, as this chart shows. Based on future studies, it appears that pumps will be in the hot leg more frequently, with the possible exception of plants designed to the pot concept (General Electric).

A-16

The same arguments are debated with respect to placement of the secondary pumps. However, now the situation has changed somewhat. One of the AI concepts is to maintain the secondary side of the IHX at a slightly higher pressure than the primary side. Thus, should there be a leak in the IHX, it would be nonradioactive secondary sodium into the primary system, rather than radioactive primary sodium into the secondary system. This precaution paid off at HNPF where an IHX leak was experienced during critical operation. Under these conditions, it is desirable to have the secondary sodium pump just upstream of the IHX (in the cold leg).

Conversely, if the secondary pump is in the hot leg, it is necessary to increase the gas pressure over the secondary sodium system, which has deleterious effects in terms of cost, and in terms of leakage of secondary cover gas. On the other side, there is a disadvantage in lowering the sodium pressure in the steam generator complex, as we shall see later. AI has decided to place the secondary pumps in our 500-Mwe loop in the cold leg. This is at variance with the plans at HNPF and SRE, where the secondary pumps were in the hot leg.

A-16-A

While you people are not particularly interested with the steam end of the station per se, it is interesting to see how placement of the secondary sodium pumps affects operation of the turbine and steam raising equipment. In this chart, we have plotted steam pressure and sodium pressure in the reheater as a function of load, with pump in the hot and cold legs. One requirement of the system is that the steam pressure must exceed sodium pressure. Thus in event of a leak, it would be a steam leak into sodium, without possibility of sodium oxides leaking into the turbine. As you can see from this chart, on low loads, the reheater steam pressure drops below sodium pressure. Thus, it is necessary to insert a back pressure valve in the hot reheat line, to maintain this pressure above sodium pressure at low loads. For the case of the hot leg pump, this valve must operate below ~30% load; whereas with the cold leg pump, the crossover point is ~17%. Since we do not plan power operation below ~25% load, it is preferable from this standpoint to put the secondary pump in the cold leg of the system.

A-17

It is interesting to tabulate what others are doing in terms of pumps. This chart shows a tabulation of the most important sodium pump installations either in service, or planned. It would appear that the proposed FFTF pumps are quite comparable to those at EFFBR, in terms of head, capacity, and temperature. All pumps in this range have been the centrifugal type, except for the secondary pump at EBR II. All centrifugal pumps utilize the free surface type of shaft seal. The eddy current coupling has proven quite popular up to now. However, it is believed that the practical range of ~3000 to 4000 hp in these units will be reached; other means of speed control will be necessary in the larger pumps. Incidentally, in the larger sizes, the eddy current couplings give off excessive quantities of heat, which must be accounted for, either in the building heat removal equipment, or by liquid cooling of the couplings themselves.

For the larger pumps, it appears the near future preference will be wound rotor motors with liquid rheostats. These do not have full range turn-down capability, but this may not be necessary in power plant installations. The preferred material for the pumps is Type 304 stainless steel except for the secondary pump at EFFBR. This pump was made of 2-1/4 Cr - 1 Mo, to be compatible with the material of the steam generator.

A-18

This table shows the characteristics of the pumps installed in the two AI designed sodium reactor plants. Note the hours of operation. These pumps worked quite satisfactorily after the bugs had been worked out, as we shall see later. Both units were driven with electric motors. Those at SRE had dc motors, while those at Hallam were driven through EM couplings.

A-19

This slide shows the projected characteristics of the primary sodium pump for the AI 500-Mw plant primary pump. The head expected is ~450 ft which is considerably above most pumps in sodium service to date. At the time this was prepared, flow was ~38,000 gal/min and you will notice that the pump efficiency curve is designed to give maximum efficiency at that point. One characteristic of many sodium pumps is the rather shallow pump characteristic curve. Under these conditions some pumps will become unstable at certain flows which creates one of the problems that must be worked out by the pump manufacturer.

A-20

This is a similar chart showing flow vs head characteristics of the secondary pump for the same plant. Secondary flow is somewhat larger than the primary — say 41,000 gpm — the head is somewhat lower, and you will notice that the system head in general is a parabola or a square function. This is true of all constant hydraulic systems. This pump characteristic curve is only one of a family of curves — this showing the 100% case. There will be parallel curves at other speeds. As you know the flow in the pump is proportional to the pump speed. This family of curves results in a number of design points depending on the flow desired and the revolutions per minute of the pumps. The flow vs revolutions per minute curve is generated at the intersection between the pump characteristic curves at different speeds and the system head curves.

A-21

This cut is an artist's concept of one of the pumps proposed for the AI 500-Mwe FBR. It shows some of the features we have not discussed as yet. The pump is installed in the concrete shield floor above the primary sodium equipment vault, with the outer barrel poured in concrete. At the upper end of the barrel, you see torque bars to fix the barrel in concrete. This also means there must be a design accommodation for the difference in temperature between the sodium in the pump, and the allowable temperature of the concrete. This change of temperature takes place along the lower part of the pump barrel by means of cooling fins on the outside of the pump barrel, coupled with cooling gas flow, up the outer periphery of the pump barrel. It is vital that the temperature be constant around the periphery of the pump at any elevation. Otherwise, the pump barrel will bend, causing the pump to bind, as we shall see later. The sketch also shows thermal barriers inside the pump, and this space inside the pump must be cooled in parallel with the outer barrel.

A-22

In the secondary systems, there is need for an expansion tank to absorb the volume changes in the sodium due to changes in the level. This viewgraph shows the main secondary pump for the SRE PEP unit. This pump was never operated except for isothermal circulation of sodium since nuclear operation of the SRE after the PEP modification was never authorized. However, it does show some rather interesting features. The pump itself is the secondary sodium expansion tank and was designed as a sphere to minimize some of the stress calculation problems in the pump barrel. Flow is in the side, downward through the impeller and down through a diffuser into the lower portion of the pump with the outlet on the bottom of the tank. This was done for a number of reasons. By having the pump centered in the tank with the flow downward through the bottom, thermal expansion problems were minimized, the only expansion being from the support plate of the assembly in a vertical direction which did not affect the pump alignment. Again we see a labyrinth seal between the high pressure chamber and the low pressure chamber which permitted easy insertion and removal of the pump. You will notice the line serving the hydrostatic bearing from the pump discharge plenum. There is an instrument tube extending down from the upper portion of the pump barrel. In the neck of this tank you will see radiation heat shield type of insulation to keep the bearing assembly cool. Radiant type reflective insulation is quite widely used in sodium design. Again, in this design the pump shaft is hollow to minimize heat flow up the shaft and to assist in keeping the bearing cool.

A-23

This cut shows a schematic diagram of the Fermi Pump. This pump has a rather interesting feature in that there are two hydrostatic bearings, each fed by high pressure sodium from the high pressure plenum. You can see the lines feeding the two pump radial bearings. These appeared to introduce some problems - the main one being that of keeping the two radial bearings lined up properly. It is much more difficult to design the pump with two radial bearings than with one as the Hallam pump was designed. Also the design of the lubrication for the upper hydrostatic bearing must be such that the overflow or waterfall effect from this bearing does not result in excessive gas entrainment which is then carried downward into the pump and through the system. I have checked with the Fermi people, and apparently they have had no problem with this at the Fermi conditions. However, this is no guarantee that this will not be a problem in other installations.

This pump also shows the drive mechanism which was chosen for the Fermi pump. This was a wound rotor variable speed motor operated by a water box rheostat with a pony motor on top of the barrel. During periods of power outage it is necessary to maintain sodium flow to prevent overheating the core from the afterglow heat. The pony motor is turned on using auxiliary power. This, I believe, is approximately a 5-hp motor and is sufficient to turn the pump fast enough to remove ~5% of the power from the core. Again, this sketch shows the normal shield plug which is built into a primary pump.

A-24

This view shows a pump quite similar to the Fermi pump with one exception. This pump was designed for use with a pot type reactor and, therefore, has no outer barrel to the pump. The pump is intended to be mounted in the sodium pot above the reactor. It would appear from this sketch that the pump shaft is hollow. This is a normal design for the pump shaft, one of the main reasons being to prevent the passage of heat up the shaft and to minimize the cooling problem at the pump barrel above. There are baffles inside the shaft to minimize the flow of heat. There appear also to be several baffles outside the shaft in the pump supporting barrel itself, also as a reflective insulation measure. Again, you see the built-in shield plug on the pump. Design of these shield plugs is quite interesting in that steel balls are the usual first layer of insulation. These serve two purposes — shielding and thermal insulation, which help reduce the temperature of the system so that lower temperature thermal insulation can be used above. Also, note that the upper end of the pump shaft is solid. This serves as shielding in the shielded area.

A-25

The British PFR reactor is about ready for operation, I believe, and it is interesting to see the type of pump selected. In a general way, the pump resembles the EFFBR pump, adapted for use in a pot type reactor. However, there are a few noteworthy differences. The PFR primary pump is a mixed flow impeller pump. This is rather unusual for a pump at the head these pumps are working. There is a shroud around the inlet nozzle, which tends to minimize the possibility of entraining gases from vortex action above the pump. The upper end of the pump is supported from a thrust bearing mounted down inside the shield plug, whereas in U.S. practice, the thrust bearing is at floor level where it is accessible for ease of observation and maintenance. This feature probably reduces the headroom required for the pump drive.

The most interesting feature of this pump is the hydraulic coupling with a 5:1 turndown ratio. In this country, hydraulic couplings with vertical shafts are not available except in the range of 1 to 10 hp. If this coupling is successful, it could fill a gap in the horsepower range above which EM couplings are not feasible. It should also prove more economical than EM couplings in two ways, in first cost, and in efficiency, resulting in reduced cost of the heat removal equipment.

A-26

Here is a view of the secondary pump for the PFR reactor. This pump is quite similar to the primary pump, except that it is designed for installation in the piping instead of in a pot type reactor. It is not clear in this sketch, nor was it clear in the text, how fluctuations in level were accommodated. Since the sodium level is quite high in the tank, it would indicate that there is a level control in the pump barrel, and that there is another expansion tank elsewhere in the secondary sodium system. If the sodium level were to drop very much in this tank, gas would probably be entrained. The vertical shaft variable speed hydraulic coupling was used on this pump also. I am not aware this type of speed control device is available in this country.

A-27

I have tabulated a number of pumps on this graph in an attempt to show the experience with centrifugal pumps in sodium. Most pumps have had some bugs when originally started. The SRE pumps were satisfactory except for the freeze seals, which permitted some gas to enter the system. The seals later failed, releasing tetralin into the primary system. This resulted in an extended shutdown of the system. Modifications included a change to the free surface type of seal.

The PFR pumps are reported to present difficulties with cavitation. This may be due to the selection of the mixed flow impellers. I do not know what the disposition of this problem is as yet. We will discuss some of the problems with the HNPF pumps later. However, I believe we have accumulated sufficient experience to state that the preference in large pumps is the centrifugal pump with the free surface type seal. Also, the utilities people have expressed a definite preference for variable pump speed flow control in lieu of valve control. It appears that some form incorporating both concepts of control may be required. For larger sizes, drives with wide range control are not available, as yet. The best we can hope for is about 5:1 turndown with present equipment. Thus, valves will be used for flow control at low flow.

A-28

This slide shows a few of the pump problems which were experienced at SRE PEP and which are of interest to avoid the same problems in the future. At the SRE we had an overflow into what we call a balancing leg — a simulated free surface where the overflow from the top of the pump barrel was permitted to return into an area of low pressure (the pump suction). The problem here was that the diameter of the balancing leg was so small that the downward velocity of the sodium in the bottom of the leg was quite high, possibly on the order of several feet per second. Under these conditions, gas that was entrained in the upper portion of the leg, in a sort of waterfall effect, was carried downward and entered the pump suction where it was distributed then throughout the sodium system. The result was excessive gas entrainment passing through the core. This problem was corrected by closing off the gas entrance into the dip leg. With this, it was necessary to install a flow control valve in the pump overflow line to control the pressure drop through this line and thus prevent draining all the sodium out of the top of the pump barrel. We'll see that better a little later in another slide.

Hydraulic calculations on the system indicated that, if the valve were set properly to control the flow at one set of flow conditions, then the level of sodium in the pump barrel would remain constant over a wide range of flow conditions. This proved to be correct, and the control valve was manually set at a constant position which permitted satisfactory operation over the entire range of desired flows.

A-29

A number of problems with the pumps arose at Hallam which were all solved by rather simple corrections. In the secondary pumps, gas was entrained in the expansion tank at the suction line. This expansion tank was designed so that the full flow of the sodium (~7000 gpm) entered the expansion tank from the side and passed upward over a weir which was installed in the tank with approximately a quarter of a tank volume on the inlet side. The velocity in the tank was supposed to be ≤1 ft/sec, and the sodium was supposed to pass over the top of the weir, and downward, thus permitting disengagement of any entrained gases. The fact of the matter was that the tank operated in just the opposite manner and, as the sodium passed over the top of the weir due to the turbulence at the surface, gas was entrained in the sodium. This gas then found pockets in the secondary sodium system and collected. The net result was that the level of the sodium in the expansion tank began to rise and it was found that it was impossible to operate over ~60% of rating because there was a chance of overflowing the tank. This problem was corrected by bypassing the major portion of the sodium around the expansion tank into the pump, and allowing a relatively small purge through the tank itself. This experience indicates that gas entrainment can be a very serious problem if major consideration is not given to the flow velocities and conditions of the sodium at the various surfaces.

Another problem was evidenced in the primary pumps at the Hallam plant. Flow through the backside of the pump impeller was too great. This caused a drawdown of the sodium in the pump barrel to the extent that gas was being drawn into the eye of the impeller through the radial bearing and the backside of the impeller and was being pumped through the system. This was corrected by reducing the size of the orifices in the backside of the impeller, resulting in a net overflow, rather than a net deficiency of sodium in the upper pump barrel.

Finally, we had a problem with unequal temperature distribution around the periphery of the secondary pump. If you will notice, on these pumps, the pump barrel is a very stiff configuration. Now, if one side becomes somewhat warmer than the other, the pump barrel will tend to distort. This results in binding of the pump impeller at the bottom hydrostatic bearing. At Hallam, it resulted in complete stoppage of the secondary pumps. This was corrected by providing forced draft cooling to the pump barrel. If you take a look at these pumps, you will notice that there is a rather severe temperature gradient from, in the case of Hallam, 960°F at the sodium surface to say 100 to 150°F at the top of the pump where the support is provided. Unless this temperature gradient is maintained such that the exact length of the pump barrel around its entire periphery is essentially constant or at least equal, then the pump barrel will distort and will cause this problem.

A-30

This photograph shows the pump barrel of the SRE PEP pump before its installation in concrete. You will notice on the upper portion of the barrel, the reinforcing bars which will tie the barrel to the concrete. You will also notice the flange at the top of the barrel, and a second flange below the shield area. This flange is welded to the cell liner giving a gas-tight seal of the vault. Just below the vault seal flange is a coil of several turns of tubing. This tubing is serviced with cool kerosene, to keep the heat from the pump from overheating the concrete. Below the kerosene coils, the cooling fins are used to cool the pump barrel so that the temperature gradient around the pump barrel is constant, thus preventing warping of the barrel. In installation, the pump is insulated. However, at the finned area, the insulation is installed around a wrapper sheet outside these fins, permitting the cell atmosphere to cool the pump barrel. The line leaving the pump about midway of the finned area is the vent balance line, connecting the pump atmosphere to that of the reactor.

Up to now, we have been discussing the centrifugal pumps for main heat transfer systems. In addition, electromagnetic pumps are available for sodium services. These pumps are not very efficient. On the other hand, they do not have any openings into the liquid metal envelope, thus present no seal problems. For these reasons, they are usually chosen for sodium service applications, particularly for intermittent service where efficiency is not an important factor.

A-31

This slide shows a set of coils of an EM pump. Note the flattened section of pipe in between the two coils. This is the place where the pressure is generated in the sodium. If we go back to the right hand rule, of course, we realize that by putting an electrical field in one direction and a magnetic field in another, a force is generated perpendicular to these fields. This force drives the sodium in the electromagnetic pump. This particular pump has $\sim$12 coils. In general, a linear induction EM pump generates a pressure proportional to its length. As a rule of thumb, $\sim$1 psi/in. of length can be generated. You can readily see that a pump such as this, generating relatively high pressure, can get quite long and bulky.

In design of these pumps, heat is a major concern. Not only is the sodium quite hot, often running up to 1200°F, it may be radioactive, thus generating gamma heat in the coils. Further, the pumps are quite inefficient, and a great deal of heat is dissipated from the coils. The coils are potted in a special high temperature insulating material to withstand the operating temperatures. In addition, the pumps must be installed in such a way that the generated heat can be dissipated to the surroundings. To minimize magnetic flux loss, clearance must be small between the coils and the throat. This, in turn, limits what may be done in insulating the coils from the throat section.

A-32

This slide shows a photographic view of a small NaK pump. This pump was designed for one of the SNAP 2 reactors. It has a rating of ~25 gpm of NaK at 1000°F and 17 psi. NaK flows into one of the pipes shown and out the other. The pump can, of course, be reversed merely by reversing the leads of the three phases. Inside the wire cage you will see the pump coils which generate the magnetic field causing flow. This particular pump was mounted on wheels to absorb all the expansion and thus relieve the pump throat of any possible pipe stresses. The throat section of the pump becomes quite hot during operation; and it cannot sustain high reaction stresses from the piping at operating temperature.

A-33

This viewgraph shows one of the HNPF EM pumps. The view shows the pump case and the flattened section of pipe for the throat with the inlet and outlet pipes attached. The coils have been removed in this particular photograph to show the pump more clearly. The Hallam pump was designed for ~100 gpm flow with a generated head of ~40 psi. This pump worked quite well. It is interesting to note the wide open construction. This permits gas circulation around the coils and throat section, thus insuring cooling of the pump. The wire mesh case is for personnel protection.

The EM pumps discussed so far have been of the linear induction type, i.e., the electromagnetic field is made to travel in a line, as three-phase current is used with the coils energized in succession. In addition, the field may be made to rotate, and the same pumping principle may then be applied to a helical rather than a linear path. This principle may be applied by rotating the field electrically, or by mechanically rotating the field coils which, in turn, generates the rotating field. A pump made by GE utilizes the electrically rotated field.

A-34

AI developed the principle of a mechanically rotated field. In this sketch, you see a rotor with the field windings in a skewed pattern. Sodium flows in the helical annulus, and is given a pressure by the induced rotating magnetic field established by the rotating core. The annulus is surrounded by a heavy steel core for a flux return path. This pump is considerably more efficient than the linear induction pump. However, experience with this pump is limited due to lack of testing. The pump has the same advantage as the linear pump in that no openings are made in the sodium envelope. For higher pressure operation, this pump is far superior to the linear pump which gets excessively long at higher pressures.

A-35

This pump does not require a helical path. This print shows a pump having an annulus without partitions. The pressure is generated strictly by the rotating magnetic field. This particular pump had to be built without partitions in the annulus due to the application which prohibited their use.

A-36

This photograph shows the rotor of one of these pumps built at AI. This pump was rated at about 2500 gpm at ~37 psi, and operated on test for about 6 wk at ~800°F. The test was discontinued due to lack of funds.

A-37

This is an overview of a NaK pump built for Rocketdyne for a test facility. This pump pumped NaK at 430 psi and 52 gpm, and operated for about a month at 600°F. The test was completed and the pump was shut down.

The pump with the open annulus throat operates in molten aluminum at ~1600°F and 2000 gpm, developing ~8 psi head.

B. INTERMEDIATE HEAT EXCHANGERS

Heat from the nuclear reactor core is removed through the primary liquid metal cooling system, and is transferred to the secondary cooling system in the intermediate heat exchanger. This is one of the more important and expensive items of equipment in the plant.

A-38

This viewgraph shows the basic requirements of the IHX. Primarily, this provides the method for transferring heat from the primary to the secondary cooling system under both normal and abnormal conditions. This is one of the barriers for containing the primary sodium. In some respects it is the most critical, since it is probably a single wall on the order of 1/16-in.-thickness. Most of the remaining primary sodium envelope consists of more than one wall, and generally of much thicker material.

The IHX must withstand physical and thermal transients without breach of containment. In particular, it must withstand the forces of a sodium water reaction in the steam generator; and must withstand whatever pressure is considered incident to a DBA accident, without loss of primary sodium.

A-39

In designing the IHX, a number of potential problems became evident and had to be remedied. Since velocities in liquid metal heat exchangers are normally much higher than in industrial practice, instances of damage have been reported due to tube vibration. Recognizing this factor, tube supports are designed to prevent this phenomenon. Preheating is a much more severe condition than is normal operation. Since the IHX is quite large, heat is transmitted from the shell to the inner tubes only with difficulty. Therefore, preheating must be very slow to avoid having a hot shell and cool tubes in the center of the bundle. If preheating is too rapid, and provision was not made for differential expansion between tubes and shell, either overstress or tube failure could result.

If we postulate a few failed fuel pins, calculations indicate that the primary side of the IHX will be excessively hot from radiation; and it would not be feasible to approach the unit for maintenance. Thus, present practice is to place the primary sodium on the shell side of the exchanger. Under these conditions, in event of a tube leak, the ends of the tubes are on the nonradioactive tube side of the unit, and it is at least feasible that the tube ends could be maintained semiremotely without the need for decontaminating the IHX.

Most of the larger units create a flow problem in the entrance and exit regions, due to the large diameter of the shell and the relatively short proportions of the tube bundle. At AI, we plan to study this problem from both an analytical point of view and with hydraulic model tests to make certain that the entrance and exit baffling is satisfactory and to assure uniform flow and temperatures.

Some designs are such as to result in stagnation points or even reverse flow in some of the tubes during low flow operation. The bundles are analyzed for this phenomenon. This is a common problem generally found in units of horizontal configuration. Thus, it is preferable to utilize vertical configurations. Based on heat transfer calculations and economics, most IHX's are true single-pass counterflow units. In mounting vertically, it is preferable to arrange the flow pattern to complement natural convection flow. This minimizes the probability of flow reversal in event of power failure. Thus, the hot primary sodium enters the unit at the top, and the cooler primary sodium exits from the bottom shell nozzle. Conversely, the cold secondary sodium enters the bottom of the tubes, and the heated secondary sodium exists from the top end of the tubes.

We anticipate that we will successfully plug tubes remotely. Presently, however, one of the difficulties which arises is determining which tube is leaking and, subsequently, to test the repair. Thus, unit design should include a suitable method for identifying a leak, for remotely plugging the tubes on both ends, and finally, for remotely testing, ensuring quality of the repair.

In event of any failure other than a leaking tube (for example, a leak in a shell seam), it would be necessary to decontaminate the unit. Layout of the IHX includes some ~~study~~ of possible ways to decontaminate the unit sufficiently to accomplish repair of such postulated failures.

A-40

In addition to the above factors, which we have appraised in economic studies, there are a number of considerations which we feel are important, but possibly not directly analyzable on an economic basis. For example, in the larger units, space or shipping limitations may establish the preferred configuration irrespective of cost. We have found that absolute shipping limitations are strongly dependent on location. For example, if the job site is on inland water, or on the coast, there are practically no such limitations. Conversely, if rail is the only access to the site, then the entire rail line must be surveyed from the fabricator to the job. Even then, it is often possible to alleviate some of the bottlenecks if economics justify such procedures. For example, if a single bridge is governing, it is possible to remove gussets or make other minor changes for a particular load.

Between two designs, there may be a considerable difference in outage time for tube repair. If so, we would try to evaluate the advantages.

For evaluating two or more designs, we would rely heavily on units with bent tubes which can be preheated with less risk than with straight tubes. Conversely, if the cost of bent tubes is excessive, for the few times during a plant life that an IHX will be preheated, it may be more economical to accept longer preheat time. Bent tubes, in general, are more resistant to thermal shock damage also.

In studies at AI, we have tried to evaluate the relative ease for fabricating various configurations. In particular, design of the tube supports in the sine wave regions of a bent tube exchanger is difficult and costly.

In case of two designs, one of which has appreciable satisfactory service in liquid metals and another which has not, we would be inclined to adopt the tested unit to minimize risk of excessive shutdowns.

Ease of decontamination is a matter for consideration. However, it does not appear there is a great deal of difference between two units of different designs. Ease of replacement is a major item. Quite often, the IHX may govern such plant factors as: (1) height of the building, (2) capacity of the crane, (3) diameter of the building, or (4) the size of the equipment ports in the building.

A-41

In our studies at AI, we have made estimates of a number of IHX configurations in an effort to evaluate what general configuration of heat exchanger is preferable. To arrive at a total study, we have estimated probable failure rates.

This slide shows a number of the considerations that we use at AI in an attempt to determine the reliability of an intermediate heat exchanger. We have broken down the possible failure modes of the various heat exchangers and have arrived at what we think are reasonable rates of failure by multiplying the rates of failure by the unit parameters shown on this slide. We were able to come up with an estimated total outage for each unit studied. These, of course, are not accurate but they do give us a means of comparison between any two general types of unit.

It may be well to look at a number of built or proposed IHX units for liquid metal service, as a frame of reference for further study.

A-42

This is an artist's sketch of the SRE main intermediate heat exchanger. This was the original heat exchanger installed in the SRE; and was changed later during the PEP modification. It was designed as a horizontal U tube type of heat exchanger. In operation, this arrangement was found not particularly good for use in sodium service due to the possibility of stratification. For example, on low flows, it is conceivable that flow could be in one direction through the tubes on the top of the tube sheet, and in the other direction through the tubes on the bottom of the tube sheet, thus generating an internal circulation of sodium which is undesirable from a thermal stress standpoint. The tube-sheet in turn would have a thermal gradient. The same general arguments could be used to show a radial flow around the outer portion of the shell side and vertical flow through the tube bundle. Again, not a desirable situation. This configuration would not be recommended in the future. Incidentally, our work at AI has indicated that the heat transfer surface in the bend area of such a heat exchanger is essentially ineffective. Cost of this design tends to be higher because of this ineffectiveness.

A-43

This slide shows the revised main intermediate heat exchanger for the SRE PEP program. The revisions made in design for the PEP program include a change of the mounting position of the heat exchanger from a horizontal U tube to a vertical U tube. This change in configuration eliminated some of the original problems with stratification. However, there is still some possibility of stratification in the new design at low flows. In addition, the heat transfer surface in the elbow is not considered effective for heat transfer. You will notice that the tubes are supported in the elbow by disc or semi-disc baffles. This would not be considered good practice because the tubes are not completely free to expand. In the current AI designs, the tubes in the elbow area are arranged on a square pitch so that they can expand in the direction parallel to the natural axis of the unit.

This picture also shows a ferrule in the tube sheets. This was apparently installed to give some insulation to the tube sheet to protect against thermal shocks. As shown the unit is anchored at one end at the top tube sheet with a roller bearing at the far end adjacent to the U tube. One of the problems that exists with the U tube type heat exchanger, particularly in the larger sizes, is that of supports. This is not too great a problem to resolve in a small unit such as the SRE; however, in a unit for a large power plant, it would be almost too impractical. The means for accommodating vertical expansion of the unit are not apparent unless flexure of the U-section is assumed, and this is impractical in a unit of this size. Shipping large units of this design would pose another problem.

A-44

This is an artist's sketch of the intermediate heat exchanger which was installed at the Hallam facility. I believe this is valuable more in that it shows practices that will not be used in the future rather than any real value as to what will be used in the future. This heat exchanger was a vertical, straight tube, shell and tube unit with the primary sodium on the tube side. Differential expansion between shell and tubes was accomplished by installation of a bellows in the shell. You will note, in an exchanger of this type there is no provision for differential expansion between the various tubes. This may or may not be a necessity. Around the outside of this unit was a rather elaborate steel assembly structure which served to assure that the forces going into the bellows were pure axial forces; and avoided the possibility of twists or other unusual forces being imposed on the bellows.

I say this assembly is obsolete for a number of reasons. First, the primary sodium was put on the tube side of this unit. At that time, it was believed that by placing the primary sodium on the tube side, two walls would minimize the possibility of loss of primary sodium to the surroundings should there be a leak in the tubes. However, this is a double edged sword. Later studies indicated that the intermediate heat exchanger could become quite radioactive. Since tubes are plugged from the tube side, it appeared preferable that the primary sodium be on the shell side so that work involved in plugging of tubes could be done from the relatively nonradioactive secondary side of the unit.

Further, should primary sodium be on the shell side, the bellows could not be used since these are not acceptable under the provision of Section 3 of the code. There are those in sodium technology who feel that it is necessary that the various tubes in a large tube bundle of this type be free to expand independently of each other. Furthermore, the design of the nozzles in this heat exchanger will not be used in the future, because the nozzle connections are the same size as the adjacent piping. Consequently, the entrance velocity into the tube bundle on the shell side was too high as we will see a little later. Also, as we discuss larger plants, it will become evident that a single side inlet or outlet is unsatisfactory because it would be impossible to get uniform flow throughout the tube bundle on the shell side. Future intermediate heat exchangers in all probability will have an entrance belt to ensure proper distribution around the periphery of the tube bundle.

A-45

This sketch shows the design of the intermediate heat exchanger for EBR-II. In this pot type reactor, the secondary sodium flow is down through a central pipe and upward through the tubes between two tube sheets. Primary sodium is circulated in the shell side which is surrounded by a shroud. The discharge is open into the pot itself. One of the interesting points in this unit is the use of the expansion joint to take up the differential expansion between the central downcomer and the tubes surrounding it. This type of construction may not be sanctioned under today's code.

The upper portion of this unit consists of a shield plug. This is common with IHX's in pot type reactor plants. It is also used in some piped systems, although not nearly so universal.

A-46

This sketch shows the general type of intermediate heat exchanger used at the Fermi plant. There are a number of interesting features in this unit. The main one probably is the gasketed tube sheet at the top of the unit. By placing the secondary sodium on the tube side, and by allowing a gas space in the shell side, a gasketed joint is allowed between the primary and secondary sodium. Should there be a leak, it would be secondary sodium into the gas space above the primary system, and would not result in radioactivity in the secondary. With the approach it is necessary to maintain the sodium level by gas pressure in the primary side of the system, and this caused a problem. Another problem developed because the system had to be designed for an exceedingly low pressure drop since it was on the suction side of the pump. It was found after operation that there were some difficulties with proper distribution on the shell side and I believe that the thermal performance was not quite as high as was estimated. You will note that the differential expansion between the central downcomer tube, which is relatively cold secondary sodium, and the tubes which are hot, is accommodated in this design by bent tubes. There are other approaches which we will see later.

A-47

This slide shows the intermediate heat exchanger for the SCTI unit. Again, expansion between shell and tubes is accommodated by sine wave tubes, and this is the one, rather difficult, fabricating problem with this particular unit. Another interesting feature of this unit is the use of disc and donut type baffles. You will notice that the central portion of this unit consists of an open space down the center. The reason for this is that the sine wave tubes are bent in a single plane, and then bent in the configuration representing the radius of the particular tube row. Of course, it is impossible to build tubes of this type for a very small radius, and thus a hole is left in the center of the tube bundle. This hole is used as part of the flow pattern in the donut type baffles. This unit has proven quite satisfying at SCTI, but may be somewhat expensive. The nozzles have shock liners to protect the highly stressed nozzle areas from excessive thermal shock.

A-48

This sketch shows the unit provided for the Sefor reactor. It is a horizontal U tube unit in a single shell. This is probably quite satisfactory for a small unit. It is not practical to try to extrapolate such a unit to large capacities.

A-49

This is a sketch of the IHX in the Phenix reactor. The interesting part of this design is the unique method of bringing the secondary piping in at the top of the unit in a sort of concentric arrangement. Differential expansion between the pipe and shield plug is provided by a bellows on the outer edge. Some shielding is provided with a shield plug in between the inlet and outlet pipes. This does not appear a very satisfactory shielding arrangement. Perhaps there is a shadow shield above the unit above floor level. Differential expansion between the downcomer and the tubes is accommodated by bends in the tubes.

A-50

After extensive economic studies, AI concluded that the "hockey stick" arrangement is the one which appears to be most economical, although there were a number of other types of units which were acceptable probably within the error of the study. This view shows the reference IHX for the AI 500-Mwe FBR. Material is Type 304 stainless steel. The tubes are arranged on a square pitch, such that expansion is free in the bend area in a direction parallel to the natural centerline of the unit. The shell side nozzles are in the straight portion of the unit, to permit the sodium in the shell side of the bend to be stagnant. Our studies have indicated that this area is largely ineffective as heat transfer surface. Prohibiting shell side flow in this area minimizes the possibility of tube vibration. There is a rather sophisticated inlet belt at the shell nozzles to distribute the flow uniformly around the tube bundle. Not visible is a sort of orifice arrangement in the inlet and outlet areas to further insure uniform distribution. Since the unit is nearly 7-ft diameter, minor flow deviations could result in loss of heat transfer effectiveness.

This unit poses several problems inherent in the hockey stick end. The offset dimension poses somewhat of a shipping problem. The bend area is rather expensive to fabricate. A running drain would provide assurance that the bend area would not act as a stagnant area. Stagnant sodium, particularly at the cold end of the unit, could result in corrosion in that area.

The baffles are orifice type, i.e., every other tube hole is enlarged, and the sodium flow is through the annulus formed between the tube and the enlarged hole. The alternate holes serve as tube supports. Thus, shell side flow is nearly parallel to the tubes for the most part, rather than a modified cross flow which would be normal with disc and donut baffles, or with segmented baffles.

A-51

This sketch shows the general conceptual configuration of the Westinghouse 500-Mw intermediate heat exchanger. It consists of straight tubes with a floating bottom tube sheet. Secondary flow is downward in the central downcomer, up the straight tubes, and out the donut shaped collection head at the top. Differential expansion between the inlet line and the warmer portions of the unit is accommodated by fixing the inlet line at the bottom tube sheet only, allowing differential expansion between the inlet line and the annular ring which ties the two tube sheets together. Bent tubes provide for differential expansion between this wrapper sheet and the tubes themselves. This is probably not a major consideration since the differential temperature between these units is probably <100 °F during normal operation. However, preheating could be a problem with straight tubes. Another problem arises with this particular design from the method of tube plugging in the event of leaks. It appears necessary to pull the bundle to plug the tubes in the bottom tube sheet.

The use of shock liners at top of the shell side underneath the tube sheet protects the tube sheet from thermal shock. Use of a flanged joint to permit pulling the tube bundle requires a very highly leak tight seal. This must be some sort of metal gasket, in view of the service temperature.

A-52

This sketch shows the proposed design for the Combustion Engineering intermediate heat exchanger. To accommodate differential expansion between the various tubes or between the tubes and shell, sine wave bends are used in the upper portion of the unit. This is a good design; however, it does pose some problems in support of the tubes in the sine wave area. Design and fabrication of baffles in this area become quite complicated. Note that the shell nozzles are expanded to reduce the velocity of the sodium entering the shell side. This is pretty much standard with sodium-to-sodium heat exchangers to minimize tube vibration in the entrance region.

The sketch shows the tubes bent in alternate directions. In actual construction, alternate radial rows of tubes are bent in opposite directions. This minimizes the tendency of the tubes to place a torque on the tube sheet.

A-53

This is a cutout section of the old SRE intermediate heat exchanger, after operation of the SRE was complete. The heat exchanger was taken apart. You will notice that the tubes are in quite good condition. This is typical of sodium service. Sodium service does not seem to deteriorate ferrous materials a great deal. However, you can see accumulations of carbonaceous material around the baffles in the lower part of the unit. This was the result of a tetralin spill in the old SRE, and the carbonaceous material collected in the lower portions of the intermediate heat exchanger. Tests with radiation meters indicate that this carbon had been a good collector of some of the fission products that were in the system. The areas around these carbonaceous accumulations were quite radioactive. This and other evidence lead some in the industry to believe that carbon has potential as a getter for accumulating fission products in a system.

A-54

I would like to describe a few of the problems encountered with liquid metal heat exchangers in the past. At the old SRE, the U tube bundle was installed in the horizontal plane. The result was poor distribution and flow at low flow conditions. In addition, the bend section was essentially ineffective as a heat transfer area. The poor distribution lead to shell distortion and excessive thermal stresses. The situation was improved in the SRE PEP modification by installing the U bend in the vertical plane rather than in the horizontal. This of course did not correct the poor heat transfer in the bend area.

A-55

In the Hallam IHX, a leaking tube was found in Unit 1A after a relatively short period of operation. Analysis indicated that this was caused by high sodium velocity in the area adjacent to the inlet and exit impingement baffles. The high velocity induced vibration in the tubes from Von Karmen vortexing. This, in turn, led to failure of a few specific tubes by fretting against a tube support baffle. The fix was to add shims between the tubes at the entrance and exit regions. This raised the natural vibrating frequency of the tubes in this area well above the exciting frequency of the vortexing, and the problem was corrected.

A-56

This shows a partial cross section of the inlet area of the Hallam exchanger. You will notice the impingement baffle was installed at the inlet nozzle due to the very high velocities. This configuration then resulted in excessively high velocities of sodium at the edge of the baffle and particularly at the marked tube here at the corner. This tube was excited into vibration by high velocity sodium at this point, and eventually failed by fretting against one of the tube supports. After this failure was discovered, all six of the Hallam exchangers were modified by installing shims between the various tubes which prevented tube vibration. This work was done in the field and you can see here where the shell was cut to provide the shims. The shims then were welded in place on a backing plate and finally the cut portion of the shell was rewelded in place. This modification was made after an appreciable amount of radioactive operation; however, there had been no failed fuel pins in the reactor, so all of the radioactivity encountered in this modification was a trace amount of sodium 22. In future operation due to radioactivity, modifications will not be made in this manner, and undoubtedly more careful analysis will be given to tube vibration in initial design. In general, modern sodium heat exchangers are designed for excessively high velocities — much higher than is normal in conventional chemical practice; this is one reason why these problems present themselves. Now that we are aware of them, I am sure that future units will be designed to take into account the possible vibration of the tubes.

C. VALVES

The next topic I would like to discuss is valves. Very early in the development of liquid metal systems, commercial valves were accepted and used, but modifications were made to some extent in the sealing areas. Since these valves did not function reliably efforts have been underway to improve the situation. Even today, a high degree of success with valves has not been reached.

I remember a remark made recently by one of our power company associates. He stated, "We feel much more comfortable with the pump drive industry than with the valve industry." In effect, he felt that it is a sacrifice of reliability to use valves for flow control if the same job could be done with the variable speed pump drives. At SRE, the philosophy was adopted that valves created more problems than they solved, and should be used only where necessary. This may be an unduly harsh appraisal. However, experience at SRE indicated that valve maintenance was more costly in terms of shutdowns than was the value of time saved by the presence of valves in the system. Under these conditions, it would be sagacious to carefully appraise the function or functions of each and every valve in the system, and then to eliminate those valves for which there was no real need.

<u>A-57</u>

This tabulation shows some of the established requirements or characteristics demanded of a valve. I would like to emphasize that each valve does not bear each requirement. On the contrary, it is necessary to define the exact need of the specific valve, and to ask for no more. For example, it is often possible to accept a throttling valve with a low or controlled seat leakage, in preference to one with throttling capability which is also a good shutoff valve.

When a valve is used for shutoff service, it is usually not necessary that the same valve perform throttling service. All valves must be specifically constructed for zero leakage to the surroundings, which usually demands all welded construction with either bellows seals or freeze seals. All valves must be designed to resist the piping stresses at the point of installation without binding.

One of the major difficulties with gasketed joints, including the body assembly joints of conventional valves, arises during thermal cycling with the result that assembly bolts become elongated and/or gaskets yield, causing the joints to leak. Another problem is evidenced in differential thermal expansion of the stem and body. This may result in leakage through the seat, if a valve is shut and subsequently subject to thermal cycling.

Throttling at high differential heads produces a real problem with present day valves. In particular, it is pretty well established that many of the malfunctions occurring in valve bellows have been attributed to vibration, fatigue, and subsequent failure, due to high velocities in the valves during severe throttling service at high differential heads.

In all valves, corrosion resistant materials are used. The standard material is Type 304 or 316 stainless steel, with hard facing materials on seats, discs, and wearing parts. The stainless steel itself is not good for wearing parts due to gauling.

In certain valves, special requirements imposed on the valve/valve drive system include accurate positioning, rapid closure, and operation on emergency power. These latter requirements are imposed on the main heat transfer system throttling valves, to attempt to force decay of flow through the core on a schedule approximating the decay of the power generation due to a scram. It is essential to effect flow decay parallel to power decay to minimize thermal shocks in the system.

A-58

In specifying valves, we must stipulate the test requirements by which their suitability for a specific job will be judged. Again, performance must be appraised on an individual basis. For example, seal leakage has no real meaning in an all welded check valve. Seat leakage is very important in a shutoff valve, although often insignificant in a throttling valve. For emergency shutdown valves, the capability of the operator in terms of power; positioning accuracy; time to close; or emergency power requirements is of considerable concern. Zero body leakage and acceptable cleanliness are requirements of all sodium valves.

A-59

In developing suitable valves for sodium service, there are a number of problems which have not been satisfactorily solved in all cases. I understand that the AEC has on-going studies with at least two valve manufacturers in attempts to solve these problems for large valves. Design of the valve is complicated by the presence of radioactive coolant which seriously limits the capability to approach a valve for maintenance. Suitable seals should be developed for valve stems, and materials should be selected for resistance to corrosion, self-welding, and gauling. Present day valves require excessive headroom in some cases.

Valves must be designed to meet certain speeds in closure, and to resist the hammer forces which may be induced. Experience has shown that sodium will penetrate pores of metal, particularly in cast materials. Thus, design must minimize the presence of laps, pores, or other defects. Design must be such as to sustain anticipated thermal shocks, expansion, and pipe reactions without failure or distortion.

One of the major unsolved problems is that of large diameter shutoff valves designed with low head-room requirements.

Naturally, cost is an important consideration. The valves must be designed to require minimal maintenance, since they may not be approachable for maintenance during operation. The valves must be designed in conjunction with a suitable drive mechanism to assure satisfactory closure, positioning accuracy, and amenability for using an emergency power source in event of outage of normal power.

<u>A-60</u>

It is interesting to learn what sizes and designs of sodium valves have been built and tested. This chart shows a tabulation of the valves which have been installed and tested in existing reactors in this country. The Hallam valves were quite similar to the valves in the FFTF. Apparently, there is no problem with size extrapolation, although other limitations could render available valves unusable for the purposes intended. It is entirely possible that drive mechanisms will cause a major problem with FFTF valves.

<u>A-61</u>

Let us look at a few actual valve designs. This first cut shows one of the early bellows seal valves. It was strictly an adaptation of a commercial bellows seal valve. In general, valves of this type did not prove too satisfactory at SRE. Bellows failures were entirely too frequent. The stuffing box backup seals were unsatisfactory in the very dry atmospheres of nitrogen filled vaults, since they tended to dry out and leak. The seats in this valve are conventional and subject to warping. Note that the bellows seal is welded into the valve body to ensure against leakage. In a conventional valve, the bellows would be flanged into the valve body for ease of removal.

This valve body is undoubtedly of cast construction. This is unsuitable since the sodium will penetrate the pores of the metal, making it difficult to decontaminate. In particular, in event of radioactive service, there is a real potential for radioactive species becoming trapped in the pores of the metal. While cast body valves are acceptable, forged bodies are definitely preferable.

A-62

This chart shows the small bellows seal globe valves used in the Hallam reactor. These were the offset type. You will notice the extended seat arrangement inside the valve. This was a special design to avoid possible problems with seat distortion. You will also notice that the bellows seal has a shield around the bellows to protect it from flow. This particular design has a stuffing box backup behind the bellows with a leakoff device for a leak detector inside the bellows. Experience at Hallam indicated that this type valve was quite satisfactory for off-on service but was not too adaptable for throttling service, particularly where the differential pressure across the valve was great. Flow induced vibration of the discs resulted in fatigue failure of the bellows. This design permitted full use of forged parts in preference to cast parts. Again, the stuffing box backup was of questionable efficacy due to the packing drying out in the dry atmospheres.

A-63

This chart shows the main throttling valve that was used at the Hallam reactor. This proved to be a very good valve; however, it is a rather expensive valve. The basic principle of the valve is the old Pall ball valve. In this arrangement, a spherical ball is contained within a loose fitting cage — the cage is driven up and down by the valve stem. As the cage is driven down, the ball goes with it and contacts the ball pin guide which then, together with a cam in the cage, cams the ball into the valve seat. This valve has proven quite satisfactory both as a shutoff and as a control valve at Hallam, however, it does have size limitations. The largest valve that could be built on this pattern is probably between 20 and 24 in., limited by the weight of the ball. These valves always have reduced ports. This particular valve has a secondary containment shell, that is, a welded enclosure around the valve. This complicated the installation. Also in this particular valve a double jack screw arrangement with a cross arm was used to drive the valve. This was made necessary primarily by a lack of head room at the Hallam installation. The cross arm arrangement did not work well because of the play between the two drive worms of the cross arms. This resulted in binding and eventually bending of the cross arms. This was corrected in the Hallam valve by reworking the top works, it would have been desirable if the cross arm were not necessary. This valve had a freeze stem and a stuffing box backup which was not too satisfactory because of drying out of the stuffing box. As the packing dried out, the stuffing box leaked, permitting impure nitrogen from the vaults to enter the frozen sodium area, causing oxidation of the freeze seal. This caused the valve to be hard to turn. If this situation persisted, it was necessary periodically to melt out the frozen seal and refreeze it a number of time to remove the oxide, facilitating the stem to turn.

In the freeze seal concept, it is normal that the stem be larger than one in a conventional valve, since more torque is required to shear the frozen sodium seal. Further, hollow shafts are preferred to minimize the flow of heat from the valve body into the frozen seal area.

After the revisions to the cross arm arrangement, this valve could be driven from full open to full closed in about 9 or 10 sec. This is more than 1 in./sec. Some manufacturers claim they can close large high pressure valves in ~2 sec.

A-64

This sketch shows the check valve that was used at the Hallam plant. You will notice the seat is slightly offset. This was to ensure that the valve would drain properly when there was no pressure against the valve. You will also notice the knife edge type hinge pin. It was found early in the experimental work on sodium that sodium oxide would collect around conventional hinge pins and result in their freezing. This was avoided by using the knife edge hinge pin which kept sodium flowing freely around the hinge pin thus preventing oxide collection where it could bind up the valve. As in most sodium valves, this one has a welded cap. You will also notice the extended seat which counteracts problems of seat distortion during thermal transients.

A-65

This sketch shows an experimental valve which was developed in Britain and which has been reported to be quite satisfactory. It has a number of interesting features that I would like to describe. First, it is a bellows seal valve but the bellows is apparently in a frozen seal region. This indicates that at certain times, the valve is operated with frozen sodium around the bellows. Apparently this has been quite satisfactory to the British. In American practice, we experienced bellows failure when operating with frozen sodium around the bellows. This suggests an anomaly which would tend to discredit this particular failure theory.

At the upper end of the valve is a very interesting feature — the spring thrust head. In this particular design, the force to close the valve is applied with a number of spring washers, such as Bellville washers. This method permits closing the valve against a spring tension such that minor differential temperatures between the body of the valve and the valve stem do not affect the tightness of the closure. One of the problems occurring in sodium valves with leaking seats is this possible differential temperature condition.

A-66

This figure shows a sodium butterfly valve, constructed with an offset butterfly seat and disc having a steel seat ring similar to a piston ring in a car. This particular valve can be closed reasonably tight even though a butterfly valve is not considered a tight shutoff device. Again, this valve is shown with a freeze seal. The freeze seal is quite adaptable to incorporation in butterfly valves since the motion of the stem is rotary rather than linear. Valves with linear stem action pose a problem in that heat is transmitted up the stem as the valve is opened, resulting in partial melting of the frozen sodium and progressive transfer of sodium up the annulus. This problem does not exist with the rotary action stem. Eventually, this pumping action makes it necessary to melt down and clean out the seals. This is done by melting down and reforming the seal a number of times to get the partially oxidized sodium out of the seal region.

We at AI feel the butterfly valve has a good chance of being a very valuable tool for throttling service due to its relatively low cost, good throttling characteristics, rotating valve stem motion, and capability for quick closure. For many applications, the unfavorable shutoff characteristics may not be a serious deterrent. The low headroom requirement is a distinct asset.

A-67

This is a very similar valve, except that the stem is mounted at a small angle to the valve axis. This modification permits a different motion of the valve seats, and results in a valve with less seat leakage.

A-68

One of the main valve problems arising in sodium plants involves large shutoff valves. We, frankly, do not have an answer for this problem. This figure shows an ordinary wedge disc gate valve which is used for fairly large lines. The disc in this picture is known as a flexible wedge disc which permits some motion between the two sides of the disc to obtain better fitup on closure. This is a reduced port valve which is standard in large sodium valves. You will also notice that the body joint is welded. The unit has a backseat which would presumably permit repacking while under pressure. At AI we much prefer the stem freeze seals to any other type of sealing mechanism. These are always backed up by some sort of packing gland. You will notice that this valve has a hollow valve stem. This minimizes heat conduction up the shaft of the valve and also minimizes the heat capacity of the valve stem, which then negates pumping sodium up the freeze stem. The real problem with the gate type valves, particularly in the larger sizes, is the excessive headroom necessary. In the sodium equipment vaults these valves are normally mounted somewhere close to the top of the vaults which means that it is difficult to find sufficient space above them for the massive top works required. I suspect that in large plants of the future we will gradually eliminate use of large gate valves.

A-69

In specifying our valves, we establish a table showing all expected transient conditions the valves are expected to sustain during the lifetime of the plant. These transients are defined for each portion of the plant, and are extracted to the conditions each single valve or component is expected to sustain. These expected transients are then written into the specifications for the component considered. This figure shows a partial transient table for one component. The expected number of each transient, the temperature, temperature difference, and the rate of application of each transient is stated. The finished item, then, will be stress analyzed for all conditions on a fatigue damage basis, to assure that the item will sustain these transients for the anticipated life.

A-70

We normally write a general specification for all the sodium valves in a system, plant, or application, and would include a table showing the special conditions applicable to the individual valves. This table shows a partial list of the special conditions for a number of valves. Such items as operating temperature, size, function, operator requirements, pressure, etc., are outlined in this portion of the spec for each valve, or each valve for a particular function.

A-71

The freeze seal stems are designed thermally as fins, starting at the upper portion of the valve bonnet. This figure shows a plot of the temperature along a valve stem due to the use of the freeze seal. You can see that, at the upper end, the freeze seal is designed for ~130°F. This particular seal appears to have been designed for sodium at ~1000°F at the entrance to the freeze seal region. The total stem travel should be somewhat less than the distance between the point at which sodium freezes and the upper end of the freeze stem. The freeze seal is designed as a series of plates with cutouts between to minimize possible distortion due to the temperature difference between the end of the fin and the base of the fin.

A-72

We have talked about the prospective unreliability of bellows on valve stems. This photo and the next show a number of bellows failures from the SRE experience. The reasons for all the bellows failures are unknown. At SRE, the failures were attributed to attempts to open or close valves while the bellows was full of frozen sodium. This may or may not be the cause of all failures. The experience of the British would cast doubt on this philosophy.

A-73

At Hallam, we had reasonable justification for saying that the cause of some failures was due to fatigue caused by disc vibration while trying to throttle and having the valves at high differential head. There is also the possibility that oxides collected in the area around the bellows due to the cooler temperature, and caused corrosion. If a valve is not designed to prevent imposing a torque on the bellows, then this could cause failure. Finally, there is a real possibility that failure was due to being improperly fabricated and heat treated, or in welding the bellows, or to damage in assembly. The truth of the matter is that all of these factors may have resulted in bellows failure at one time or another. These pictures at least attest to the fact that we have had failures.

A-74

We have discussed valve operators, particularly for those valves which must be operated rapidly under emergency conditons. This sketch shows an operating rig used at HNPF. The drive was an air operated motor rated at ~50 hp. The reasons for choosing air were twofold. First, using a 50-hp electric motor for each of six valves would have been too expensive, had we had to operate these valves on the emergency generator. Second, it was possible to place a rather inexpensive air holder at each valve. This gave sufficient compressed air to close the valves once, even if the compressed air supply failed.

The torque was transmitted from the air motor to the valve through line shafting, which was connected through right angle gear boxes and shafting supported on pillow blocks. The position of the valves was accurately known at all times by the number of turns of the shaft in either direction. In operation, the valves were driven ~95% closed on scram. The valves then held this position for 15 sec, after which the valves were permitted to modulate based on a temperature signal. The temperature signal was not considered reliable for the first 15 sec following a scram due to thermal lag.

D. STEAM GENERATORS

The subject of steam generators is not of particular importance to the FFTF. However, some facets of steam generator practice may be of interest to some of you. Therefore, I would like to touch on this subject. In the early days of sodium cooled reactors, the steam generators were double walled. In present practice, we are going to single walled tube types. The reason for the reduced level of conservatism is that we feel we will be able to control the chemical reaction during a steam or water leak and a sodium water reaction. Thus, in the interest of economy, I believe all in the field have dropped the double wall tube concept. The steam generator is the link between nuclear heat and the economic product of nuclear power, the generation of electricity. In this respect, this is one of the most important components in the system.

A-75

This chart presents the temperature conditions for the AI 500-Mw demonstration plant. These are quite typical of modern sodium cooled reactor concepts. The top temperature for the sodium is 950°F into the superheater. This is governed primarily by the desire to use chrome-molybdenum steel in the superheater and in the reheater region. We prefer chrome-molybdenum steel because it minimizes the possibility of stress corrosion cracking. Sodium into the evaporator is at 855°F and sodium out of the evaporator returning to the intermediate heat exchanger is 700°F. Normal feedwater temperature is 470°F with superheated steam out at ~905°F. Sodium velocity in the units is between 8 and 12 ft/sec with steamside velocity close to 200 ft/sec.

As load drops off from the 100% condition, normal feedwater temperature drops drastically. For example, at 25% load, normal feedwater temperature would be ~355°F, and at 50% load, normal feedwater temperature would be about 405°F. These conditions would result in excessive temperature swings in the sodium temperature entering the reactor. To avoid this problem, we provide a high temperature feedwater heater which maintains the feedwater temperature at 420°F at all loads below ~55% of power.

A-76

At AI, we have pursued the "modular" concept of steam generator construction. That is, we build a number of smaller units rather than a single large unit for the steam generator in any one loop. The basic reason for this philosophy is that, in event of a major water leak, we assume that one or more adjacent tubes would be damaged. However, it may be difficult to determine which tubes are actually damaged, and thus an outage for complete appraisal of all tubes would be prohibitively expensive. Instead, we would remove a module containing a leaking tube and replace it with a new module. Later, we would appraise the defective module at our leisure, and determine the feasibility of repair. This viewgraph points out some of the benefits gained from such a policy. The only deficiency of this approach is capital cost. Our overall economic studies indicate the modular concept is the least costly.

A-77

We have studied three basic classes of materials for the steam generators. We selected 2-1/4 Cr-1 Mo based on its resistance to stress corrosion cracking, and its economy, coupled with wide experience in steam generator service. The Incoloy materials were not favored based on cost and lack of experience. The Type 300 series stainless steels were not favored because of their susceptibility to stress corrosion cracking.

A-78

Economic studies were made in attempting to determine the most economical size of module. As a general rule, smaller modules tend toward higher cost, but lesser cost in case of failure. On the other hand, the larger units result in lower first cost, but more cost in event of failure. This figure shows some of the considerations involved in these studies.

A-79

This figure shows the comparison — first the cost of the module vs cost of unavailability for repairs and total cost. As you can see, for very small modules, say <~200 tubes/module, the initial cost of the module becomes quite high. Conversely, as we go to a larger module, the cost of unavailability and repair becomes higher since the outage is essentially proportionate to the size of the unit.

The total cost then, according to our figures appears to result in optimum module sizes of something on the order of 200 to 1000 tubes/module.

A-80

Most modern steam generators which are being proposed for new plants are of the single wall tube construction. Furthermore, the once-through type steam generators appear to be the coming thing. However, as a matter of interest, I would like to show you some of the features of the steam generators which were used at Hallam. These had double walled tubes because we were not sure we could control sodium water reaction. In the construction of the double walled tube, there was a monitor of helium between the two walls. The pressure in this monitor was intermediate between the sodium pressure and the steam pressure. Thus, should a leak have occurred in the sodium side, the pressure in the monitor system would have dropped; and had a leak occurred in the steam side, the pressure in the monitor system would have risen. In either case, we would have known immediately that a leak was in one of the walls and could have shut down to find the leak and make repairs. The Hallam steam generator was a kettle type reboiler. It had a kettle type reboiler on the bottom, steam separator at the top, with the superheater in between the two. This was a very expensive unit although a very good one for its purpose. It would probably be considered obsolete for future, larger plants. This design is not extrapolatible to large units. Its prohibitive cost due to the double wall tube also precludes its adaptation to very large plants.

A-81

This sketch shows one of the modules proposed for the AI modular steam generator. Again, we have adopted the "hockey stick" design, to provide for differential expansion between tubes and shell. The problem presented while preheating the steam generator is not nearly as severe as with the IHX, since auxiliary steam can be used for preheating. By controlling the pressure in the unit, preheating can be controlled very accurately. This view shows a rupture disc at the center of the module. We believe it is now feasible to build satisfactory units without rupture discs on the modules. This is possible if we go to larger units (larger diameter to length ratio), and make provisions for sufficient relief on the sodium headers. This view also shows the method of tube attachment of the tubes to the tube sheets. A butt weld was used to eliminate the possibility of crevices on the sodium side. Such crevices could lead to failure by stress corrosion cracking.

A-82

This viewgraph shows a little later model of the AI unit. The main difference between this one and the one shown in the previous view is size. We are quite concerned about the possibility of a leak in the region adjacent to the tube sheet, and subsequent cutting of the shell to the point of failure. We now propose to install a damage shield around the bundle at this point to minimize such a possibility.

A-83

This shows a sketch of an assembled AI modular steam generator. The excessive piping required to pipe a number of modules is the primary reason for the high initial cost of the modular concept. Since small, mass produced components can be integrated into the modules, the cost of heat exchanger surface, per se, can be reduced with the modular approach.

A-84

This photograph shows a number of views of the AI module in process of fabrication, giving a concept of the size. These pictures were taken during fabrication of a hydraulic mockup of the unit. Subsequent to the time these photographs were made, we have adopted a larger module as the reference design. We found the hydraulic mockup very useful in observing for possible tube vibration; and in verifying pressure drop calculations. The fabrication experience was also useful in defining manufacturing problems prior to attempting to assemble a unit which must resist the high pressures and temperatures of a real steam generator.

A-85

This figure shows the program temperatures of the various portions of the AI 500-Mw plant. This obviously is not directly applicable to the FFTF however, the principle shown, I believe, does have application to your plant. We do not attempt to maintain the temperature throughout the system constant over the load range that we plan to operate. Rather, we plan to program the various temperatures in accordance with load. If you will examine the usual heat transfer equation, $Q = UA\Delta T$ for the IHX, for example, it is quite obvious that, as the total heat transfer Q changes, something must change on the other side of the equation. The area is fixed so that it can not change and the U in general is fairly constant for sodium service. Thus the only thing that we can change is the temperature or the ΔT. So this picture shows our plans for allowing the ΔT to drop as load drops, thus avoiding the possibility of overheating steam at low flows. There is another reason for having this type of program and that is to be able to control the reactor.

A-86

One of the most serious concerns we have with the fast breeder reactor is the possibility of a leak in the steam generator which would result in water or steam leaking into the sodium. The resulting sodium water reaction would result in a very great increase in pressure on the sodium side of the unit. We protect from this event by the use of rupture discs on each module and also on the sodium headers. In particular, we are quite concerned about the possible pressure at the intermediate heat exchanger since a leak of the tubes in the intermediate heat exchanger could conceivably result in a loss of radioactivity. This slide shows that the pressures at the faulted module are anticipated to be quite high. However, the rupture discs reduce this pressure to something on the order of <400 psi in IHX which is quite satisfactory for use with the design pressure of ~ 200 psi. These curves were derived by making a computer run of the anticipated pressures at various points in a model system.

E. AIR COOLED HEAT EXCHANGERS

Air cooled Dump Heat Exchangers have limited interest in power reactor technology, since they are directly applicable to test reactors only, unless they are chosen for emergency cooling. Thus, the technology has only been developed to a limited extent. One of the first units of which I am aware for use in liquid metal service was the dump heat exchanger at SRE. As we would expect, this was an adaptation of a unit designed for water service. As such, it was not what we would design today.

A-87

This sketch shows the basic concept of the SRE PEP main airblast heat exchanger. Air is blown in at the side of the unit with a centrifugal blower driven by a variable speed drive and through the cooling coils contained within the box. An upper off take line was installed with a damper. This unit is modified rather drastically from the original SRE airblast heat exchanger. Originally there were open louvers on the sides, both below and above the coils. The fan was a large propeller type fan mounted in a horizontal position underneath the coils. This unit was quite unsatisfactory for many reasons. First, it was not properly contained and insulated to facilitate the preheating. Second, there were a number of blade type dampers above the coils, which, after being heated for a limited period of time, warped and would not operate as louvers. Finally, the coils themselves began to sag. The modifications shown in this sketch were directed toward correcting these deficiencies. When the modifications were made to the case, it was necessary to go to a centrifugal fan since the propeller type fan did not generate sufficient pressure. You will notice a hydraulically actuated damper at the top. This is to permit isolation of the unit in the event of leakage or fire. The same hydraulic actuated mechanism is shown on a shutoff damper at the suction side. In the event of a leakage or fire, a nitrogen line was provided to permit gas blanketing of the unit to suppress any fire. Basically, the unit contained two rows of tubes, one above the other. Much more compact and economical units would contain, perhaps, somewhere between 8 and 12 rows of coils.

A-88

Here are some of the design parameters of the SRE air blast heat exchanger as proposed in the SRE-PEP revision. The revised unit should have a capacity of 20 Mwt. It has ~34,000 sq ft of heat exchanger consisting of 1 in. OD fin tubes. Two 50-hp motors are used to drive the two fans. As you can see, the original sodium temperature at inlet was 900°F, and at outlet 440°F with air at 100°F. This required a 200,000 cfm air flow. The proposed new outlet conditions are to raise the inlet temperature to 1150°F, and the outlet to 600°F. The overall capacity and air flow are to remain the same.

A better design than that for the SRE is the air blast bypass cooler on the SCTI. This unit has a heat exchanger surface of ~8000 sq ft. The tubes are Type 304 stainless steel, with 4 to 6 chrome-molybdenum fins. The unit is rated at 75,000 cfm of air at 10 in. WC pressure drop. The fan is driven with a variable speed electric drive, with a speed turndown of about 11:1.

The unit is ~8 ft-6 in. by 6 ft-9 in. by ~7 ft deep. Capacity is ~8.5 Mwt. The design of this unit is much more compact than that of the SRE unit, since the coils are about 12 coils deep in lieu of two rows deep at SRE. Being much more compact, the unit is easier to preheat; and is more amenable to shut off in event of leak and fire.

The unit has a gas burner at the bottom plenum with a rating of 200,000 Btu/hr. This preheat system is reported to be quite satisfactory. Originally, the outlet dampers were operated by fan pressure. In recent modification, the outlet dampers will be operated manually. One problem is the fact that the unit has no specific provision for rain protection except closing the outlet dampers. Air velocity seems sufficient for rain protection under normal conditions during operation.

A-89

This chart shows some of the preliminary design parameters for the FFTF dump heat exchangers. From the temperature point of view, the design does not seem to pose any unusual requirements more stringent than those at SCTI. The unit is larger, however, being about 33 Mwt whereas the SCTI unit is about 8.5 Mwt.

A-90

This figure shows some of the more important design features of the proposed FFTF unit. These charts were prepared about three to six months ago, and may be somewhat obsolete. The interesting feature of this chart is the proposal that the normal preheat be by electricity, with gas back-up. The unit at SCTI was preheated by gas, which was reported quite satisfactory. There may be a difference in requirements between the two units. At SCTI, the unit was not used except for transient testing, or for emergencies. Thus, it normally required preheat. In the case of the FFTF units, they will normally be in heat rejection service, and will not require preheat.

A-91

This viewgraph shows some of the coil details for the proposed FFTF dump heat exchanger. It is interesting to compare some of the parameters with those of the SCTI exchanger, since that is the most satisfactory to date to the knowledge of the author. The FFTF unit is designed as an 8 pass unit vs 14 passes for the SCTI unit. Material for tubes is the same. The SCTI unit used 4 to 6 chrome-molybdenum steel fins vs Type 410 stainless steel for the FFTF. Fin OD's are the same. Heat exchanger surface is 8000 in the SCTI unit vs 58,500 in this unit.

A-92

This viewgraph shows an engineer's sketch of the general design for the FFTF unit. The relatively high discharge stack is rather unique as compared with other dump heat exchangers which have been built. I presume these will be provided primarily for natural convection cooling in event of power loss for the fans.

A-93

This viewgraph shows a conceptual sketch of the FFTF system. Note the arrangement for the preheat system. To avoid mounting electric heaters in the main duct, as the sketch shows, the electric heaters were installed in an auxiliary duct with a blower and bypass dampers. This appears more practical than the scheme used at SRE. This arrangement has also been proposed for preheating with steam at other installations. The emergency standby heater is mounted directly in the plenum under the sodium coils. The inlet and outlet dampers are, apparently, operated either manually from the control room; or with temperature modulation by the air temperature from the unit.

F. FREEZE TRAPS

Freeze traps are used primarily at vents at the high points of systems where it is anticipated that the vents will be used for filling the system, after which the vents will be closed against a full sodium system during normal operation. In more conventional practices, ordinary vent valves are used for this purpose. However, for a number of reasons, freeze traps are considered more desirable in sodium systems. First, it is fortuitous that the melting point of sodium is 208°F, just above room temperature. This is a practical freeze trap temperature, permitting melt out at a relatively low temperature. Second, a hydrostatically tight seal can be made with frozen sodium. Finally, sodium valves are expensive, and sometimes not too reliable, particularly where it is possible that the valve or system at the point under consideration will be frozen at times. Therefore, the freeze seal has proven highly reliable, simple, and economical.

A-94

This is an artist's sketch of a freeze trap that was developed at SRE, and later modified for use at the SCTI. The trap consists of a piece of finned tubing, with an inlet and an outlet. Down the middle of the trap is an inner liner which forms an annulus ~1/16 to 1/32 in. An electric heater is installed inside this sleeve or well. Thus, the entire assembly is all welded, with respect to the outside. The heater may be installed or removed without disturbing the piping connections. The unit is welded to the sodium system at the bottom, and to the vent system at the top.

In operation, the sodium is allowed to rise in the system, pushing the cover gas out the vent ahead of it. When the sodium reaches the finned section of the trap, it freezes in the annulus inside of the finned tubing. From then until the freeze plug is re-melted, a solid sodium seal is formed.

To re-vent the system, the trap is melted out using the electric heater, and inert gas pressure is applied above the trap until the sodium plug is melted.

A-95

This sketch shows a slightly different form of the freeze trap. This is the trap that was provided for the HNPF reactor. The trap was welded to the sodium system at the base of the float cage at this point, and to a vent pipe at the vent here.

In operation, the system was filled with sodium and the cover gas was forced out ahead of the sodium around the float, through the float orifice, and out the annulus in the finned section at this point.

When liquid sodium reached the float, the float rose and partially plugged the orifice, much in the manner of a float trap. This partial plugging of the orifice slowed the flow of sodium which then froze in the finned area.

For melting out this trap, the heater was turned on, and the stem portion was turned. This forced the float down and out of the orifice through the cam, and permitted draining of the float cage and the system.

This unit was satisfactory with one exception. In the very dry atmosphere of the nitrogen filled vaults, the packing around the shaft at this point dried out. This permitted cell atmosphere to enter the freeze section, and partially oxidized the sodium in the freeze seal portion of the system. The stem then became very hard to turn. It was not feasible to maintain helium in the upper portion of the freeze section, since leakage was too expensive.

Obviously, the HNPF unit was much more sophisticated than was the SRE/SCTI unit. In addition, it is not clear if it were anymore satisfactory. In fact, it is questionable if it were anywhere near as satisfactory. It would appear that the simple unit was the better.

G. COLD TRAPS

The basic purification unit for sodium systems is the cold trap. In this unit, sodium is cooled down to some temperature between its freezing point and about 300°F. Under these conditions, oxides and other impurities become insoluble and precipitate out. If, under these conditions, we have a means of trapping the precipitate, then it is permanently removed from the sodium system. In this form of purification, the oxide content of the average system can be maintained as low as about 5 to 10 parts per million. This is satisfactory for most heat transfer systems of stainless steel material.

A-96

At AI we prefer the gas cooled cold trap. The basic reason for this preference is that the gas cooled cold trap has only a single connection as AI designed it, and it is the connection between the trap and the sodium system. There is no connection required for the cooling medium. This sketch shows diagrammatically how the AI unit works. Sodium passes into the top of the unit and then down around a relatively small economizer coil where the temperature of the sodium drops somewhat, exchanging heat with the sodium leaving through the coils. From there the sodium passes down through a packed bed section around a series of disc and donut baffles where it is cooled on a thermal gradient by the nitrogen passing up the outside of the unit. The outside of the unit is covered with a number of fins which transmit the heat from the sodium in the vessel to the cooling medium. Once at the bottom of the unit, the sodium flows up an inner pipe through the heat exchanger to the system. A thermocouple extending down to the bottom of the unit maintains the temperature by controlling the nitrogen flow at a set temperature. The temperature which we operate the unit is usually ~50°F below the system plugging temperature but not <~225 or 230°F to assure the trap will not freeze up. This particular unit as used at Hallam had a capacity of ~250 lb of sodium oxide. A trap of this type is not considered highly efficient, and will contain ~20% of its theoretical capacity of sodium oxide before it plugs up. These traps are fabricated of carbon steel since they are disposable units. We consider cold traps, particularly in radioactive service, disposable units. It is much more economical to have the units buried in radioactive burial grounds than it is to attempt to clean and renovate them, in which case we would have the additional problem of disposing of the sodium oxide.

At Hallam we did salvage a number of these units prior to going critical, and discovered it cost approximately the same as the cost of new units. However, at the time it was expeditious to regenerate the units. I'll tell you an interesting story here about regenerating one of these units. Our procedure was to hang the unit up in the air and melt out all liquid sodium. This removed ~70 to 80% of the sodium in the unit. Then the remainder of the sodium in the unit was reacted with steam in a nitrogen carrier, and finally flushed out with a deep water rinse. Once the unit was cleaned in this manner, the internals were removed and sent to a local fabricator for refurbishing. His procedure was to wet sandblast the interior of the unit. When sandblasting was to be attempted for the first time, he assigned the duty to one of the laborers who was inexperienced in this type of work. The laborer got quite a fireworks display as the water and sand hit the unit. He became quite alarmed and astounded, afraid that he might have caused a nuclear reaction of some sort. However, we assured him that no radioactivity was present, and that the fireworks was the reaction of sandblasting material on the small amount of sodium that had been trapped in the pores of the metal. This is one example of sodium penetration into pores of metals. Some of these units were examined after sandblasting and the metal was found nearly perfect. As a matter of fact, even after sandblasting, the original mill identification could be seen on the tubing of the heat exchanger coil. This also demonstrates that service in the cold trap was not at all corrosive.

A-97

We have had a number of requests to delete the mesh packing in the cold traps. Basically, the mesh is a point at which sodium oxides can nucleate and attach themselves to the interior of the cold trap. This prevents their passing on through, and being swept along with the sodium in an entrained condition. This slide shows the standard HNPF cold trap along with an experimental trap which did not contain the packing, used at Hallam. In the packless trap, called the "gutless wonder," the shell portion of a conventional trap was used, actually one of the reworked traps. In the bottom were a series of tubular or cylindrical baffles where hopefully the sodium oxide would accumulate. The inlet sodium passed into the accumulator section and down around an annular space between the outer wall and the inner sleeve of the unit where the temperature of the sodium was dropped by the cooling fins on the outside. At a point ~20% above the bottom of the trap, the sodium turned upward through the inner sleeve, a zone of very low velocity, and finally out the coils of the economizer heat exchanger. In operation this worked quite well although not as efficient as the packed trap. However, in the operation at Hallam, the cold traps were serviced by the main sodium pumps. As the load on the main plant varied, the pressure on the discharge side of the main pumps varied, and caused the flow through the cold trap to vary. The result was that, on changes of flow in the main plant (or changes of power), the accumulated oxide between the cylindrical barriers at the bottom was flushed out due to the change in flow, and was carried back into the system. We found that, rather than actually reducing the oxide in the system, we were simply taking it out and replacing it again on changes of flow. Since the Hallam plant was not equipped with flow control devices on the cold trap system, it was decided that the "gutless wonder" was not really as satisfactory as the packed one. Incidentally, the experiments indicated that it required a longer time to reduce the oxide content of the sodium with a packless trap than with the conventional packed trap.

Other purification units in general use are the hot traps. There are a number of types. However, the zirconium filled unit for oxygen scavenging and the stainless steel foil unit for carbon removal are most popular. In these units, the packing material is coiled in such a way that the sodium passes a large surface area of the gettering material at low velocities. In the HNPF hot trap, 20-mil foil was wrapped in helical coils at ~60-mil spacing, leaving passages of 40 mil between stainless sheets. This spacing was maintained by dimpling the sheets prior to coiling.

A-98

Hot traps must be maintained at elevated temperatures in the 1000 to 1400°F range for proper gettering. This viewgraph shows the hot trap heater which was used at HNPF. The unit consisted of a vertical pipe shell with the flow from bottom to the side outlet. This arrangement is necessary to assure that the units will not burn out due to unpredictable convection currents.

At the upper end of the unit underneath the tube sheet, there is a space where there is likely to be gas collected. Cold ends were provided on the heaters so they would not burn out by gas blanketing. The heater elements were stainless steel sheathed resistance heaters. They were welded to the tube sheet both at the outside and inside of the tube sheet. For this reason, it was not possible to form a tight bundle, and sodium velocity past the heater elements is very low.

Finally, outside of the tube sheet, there was about a 5-in. cold end of the heater elements between the tube sheet and the junction box. This was to permit installation of insulation underneath the junction box to protect it from overheating. The entire unit was equipped with preheaters and insulation.

H. VAPOR TRAPS

As freeze traps are used at the high points of systems filled with sodium to prevent the entry of sodium into the vent piping, so vapor traps are used at the high points of gas spaces over sodium systems to prevent the entry of sodium vapor into the gas piping. Where gas space is available above liquid metals, vapors from the liquid metals create a problem. The vapor pressure of sodium is essentially zero at temperatures below ~800°F. As steaming temperatures are approached, say ~1000 to 1200°F, the vapor pressure of sodium becomes quite appreciable. If we have a large flow of gas out of a sodium containing vessel for long periods of time, sodium vapor passes out of the vessel with the gas and deposits in the cooler portions of the vent system. Eventually, this condition would plug the lines with frozen sodium. More serious is the presence of oxygen or moisture in the vent lines, which results in sodium oxide deposits. The consequences of this condition would necessitate replacement of the plugged vent lines. This could be a real nuisance in a radioactive sodium plant; therefore, the use of vapor traps is mandatory in the vent lines of sodium where the temperature reaches above 300 or 400°F.

I'll discuss a few of these vapor traps, which can be divided into two basic types, the accumulating trap and the nonaccumulating trap. We could also segregate them into two types: intermittent flow, and continuous flow. In the accumulating trap, the sodium vapor is condensed and retained as a solid material within the trap. Eventually the material must be removed by melting out the accumulated sodium. In the nonaccumulating trap, the sodium is condensed out well above its freezing point. Thus the liquid sodium is allowed to run back into the originating vessel. In the intermittent type, the trap is effective only as long as it is cool. Should a sudden rush of gas enter the trap, the sodium would condense out and the trap would operate satisfactorily. However, if the flow of gas continues to the extent that the trap itself is warmed up, then the trap no longer serves as a satisfactory vapor trap. The continuous duty trap has some means of continuous heat removal.

A-99

This figure shows the vapor traps used at the Hallam Nuclear Power Facility. Unfortunately, this particular figure was drawn upside down. The flow is into an outer annular space which is filled with stainless steel mesh. As the gas flows along this annular space, the sodium condenses out onto the cold mesh material. The return flow is through an inner pipe and out a small pipe at the top of the unit, (which shows at the bottom here). That sodium which is condensed above the freezing point of sodium runs back down into the originating vessel. However, at least some portion of this trap is always below the freezing point of sodium so it is basically an accumulating type, and satisfactory only for intermittent service and relatively low flows. Incidentally, at the Hallam plant we did have one incident in which this trap was required to take a continuous flow for an extended period of time. The continuous flow was on the order of 1 scfm. This trap proved to be unsatisfactory for that duty under continuous service. However, it was quite satisfactory for flows up to ~15 scfm for short periods of time. The trap is provided with preheaters on the outside which melt out the accumulated sodium. However, should oxygen or moisture be present, even in minute amounts, the sodium oxidizes, making it impossible to melt out the sodium. In that case, it is necessary to cut the unit open, clean, and install new mesh. This could be a messy job on a radioactive unit.

A-100

This artist's sketch shows another type of accumulating trap used at SCTI. The trap consisted of a piece of pipe 6-in. diam by ~2- to 3-ft long, with end caps and screens at both ends. The volume between the two screen cones was filled with iron shot. During intermittent outage periods, the unit cooled off to room temperature. When there was a rush of gas (as for example, when a relief valve opened) the gas would be chilled, and the sodium vapor would condense out on the shot. This unit is more compact than the HNPF unit. There have been no extensive quantitative tests on either unit. However, it appears that this unit could sustain a longer burst of flow than the HNPF unit, on the basis of thermal capacity.

A-101

This view shows a slightly different trap. This unit was developed and tested at Argonne National Laboratory. It is a continuous duty trap, in which the entering gas is cooled, first on the mesh in the bottom of the trap, and second as it passes around the baffles in the finned portion of the unit. Presumably there is a flow of gas around the unit sufficient to maintain a low temperature in the unit. The condensed sodium is returned to the supply vessel. The capacity and temperatures at which this unit has been tested are shown. It appears to be quite satisfactory for small flows on the order of 1 to 2 scfm. There is a possibility of accumulating solid sodium in the unit if the temperature drops too low.

Pratt and Whitney developed another regenerative type trap. This unit consisted of a piece of 4-in. pipe in which an insert was installed. The insert consisted of a bayonet-type cooler in the center, through which air was blown as the cooling medium. A helix of sheet metal was wound around the cooling tube, and welded tightly to it. The sodium (or lithium) vapor was removed from the flowing stream by a combination of cooling and centrifugal force, assisted by the fact that condensed sodium was on the outer surfaces, forming a nucleation area for the condensate. This trap also is suitable for about 1 scfm. A mesh demister may or may not be provided at the top of this unit.

A-103

This and the next view give some actual test data from the P&W trap. This first graph shows the performance of the trap with NaK vapor in both helium and argon. Performance in helium is quite good up to ~1 scfm, with inlet helium at 400°F. Performance is not nearly as good with argon carrier gas. This is attributed to the difference in densities between the two gases.

A-104

At 700°F, the performance is entirely different. Again, the trap is quite satisfactory with helium carrier gas. As a matter of fact, it appears to be better than at 400°F.

On the other hand, performance is not at all acceptable when removing NaK vapor from argon. Such data would indicate a need to test proposed traps with the proposed carrier gas.

A-105

The only vapor trap of which I am aware that was tested and found satisfactory above ~1-scfm flow was the one at EFFBR. In this unit, the argon vapor passed through a central downcomer into the bottom of a tower ~13-ft high by 26 in. diam. This tower is about half full of NaK. The gas bubbles up through the NaK. The central 6 ft of the tower is filled with stainless steel mesh. As the gas is bubbled up through the NaK, the bubbles are broken up by the mesh, and cooled by the NaK. This absorbs the condensed sodium vapor into the NaK. The gas is scrubbed on the upper portion of the mesh as in a demister. Finally, the effluent gas is separated in a cyclone separator. This unit worked quite satisfactorily according to all reports. It is not clear what happened to oxides in the trap.

The trap was provided with a Dowtherm filled jacket around the unit for cooling. The Dowtherm, in turn, was cooled with cold water. Effluent gas temperature was ~125°F.

It seems that a disposal problem would have existed with this unit when excessive amounts of radioactive sodium accumulated. Also some provision should have been made for oxide removal.

I. PLUGGING METERS

A-106

The most widely used and proven instrument for monitoring the condition of sodium in run is the plugging meter. The one in use at AI is an intermittent instrument, from which a reading is taken about once an hour. This view shows an artist's sketch of the AI plugging meter. Sodium is brought in here from the system at cold leg temperature, and cooled in the regenerative heat exchanger, then further cooled in this finned portion of the unit. Finally, the cooled sodium passes through a special orifice at this point, and is reheated to near system temperature in the regenerative portion of the heat exchanger.

Temperature of the sodium at the orifice is monitored by a thermocouple, and is cooled at a preset rate of ~5°F/min by the temperature controlled blower. As the sodium is cooled, the flow and temperature are monitored simultaneously on a chart. If the temperature suddenly drops as a result of oxide collection in the orifice, the unit automatically opens up the orifice, stops the cooling fan, and allows the unit to heat up to the original temperature, after which a new run is started.

A-107

This graph shows an idealized plugging meter run chart, beginning at the lower portion of the page. As you see, the temperature is dropping at the controlled rate, and the flow is constant. At approximately 65 min, there is a sudden break in the flow curve, and a slight break in the temperature. At this set of conditions, the automatic control re-sets the instrument for reheat and a new run. The normal chart is not quite as clear cut as this. In some cases, two breaks rather than one are noted. The first break is often attributed to hydride precipitation. While not an exact correlation, the plugging meter reading is an excellent control signal. It is not satisfactory where very low oxide concentrations (<~5 ppm) are required.

J. PIPING SPECIALTIES

A-108

When mixing sodium of two different temperatures in a pipe line, considerable care should be taken to assure there is no severe thermal gradient at any one point in the pipe line. This slide shows one of the AI designs for a stress relieving TEE. Sodium at one temperature flows through the main line which has an inner liner to prevent that sodium from contacting the main hydraulic barrier of the sodium pipe. On the side of this unit is a smaller pipe with sodium entering at a different temperature. The area surrounding the TEE is filled with stainless steel mesh, in essence — a dead space full of stainless mesh and stagnant sodium at that point. The side inlet pipe passes through the liner so that it does not touch and is free to expand. At a drastically different temperature, the sodium is discharged close to the center of the main line and is passed through the thermal sleeve for some distance which ensures thorough mixing before the sodium, having a temperature somewhere in between the two initial temperatures, is allowed to contact the mechanical barrier of the pipe wall. We have had some experience with this thermal sleeve at SCTI and have had no problems. In the actual SCTI unit, an elbow looking upstream was used to facilitate mixing.

A-109

This sketch shows another modification of a stress relieving joint. This design comprises pipes, all nearly the same size. The through pipe in this case is 10-in., and the side inlet 8-in. The principal is the same as before, using stagnant sodium in mesh as an insulator.

A-110

Pipe supports in a sodium system are rather important and intricately constructed devices. Since the pipes are often operating at temperatures well above the useful operating temperature for carbon steel, it is necessary to make a thermal break between the pipe and the carbon steel supports. This sketch shows one method of doing that job. You see the hot pipe in the center which is supported on two fins at the bottom. These are supported on blocks of rigid insulation, which in turn are supported by a clevis pipe hanger. Outside this entire assembly is the normal pipe insulation. You will notice the electric heaters are wrapped in with the inner insulation of the unit. The features of this particular support are that the area for conduction of heat away from the pipe is minimized by the use of the two fins on the bottom of the assembly, together with the use of an insulation block between the inner support of the pipe and the clevis hanger itself. You will also notice that this construction, like all AI construction, protects the electric heater with a sort of "oven." This prevents possible overheating when bits of insulation cling between heater and pipe.

A-111

One of the problems with sodium piping is how to make penetrations through hermetically sealed cell walls, particularly with hot pipes. This cut shows some of the methods in use at AI. The first sketch shows a penetration through a vault liner by a doubly contained hot pipe. Provision must be made for expansion of the pipe, of the guard pipe, and for differential expansion between the two. In addition, it is necessary to protect the concrete from the heat of the hot sodium pipe.

In this particular approach, the differential expansion is provided with a series of bellows. Heat paths between the hot pipe and the cell liner are purposely long to minimize heat conduction. Insulation is used between inner and outer pipe or between the outer pipe and the sleeve, depending on the choice of the designer.

Some of the problems with this type of construction are how to preheat; and how to support the inner pipe in the outer pipe, allowing for differential expansion and temperature between the two. Assembly is also a real puzzle at times. If heaters or thermocouples are used on the inner pipe of double walled construction, then sound penetrations should be used in the guard pipe which will be resistant to hot sodium in event of spillage and good electrical insulation that resists the environment for the plant life. Actually, nothing inside the guard pipe is maintainable, yet the entire assembly must have a very high degree of reliability.

The remainder of the sketches show various means of passing cold pipes and electrical or instrument leads through barriers.

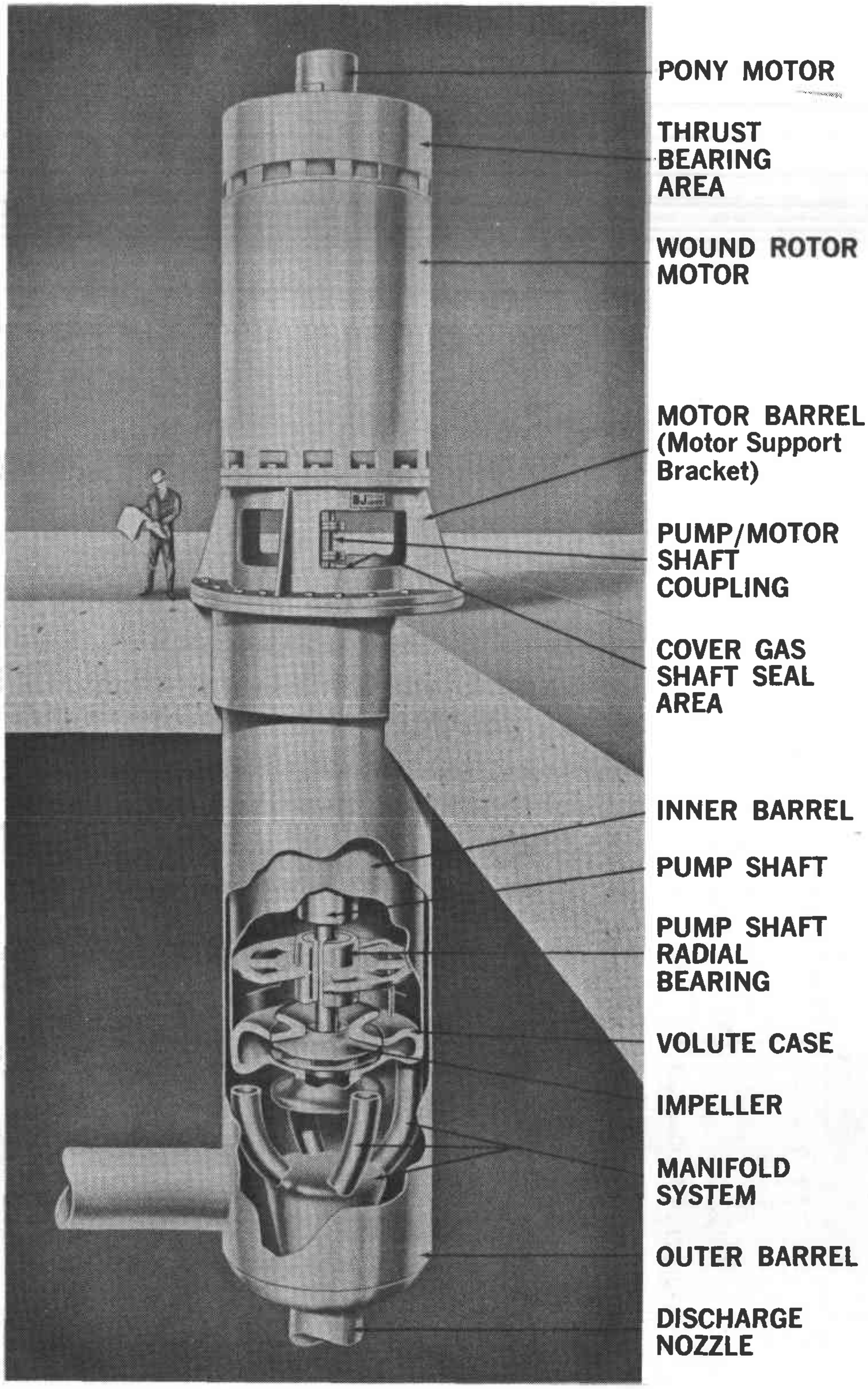
A-112

In discussing pumps, we mentioned the possibility of using balancing legs in lieu of installing pump overflows back to the reactor. The advantage of the balancing leg is that penetration into the reactor shell is avoided. In this unit, the overflow is discharged into the central downcomer. The outer annulus is connected to the pump suction. The depth of the dip leg is greater than the maximum suction head that the pump will ever pull at maximum flow which insures that gas will not be pulled into the pump. Velocity downward in the central area must be very low, preferably $<\sim 0.25$ ft/sec, to permit essentially complete gas disengagement.

The alternate to the balancing leg could be a valve or an adjustable orifice in a pipe connected to the pump suction, or it could be a pipe to the reactor. If a pipe to the reactor is used, it must be designed for a very low pressure drop, since the only head available for this flow is that difference in level between the reactor and the level in the pump. Obviously, it is expensive to provide more than a few feet for this rise level.

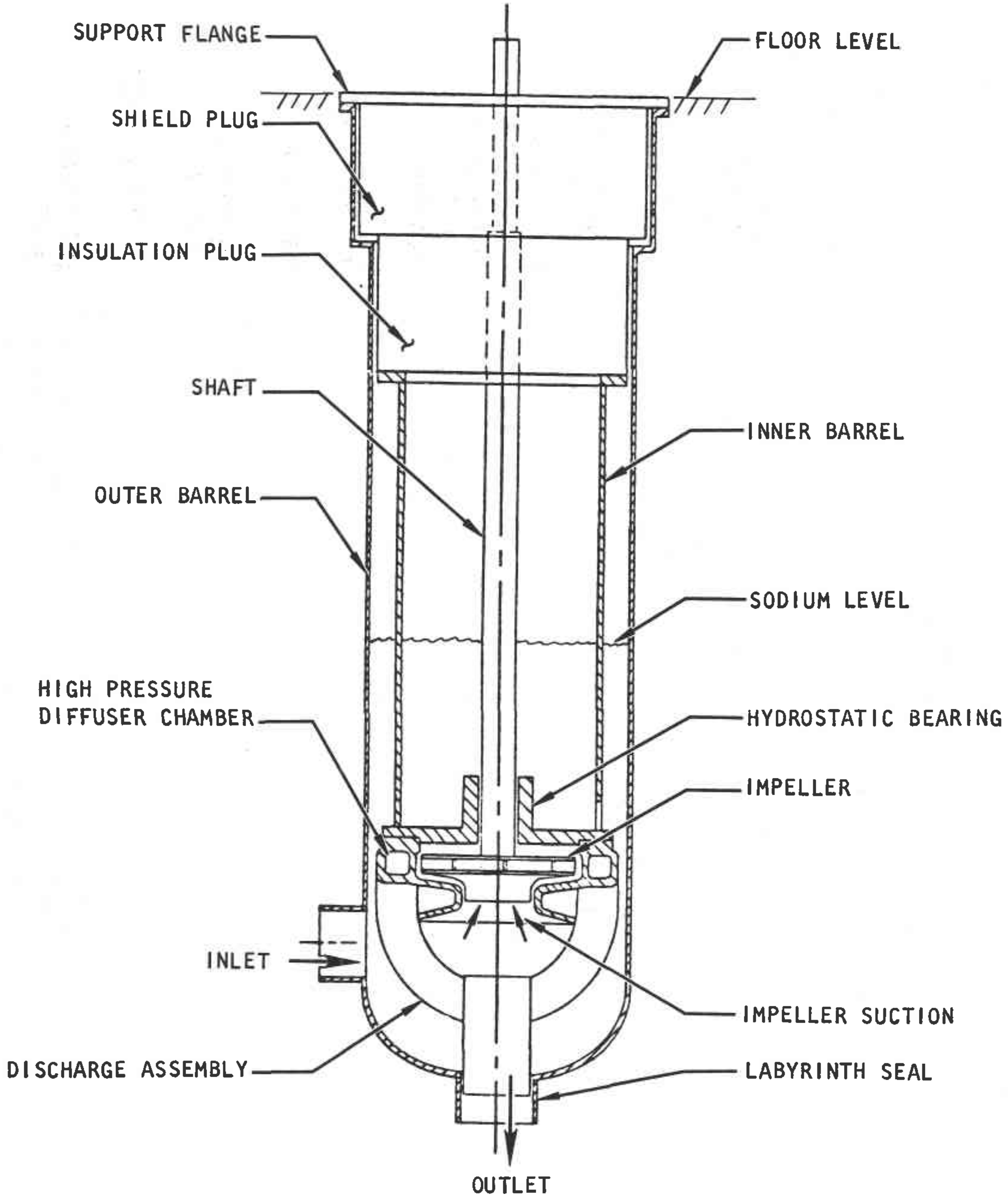
Gentlemen, this concludes the formal part of the presentation on sodium components. If there are any questions, I will be here to answer those that I can. I wish to thank you for your kind attention, and good day.

RECOMMENDED PUMP/DRIVE CONCEPT



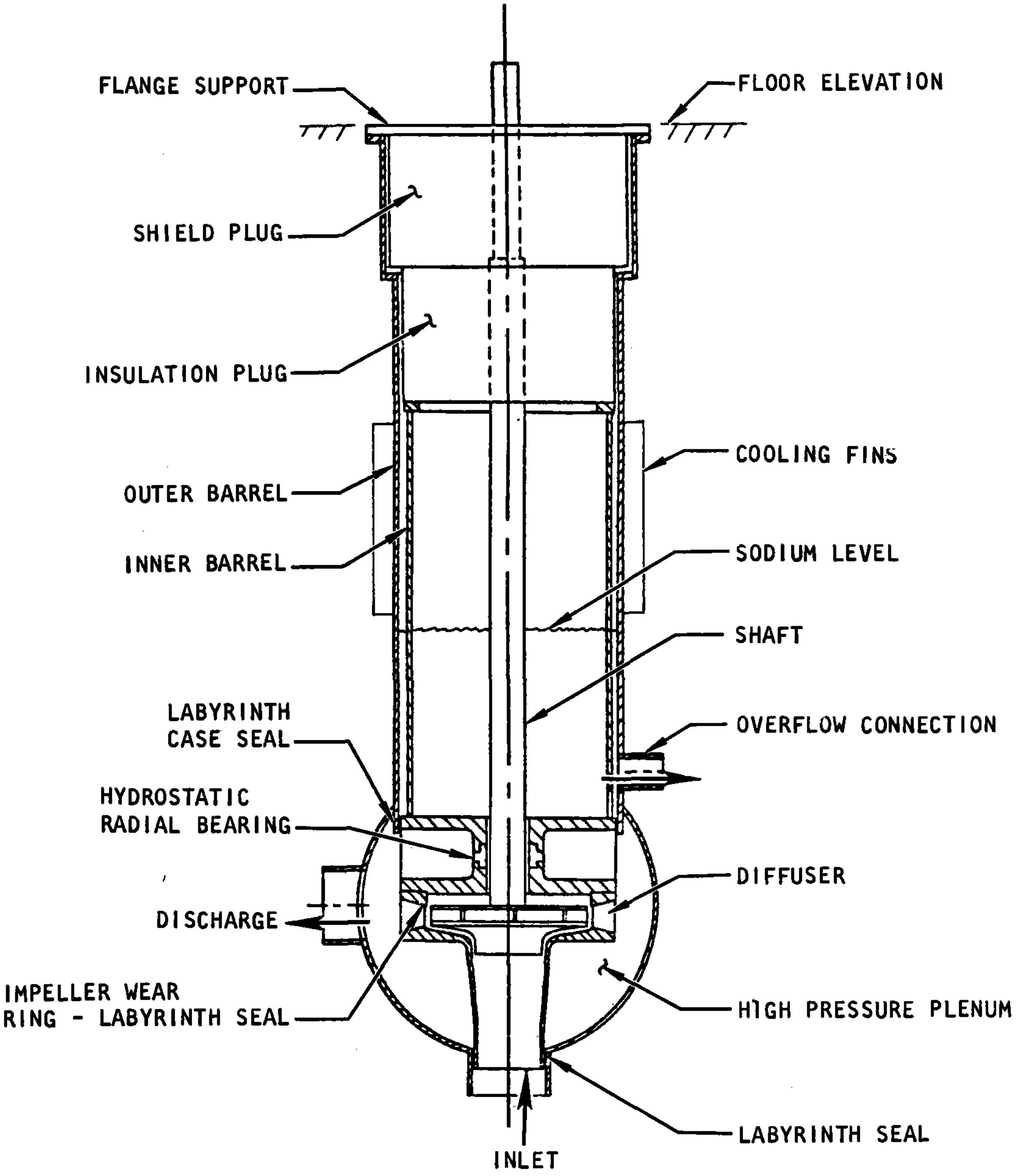
70-MA1-48-200

BASIC EFFBR TYPE PUMP



70-MA1-48-202

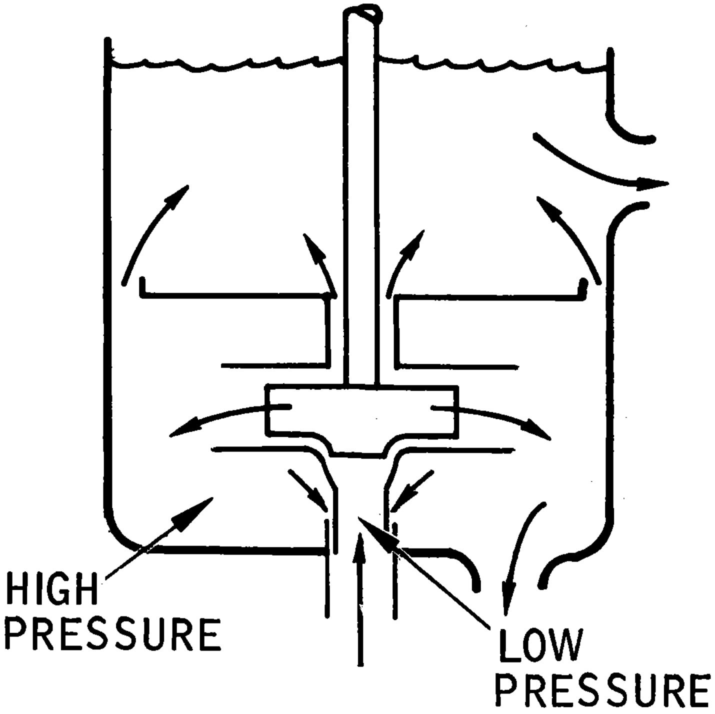
HNPF TYPE PUMP



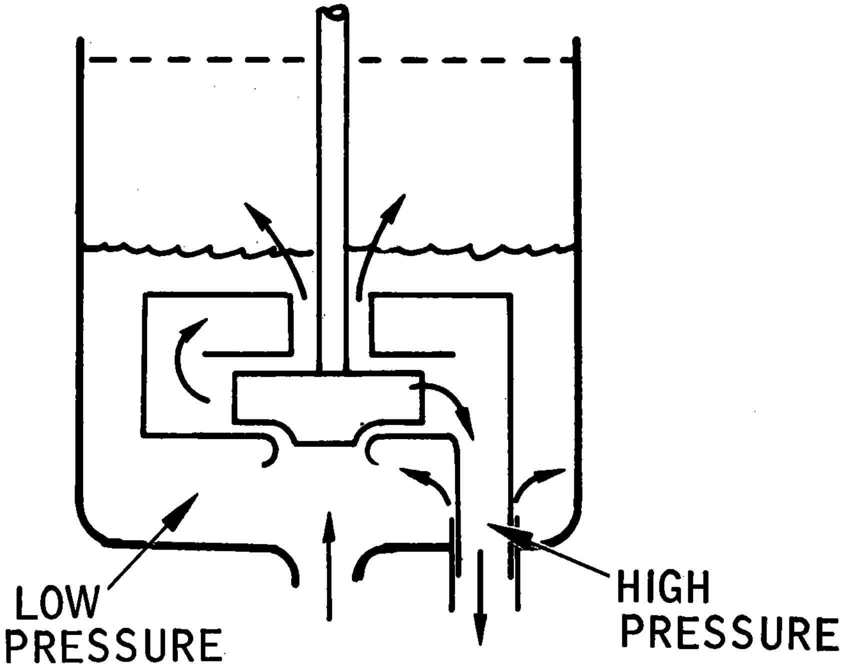
70-MA1-48-203

KEY DIFFERENCES

FERMI-HALLAM PRIMARY PUMPS



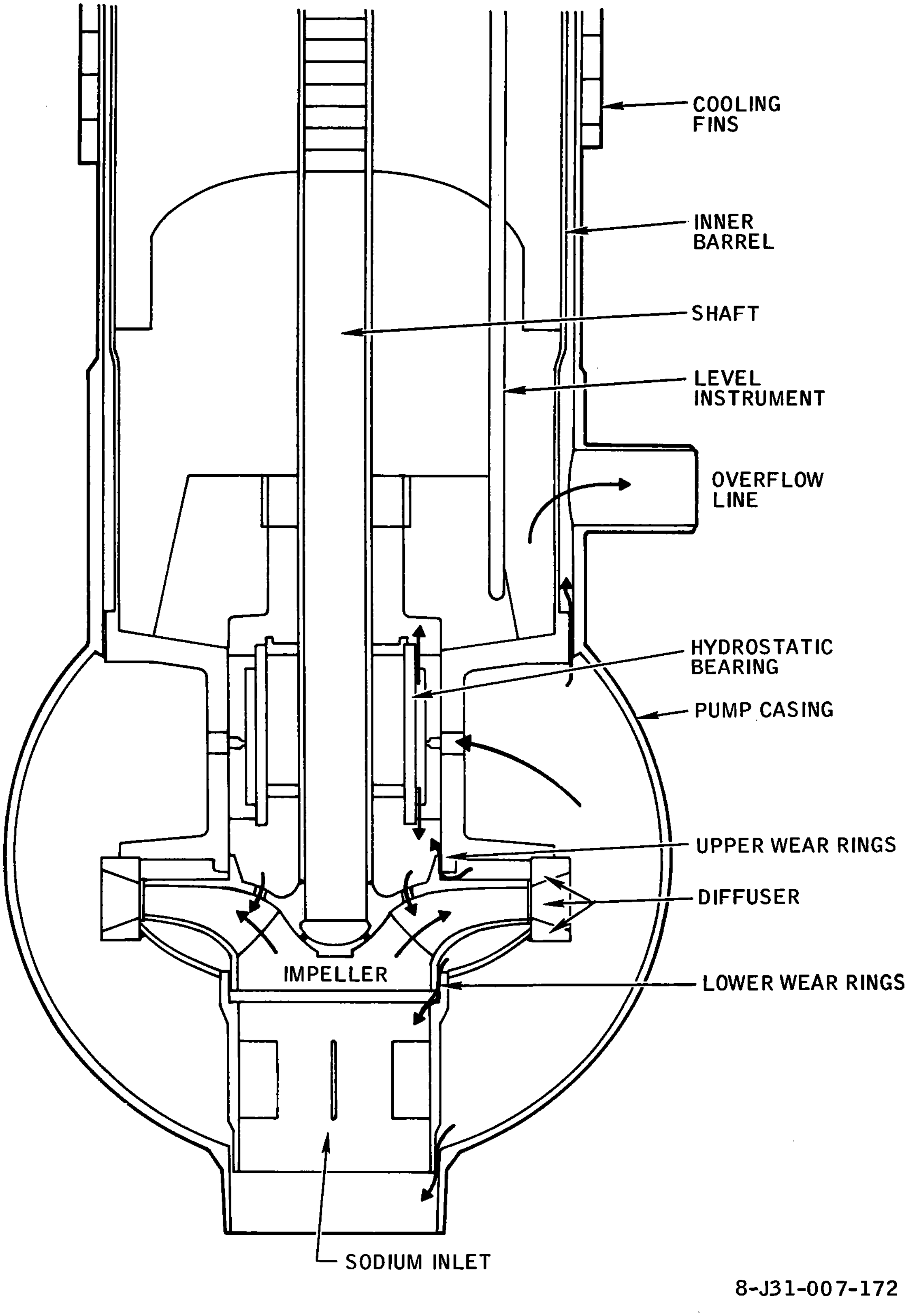
"HALLAM"



"FERMI"

70-F16-015-10

HNPF PUMP



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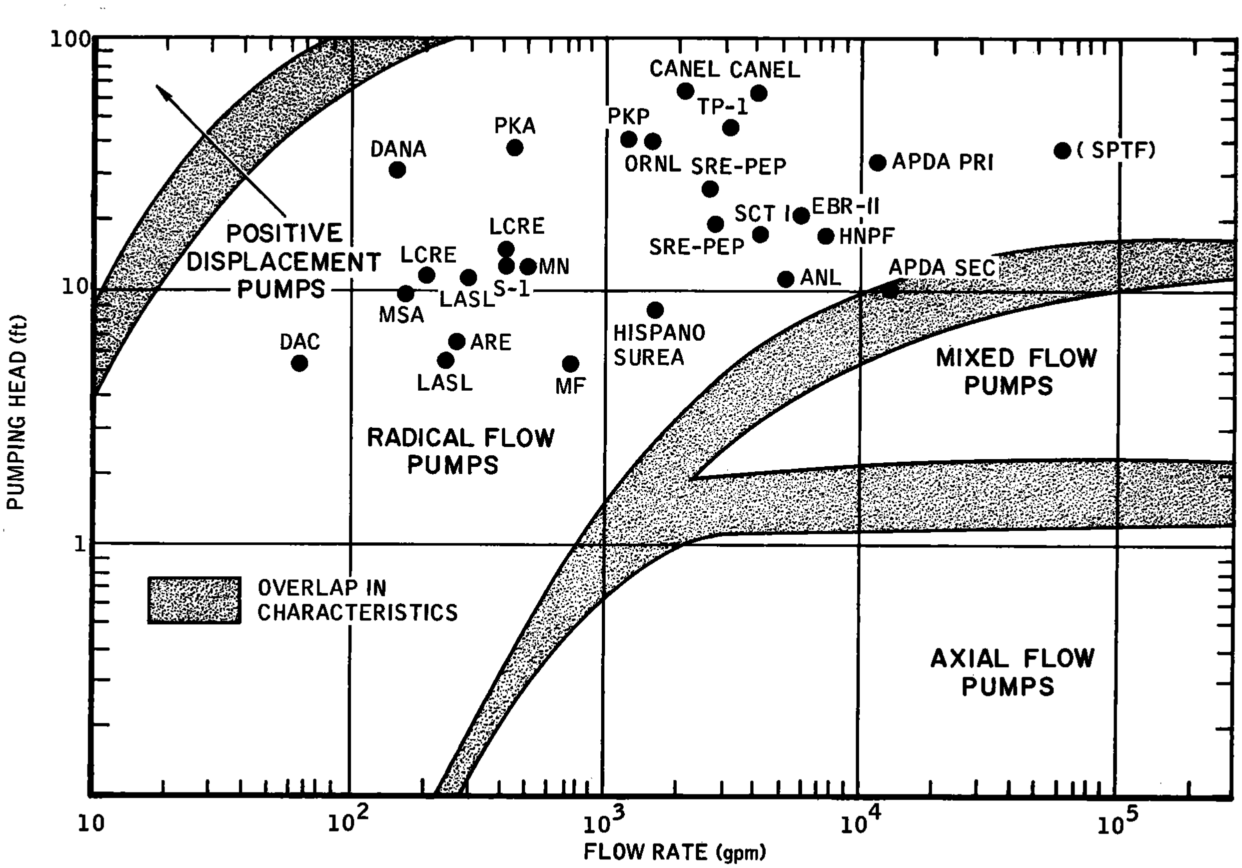

100
10
1
PUMPING HEAD (ft)
10
10^2
10^3
10^4
10^5
FLOW RATE (gpm)
POSITIVE
DISPLACEMENT
PUMPS
RADICAL FLOW
PUMPS
MIXED FLOW
PUMPS
AXIAL FLOW
PUMPS
OVERLAP IN
CHARACTERISTICS
CANEL
CANEL
TP-1
PKP
PKA
DANA
ORNL
SRE-PEP
APDA PRI
(SPTF)
SCT I
EBR-II
HNPF
SRE-PEP
LCRE
LCRE
MN
S-1
LASL
MSA
ANL
APDA SEC
HISPANO
SUREA
DAC
ARE
LASL
MF

7-7694-212-1

PUMP SELECTION

SUCTION SPECIFIC SPEED – N_s ~8000 AT 100% POWER

$$N_s = \frac{NQ^{1/2}}{(NPSH)^{3/4}}$$

N – rpm
Q – gpm

DISCHARGE SPECIFIC SPEED – N_d ~2000 AT 100% POWER

$$N_d = \frac{NQ^{1/2}}{(H)^{3/4}}$$

H – HEAD

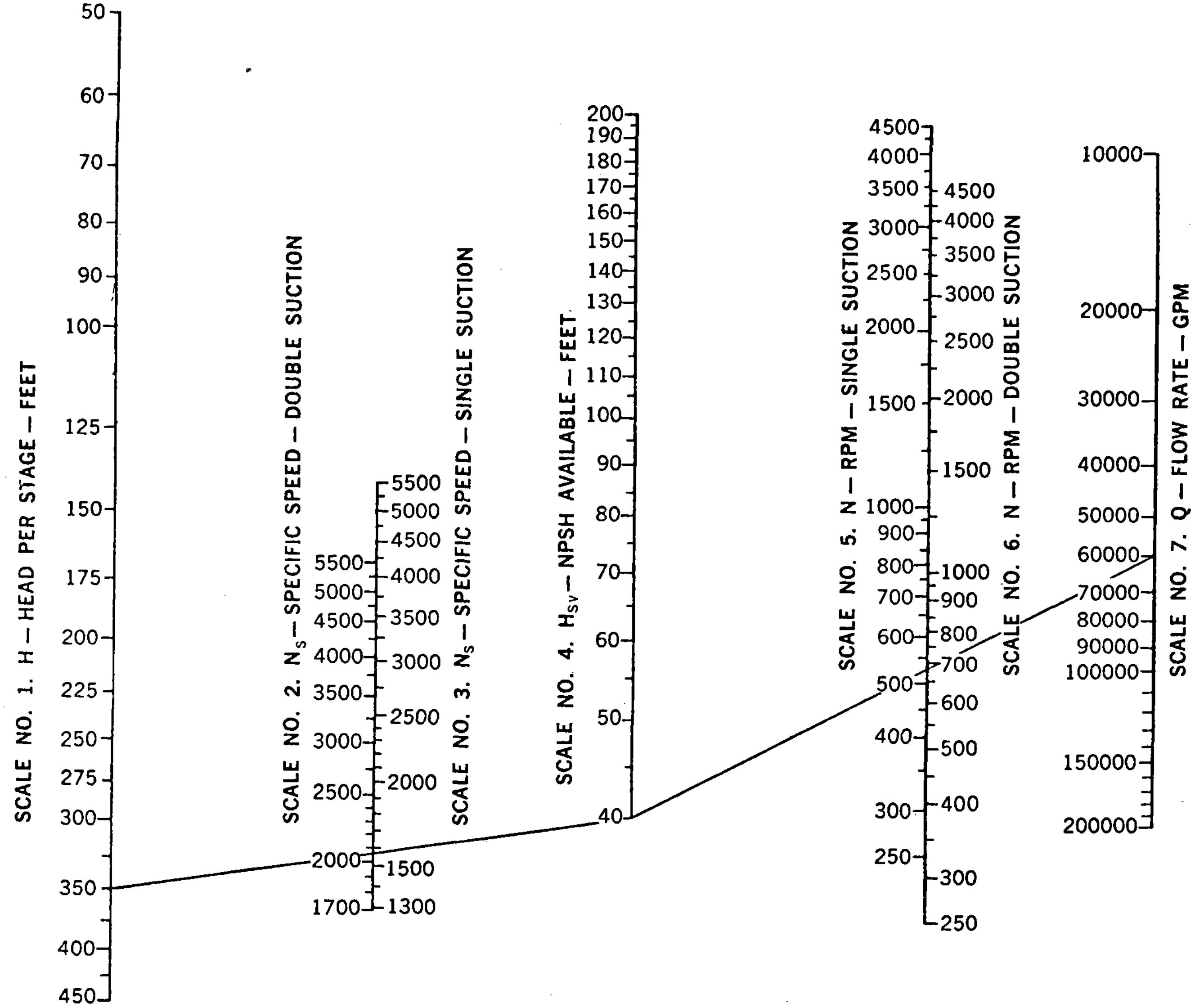
PUMP COST – C

$$\left(\frac{C_2}{C_1}\right) \cong \left(\frac{Q_2}{Q_1}\right) \left(\frac{H_2}{H_1}\right)^{1/25} \left(\frac{N_1}{N_2}\right)^{1/3}$$

70-F19-015-97

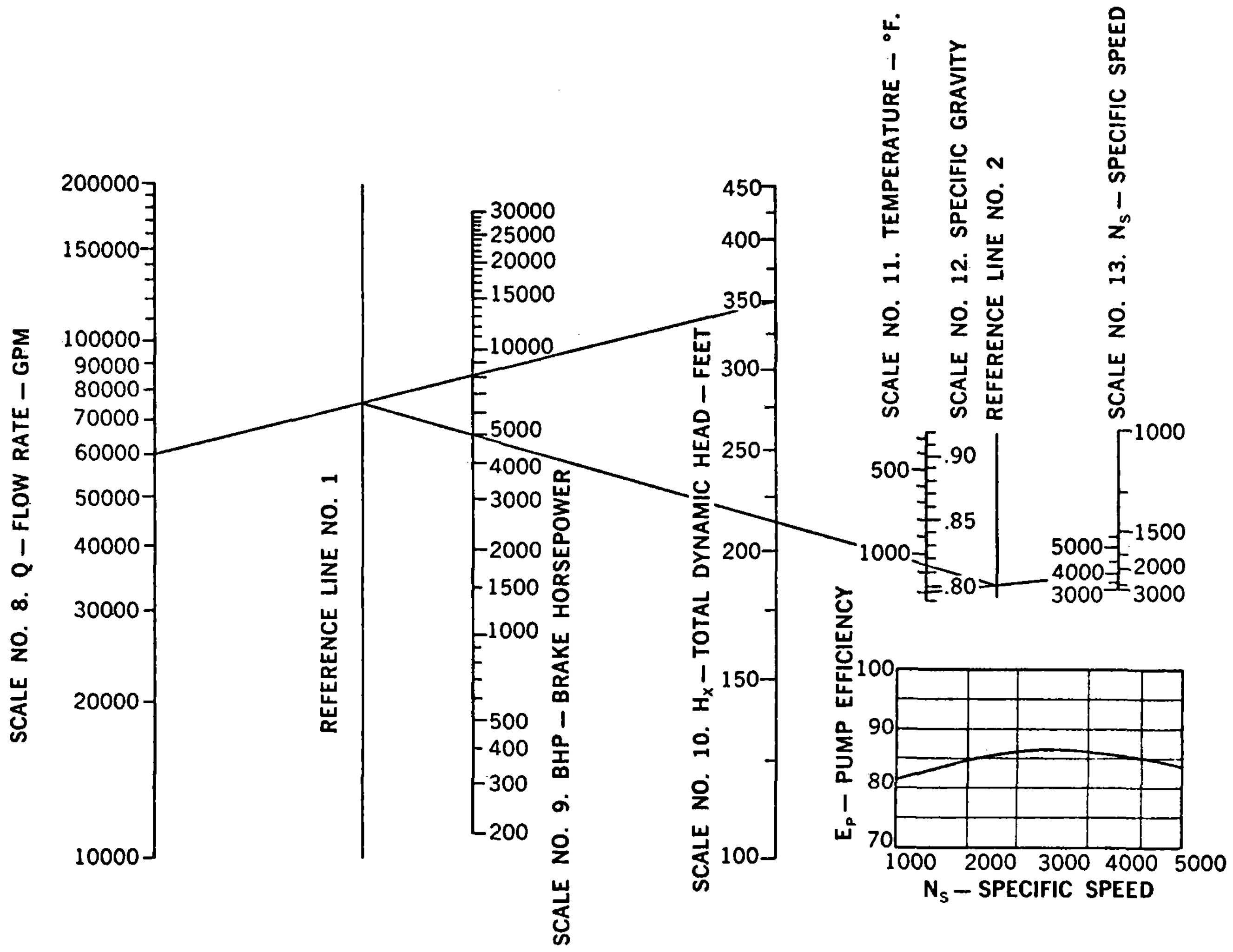
PUMP ROUGH SIZING CHARTS

1



70-MA1-48-205

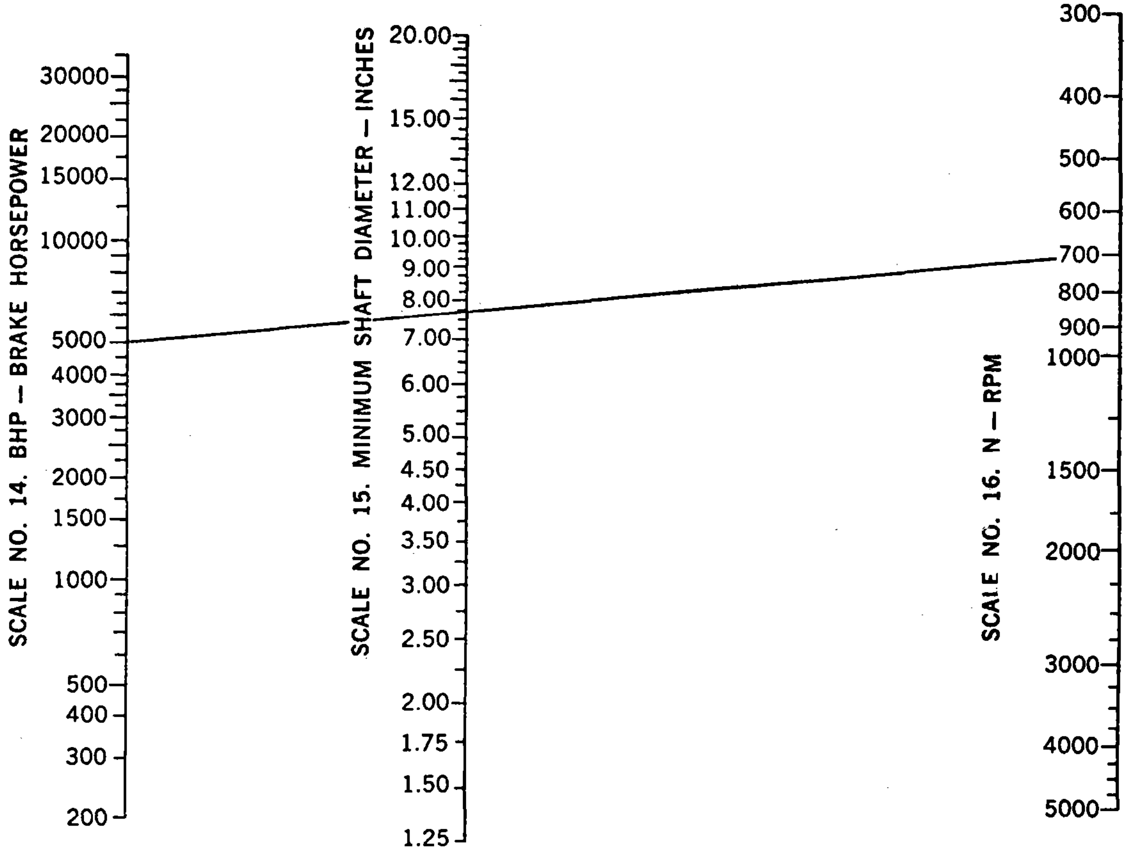
PUMP ROUGH SIZING CHARTS
2



70-MA19-48-157

PUMP ROUGH SIZING CHARTS

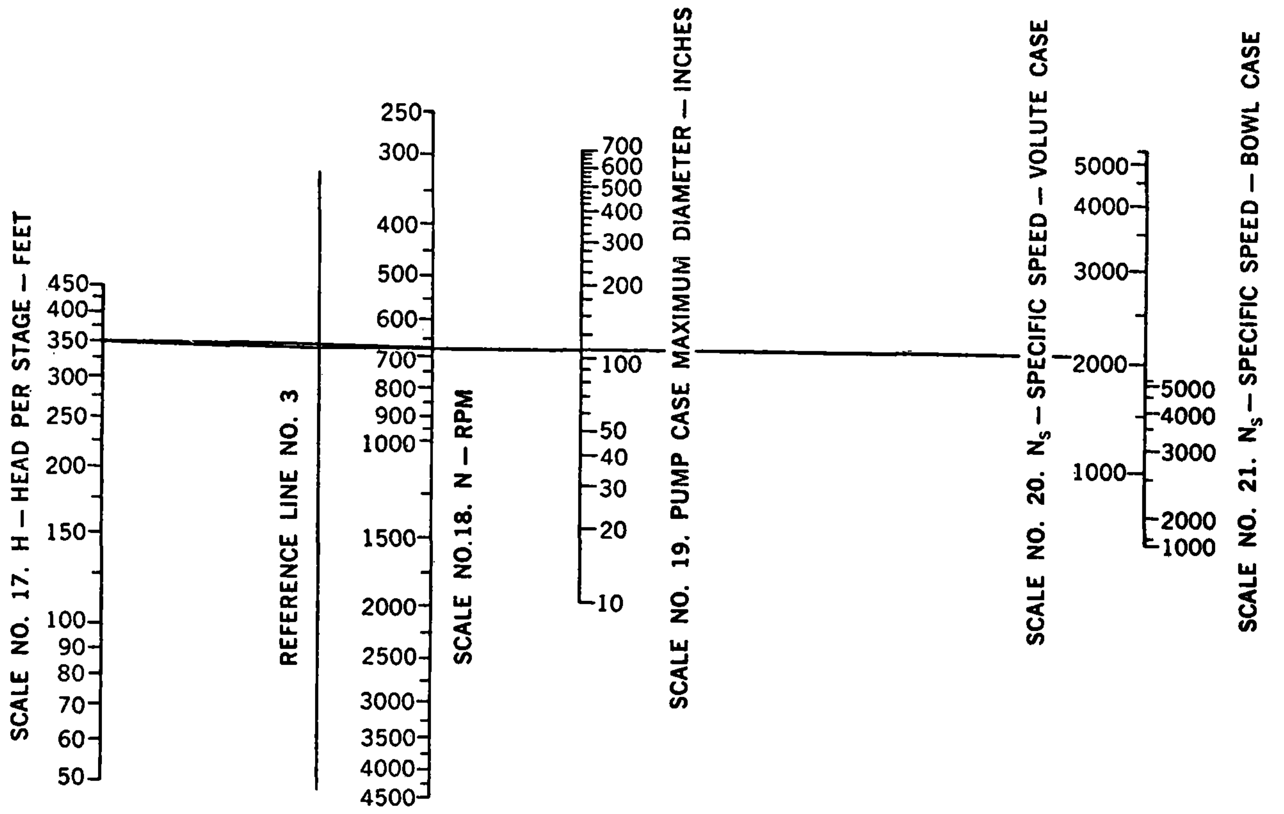
3



70-MA19-48-160

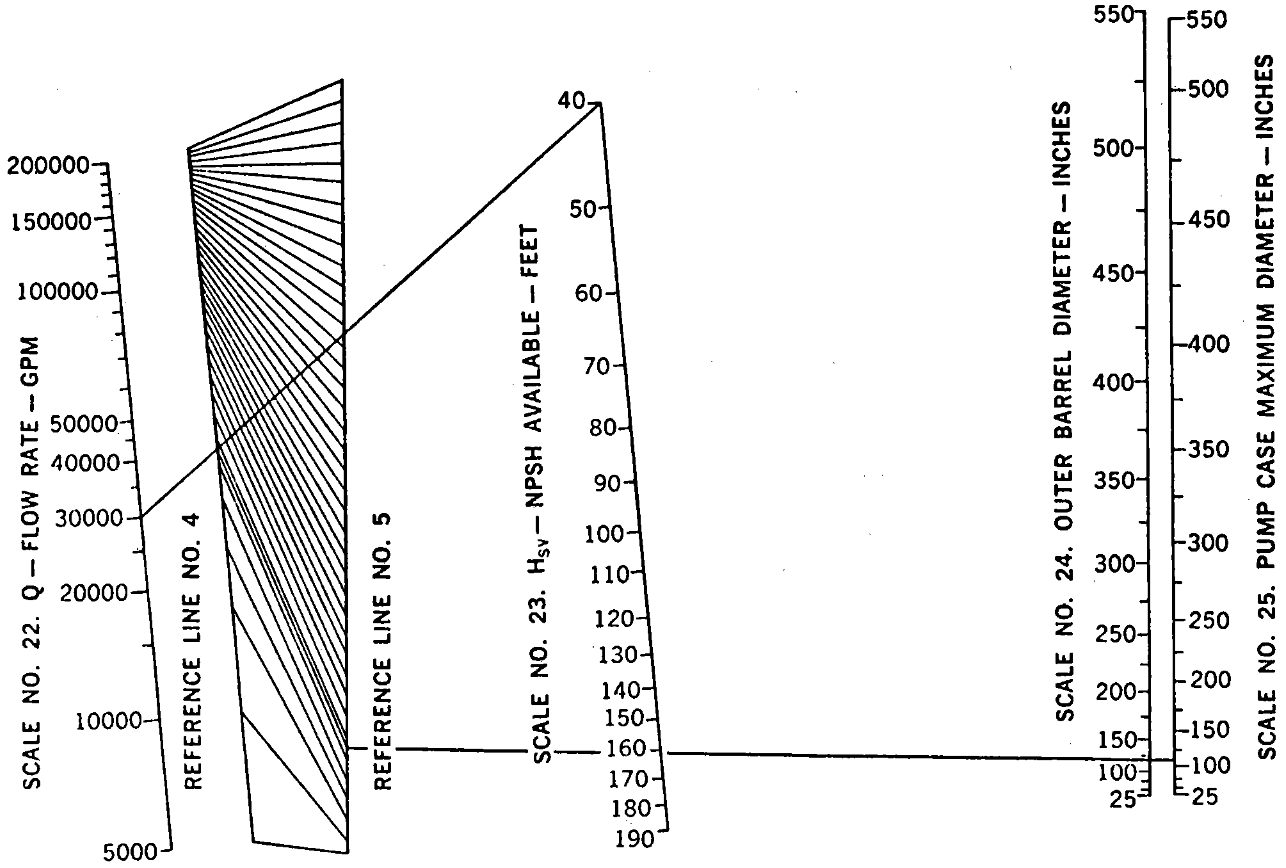
PUMP ROUGH SIZING CHARTS

4



70-MA19-48-156

PUMP ROUGH SIZING CHART
5



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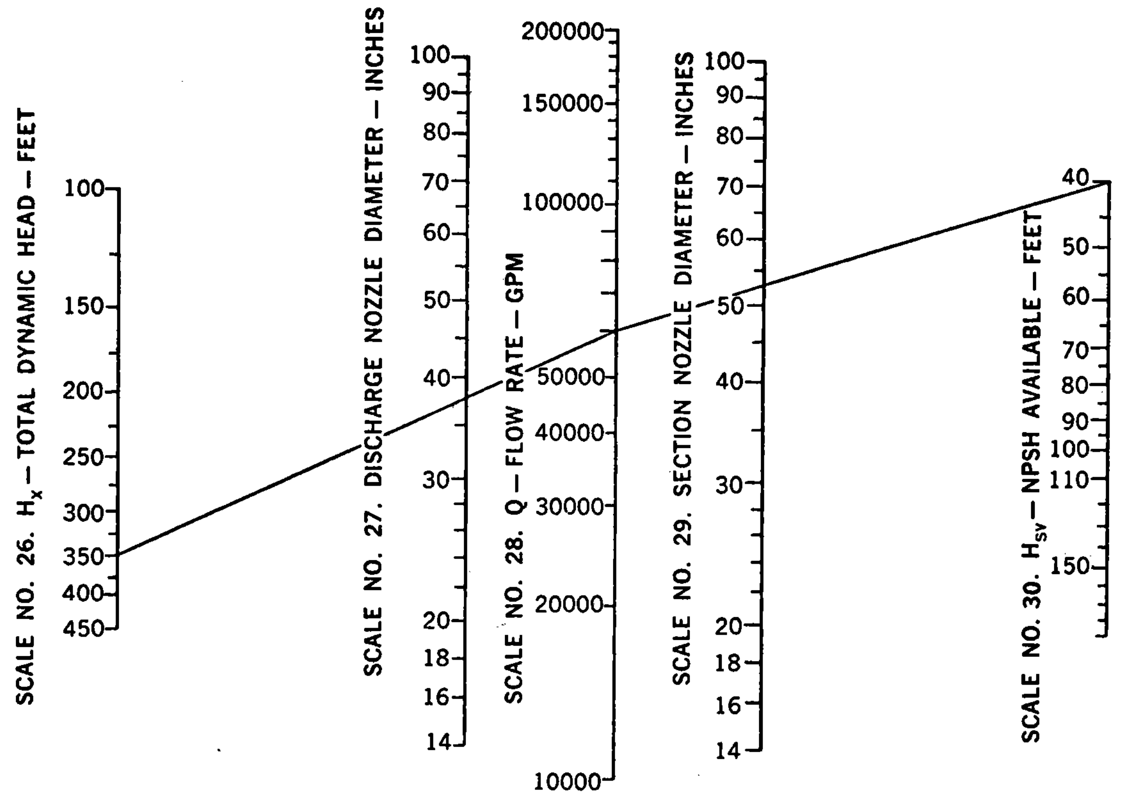
PUMP ROUGH SIZING CHARTS

6



70-MA19-48-155

TRADE STUDY— FBR LOCATION
ARGUMENT FOR HOT LEG

- LESS NPSH REQUIREMENT – SMALLER PUMPS
- SMALLER PIPING – LESS BUILDING SPACE
- LESS INERTIA – LOSS OF COOLANT
- HIGHER VELOCITIES IN IHX
- SMALLER IHX – LESS COSTLY
- LESS GAS LEAKAGE THROUGH REACTOR COVER
- LESS GAS ENTRIANMENT – LOWER PRESSURE
- OVERALL ECONOMIC ADVANTAGE

70-MA1-48-292

PUMP LOCATION CHOICES OF OTHERS

FACILITY	HOT LEG	COLD LEG
SRE	X	
HNPF	X	
FERMI		X
EBR II		X
DFR		X
PFR		X
RAPSODIE		X
PHENIX		X
BN 350		X
SEFOR		X
FARET		X
JAERI		X
Na-2	X	
US STUDIES		
AI	X	
GE		X
W		X
B&W	X	
CE	X	

70-MA1-48-127

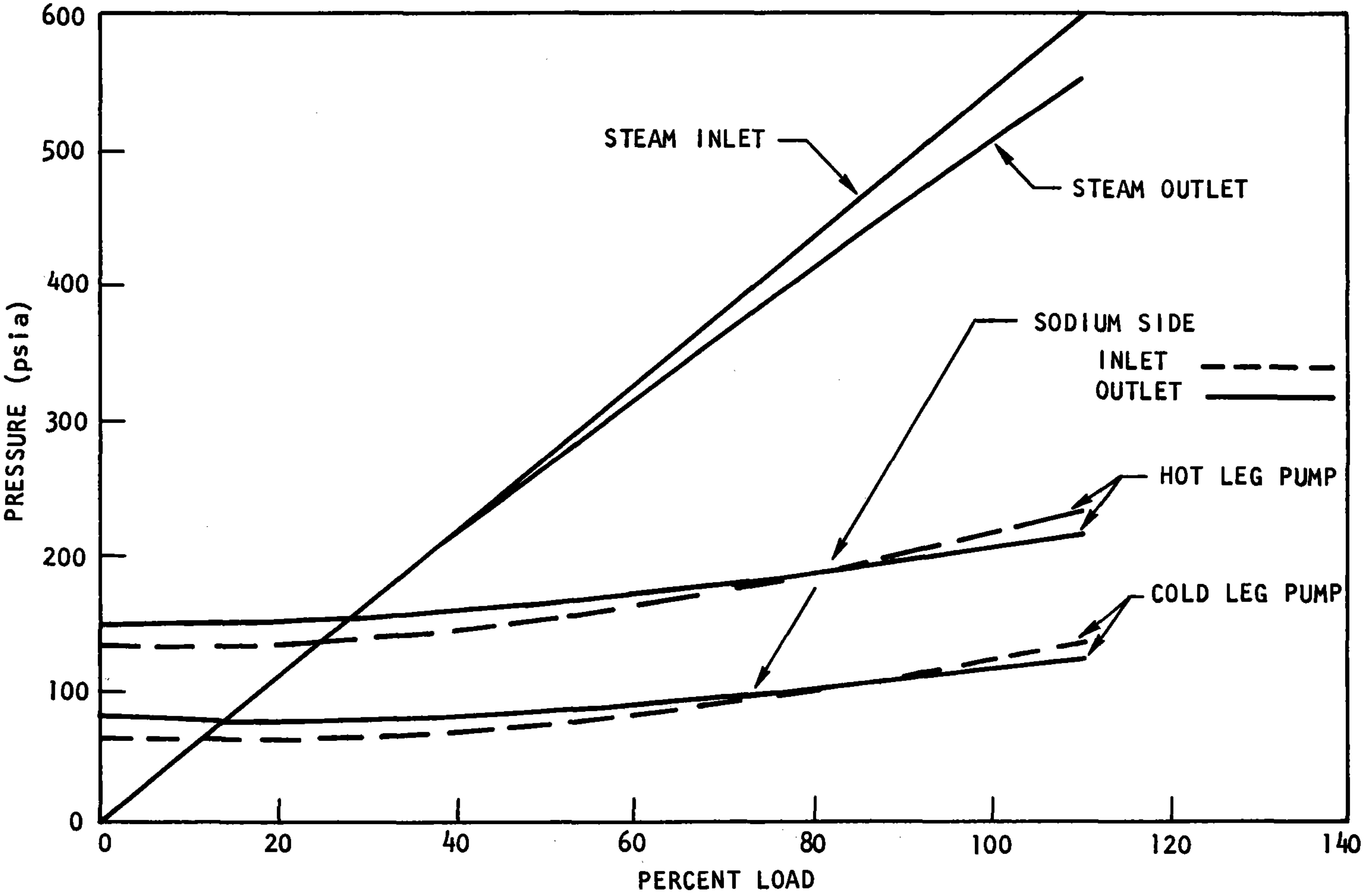
SECONDARY PUMP

HOT LEG VS COLD LEG LOCATION

HOT LEG		COLD LEG	
PRO	CON	PRO	CON
• NO ADDITIONAL PIPING TO LOCATE AT LOOP HIGH POINT	• HIGHER COVER GAS OPERATING PRESSURE	• LOWER COVER GAS OPERATING PRESSURE	• SOME ADDITIONAL PIPING TO LOCATE AT LOOP HIGH POINT
	• HIGHER SODIUM PRESSURES THROUGHOUT LOOP	• LOWER SODIUM PRESSURES THROUGHOUT LOOP	• GREATER POSSIBILITY OF CONTAMINATING PUMP WITH Na/H_2O REACITON PRODUCTS AFTER A STEAM GENERATOR LEAK
	• HIGHER OPERATING TEMPERATURES	• LOWER OPERATING TEMPERATURES	
	• HIGHER PUMPING COSTS	• LOWER PUMPING COSTS	

RECOMMENDATION: LOCATE PUMP IN COLD LEG

SODIUM/STEAM PRESSURES IN REHEATER



70-MA1-48-116

CHARACTERISTICS OF SODIUM PUMPS

PRIMARY SYSTEM PUMPS	HALLAM	EBR-2	ENRICO FERMI	500 MWe FBR	P.F.R.	ANL 1000 MWe	FFTF 400 MWt
DESIGN TYPE	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE-SURFACE
NUMBER OF UNITS	2	2	3	3	3	3	4
CAPACITY, GPM	7200	5500	38,500	38,500	21,100	62,500	11,750
DYNAMIC HEAD, FT.	160	200	310	379	333	375	385
DESIGN TEMP., °F	1000	800	1000	1100	752	1175	800
MOTOR SPEED, RPM	900	1075	900	600	960	520	870
MOTOR POWER, HP	350	350	1060	4000	200	6000	1300
SEALING ARRANGEMENT	MECHANICAL SHAFT SEAL	HERMETICALLY SEALED DRIVE MOTOR	MECHANICAL SHAFT SEAL	MECHANICAL SHAFT SEAL	MECHANICAL SHAFT SEAL	MECHAICAL SHAFT SEAL	MECHANICAL SHAFT SEAL
MATERIAL	304 SS	304 SS	304 SS	304 SS			
TYPE OF SPEED CONTROL	EDDY CURRENT COUPLING	VARIABLE FREQ. AND VOLTAGE	WOUND ROTOR MOTOR W/LIQUID RHEOSTAT	EDDY CURRENT COUPLING	HYDRAULIC COUPLING	WR/DC	EDDY CURRENT COUPLING

SECONDARY SYSTEM PUMPS	HALLAM	EBR-2	ENRICO FERMI	500 MWe FBR	P.F.R.	ANL 1000 MWe	FFTF 400 MWt
DESIGN TYPE	CENTRIFUGAL FREE-SURFACE	A-C LINEAR INDUCTION	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE SURFACE	CENTRIFUGAL FREE-SURFACE	CENTRIFUGAL FREE-SURFACE
NUMBER OF UNITS	3	1	3	3	3	3	4
CAPACITY, GPM	7200	6500	13,000	45,300	20,400	55,200	11,450
DYNAMIC HEAD, FT.	170	142	100	226	159	250	222
DESIGN TEMP., °F	1000	700	1000	965	752	1085	675
MOTOR SPEED, RPM	900	1180 (MG SET)	900	850	960	870	800
MOTOR POWER, HP	350	500 (MG SET)	350	3000	750	3500	745
SEALING ARRANGEMENT	MECHANICAL SHAFT SEAL	TOTAL METAL ENCLOSURE	MECHANICAL SHAFT SEAL	MECHANICAL SHAFT SEAL	MECHANICAL SHAFT SEAL	MECHANICAL SHAFT SEAL	MECHAICAL SHAFT SEAL
MATERIAL	304 SS	304 SS	2-1/4% Cr - 1% Mo	304 SS			
TYPE OF SPEED CONTROL	EDDY CURRENT COUPLING	VARIABLE VOLTAGE (MG SET)	EDDY CURRENT COUPLING	EDDY CURRENT COUPLING	HYDRAULIC COUPLING	WR/DC	EDDY CURRENT COUPLING

PROTOTYPE FFTF PUMP FAB COMPLETE	JANUARY 71
PROTOTYPE DEMO PUMP FAB COMPLETE	JANUARY 72
500 FBR PUMP P.O.	JANUARY 71

FREE SURFACE SODIUM PUMPS

• CHARACTERISTICS	SRE	HNPF
▪ CAPACITY (gpm)	2,500	7,200
▪ DESIGN TEMPERATURE (°F)	1,200	1,000
▪ TOTAL DYNAMIC HEAD (ft)	145	160
▪ MOTOR HORSEPOWER	150	350
▪ HOURS OF OPERATION	14,000	9,000

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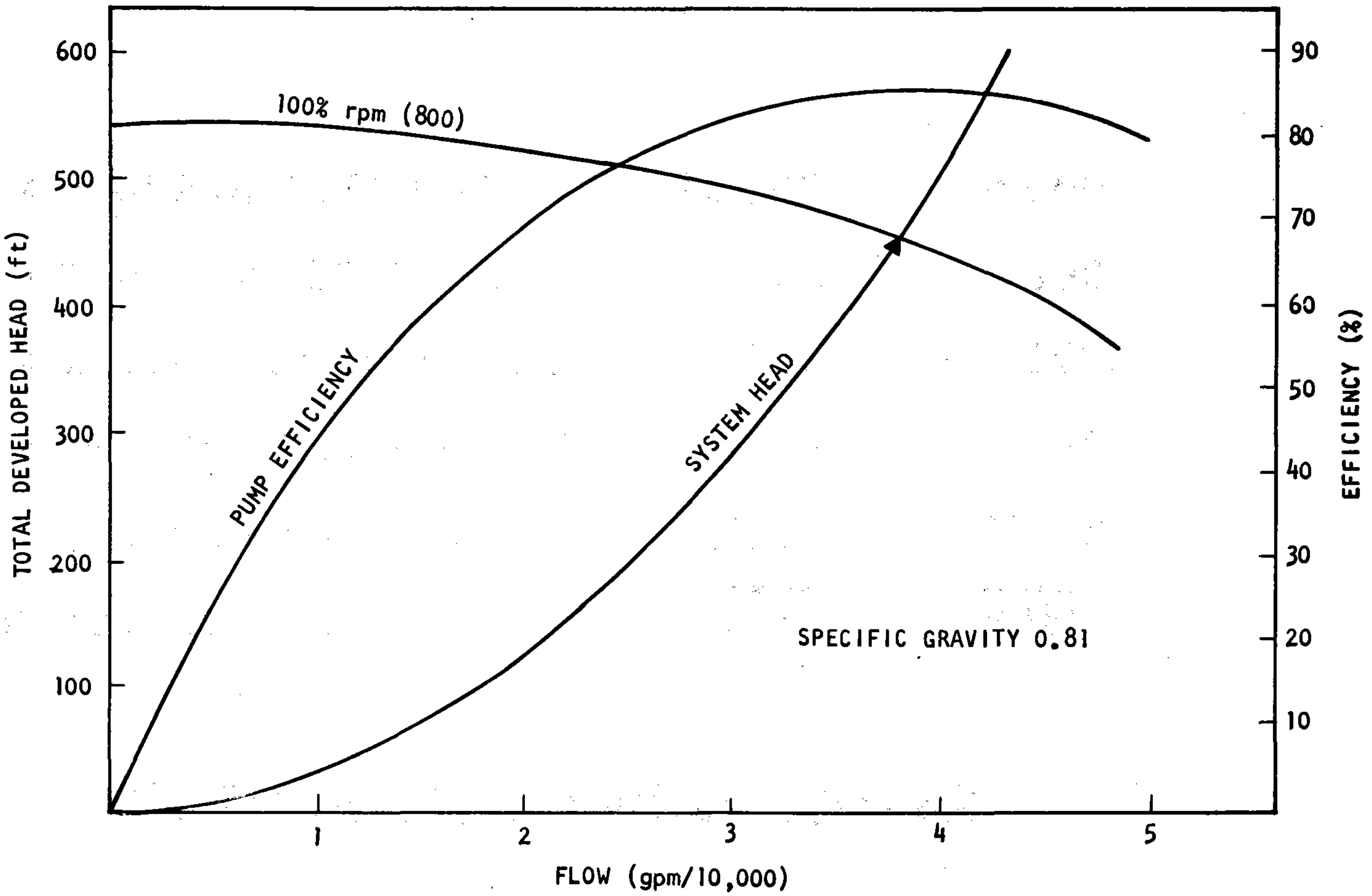
PRIMARY PUMP CHARACTERISTICS



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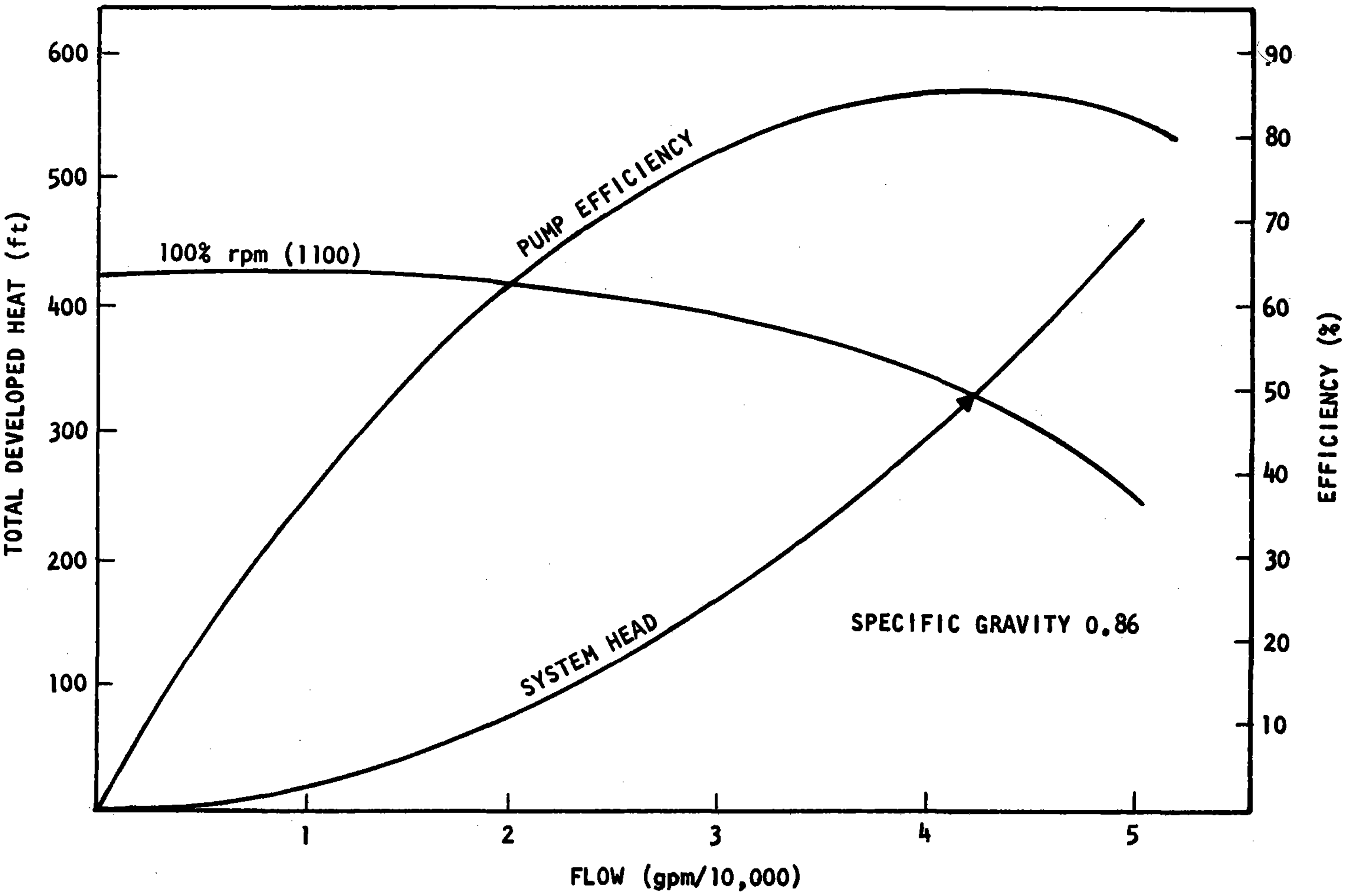
SECONDARY PUMP CHARACTERISTICS

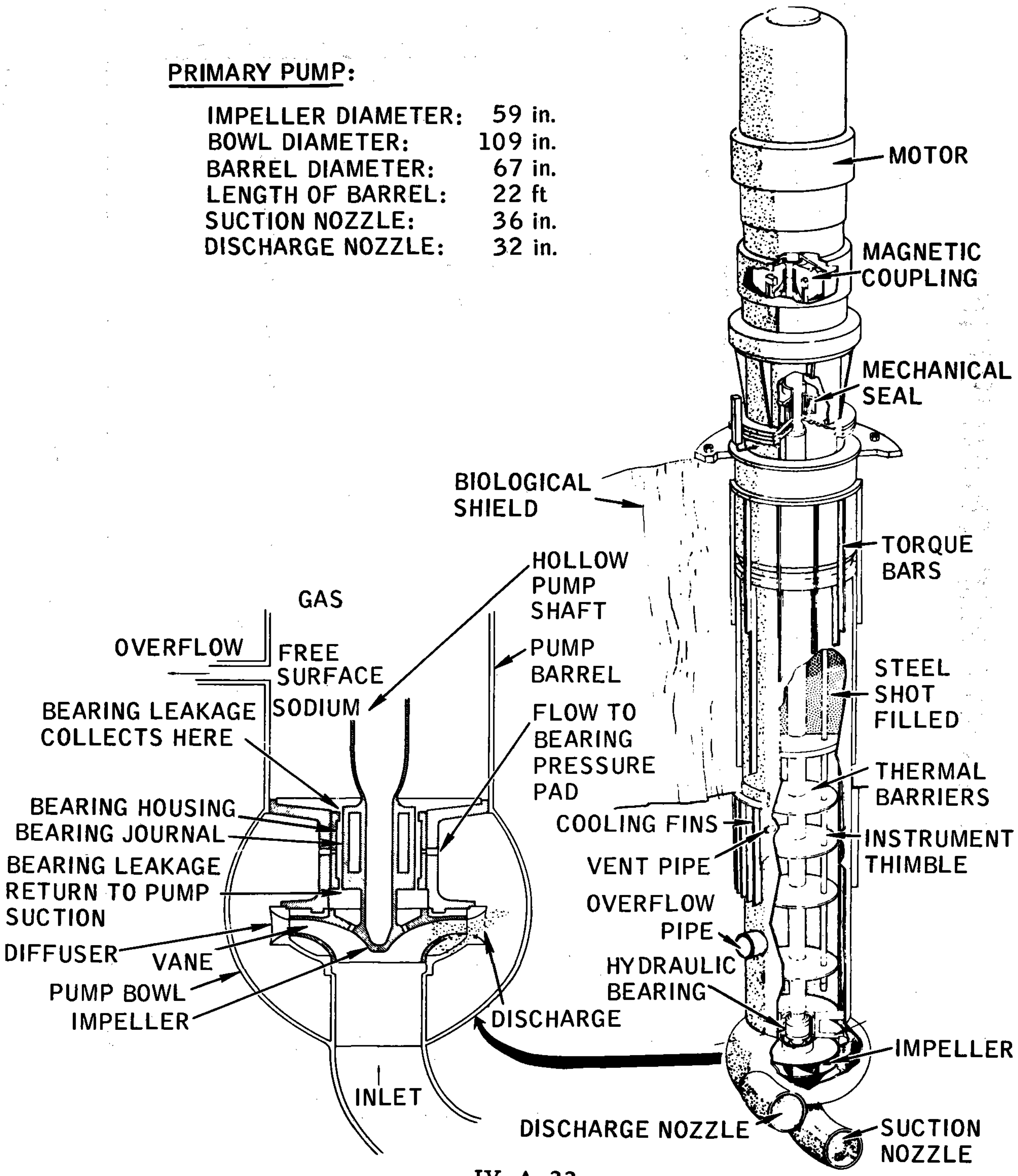


70-MA19-48-122

FREE-SURFACE SODIUM PUMP

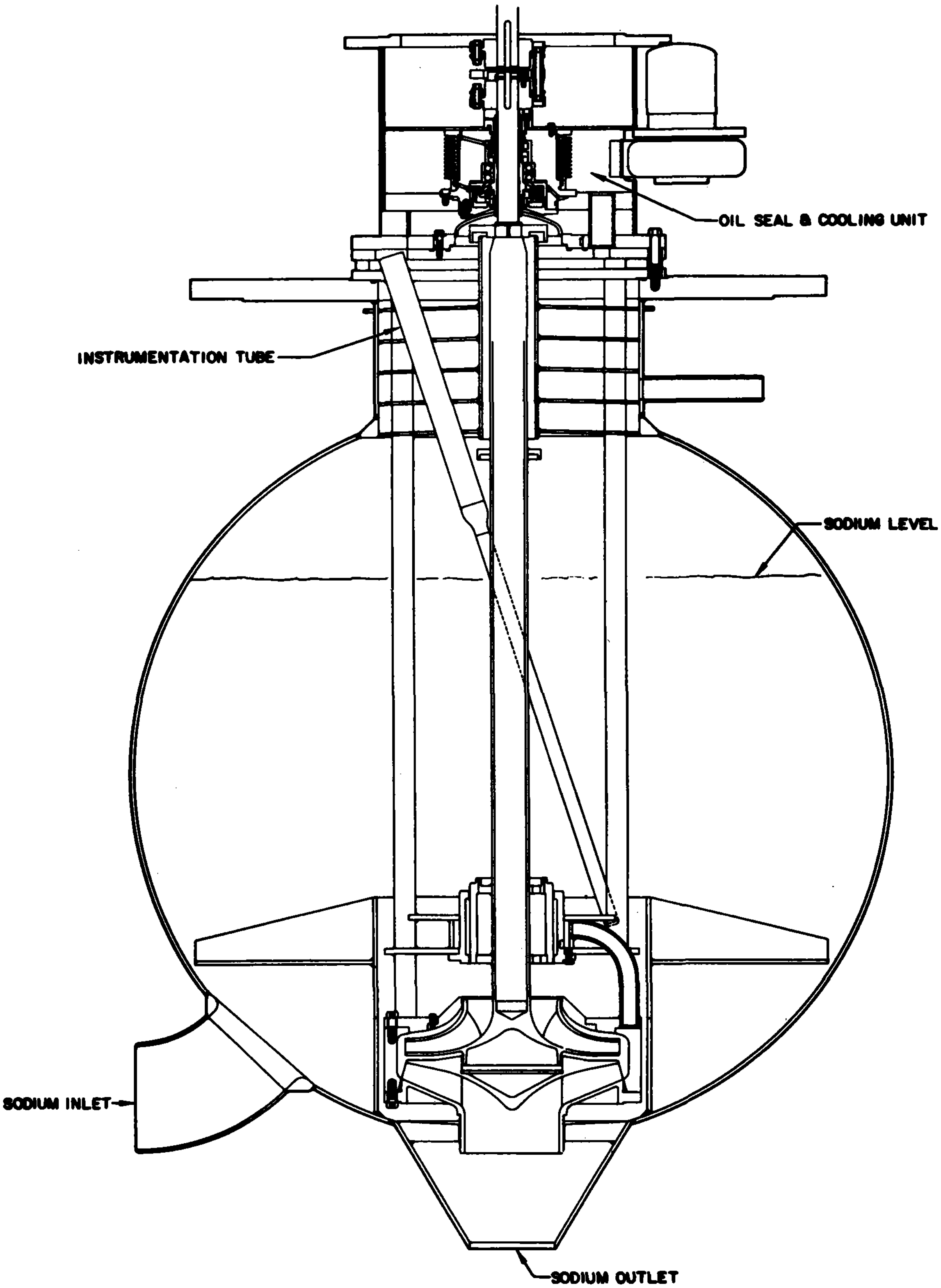
PRIMARY PUMP:

IMPELLER DIAMETER:	59 in.
BOWL DIAMETER:	109 in.
BARREL DIAMETER:	67 in.
LENGTH OF BARREL:	22 ft
SUCTION NOZZLE:	36 in.
DISCHARGE NOZZLE:	32 in.



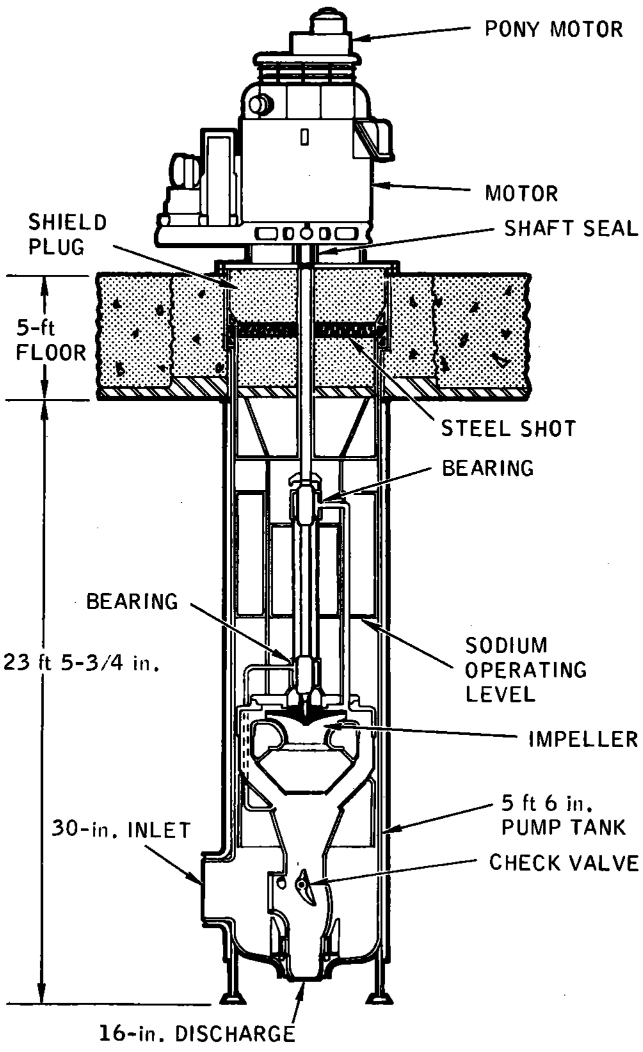
7-6095-132-11

SECONDARY SODIUM PUMP



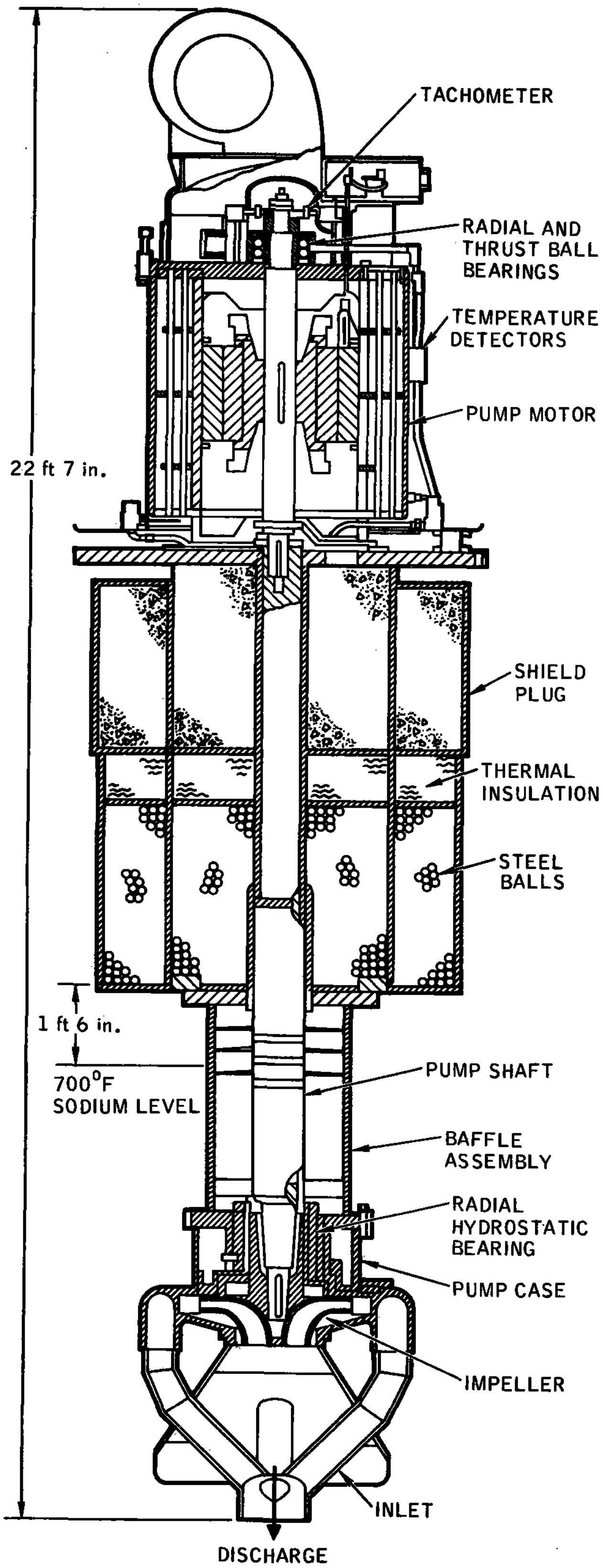
7599-5432

FERMI TYPE PUMP

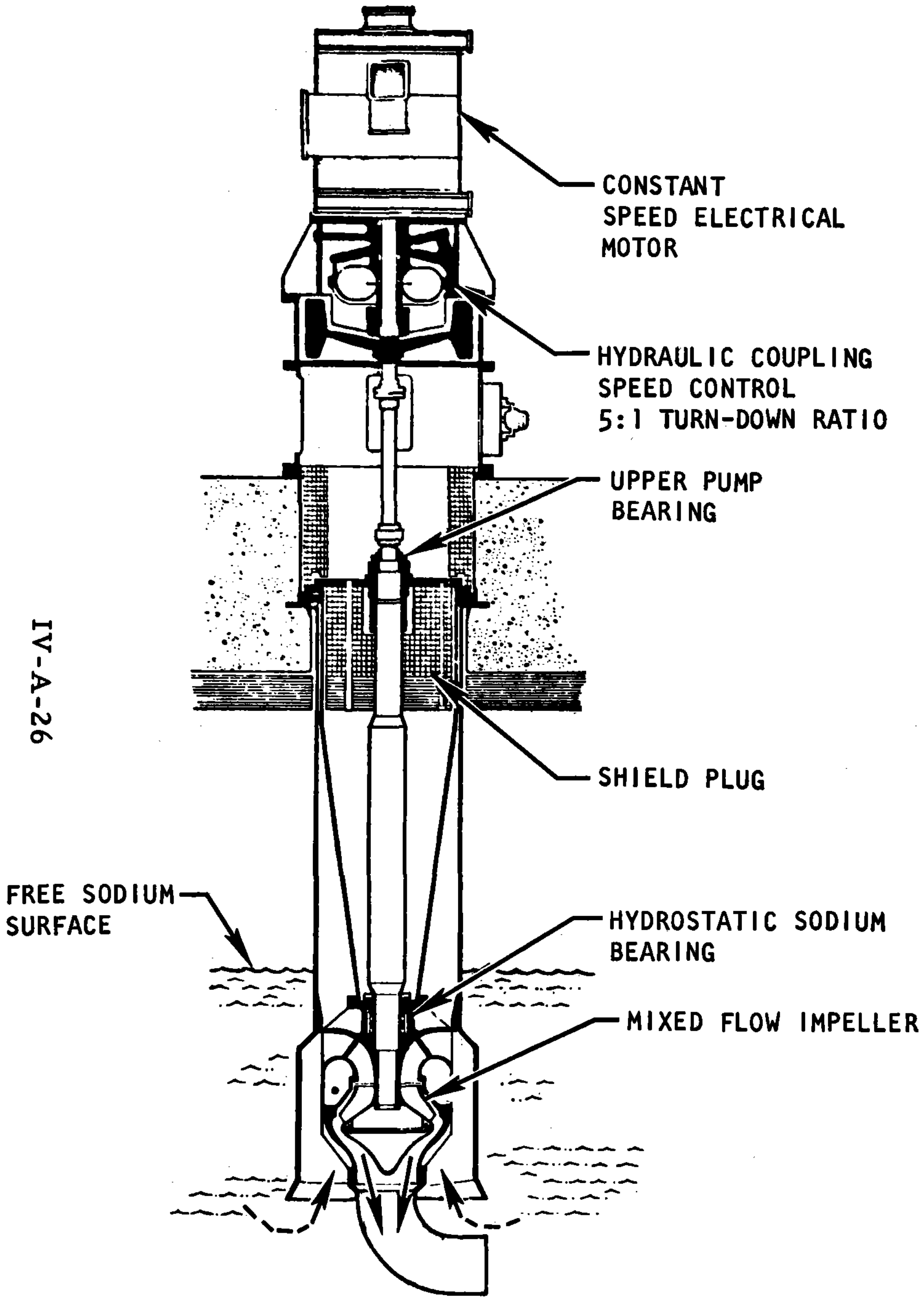


70-MA1-48-183

POT TYPE PUMP



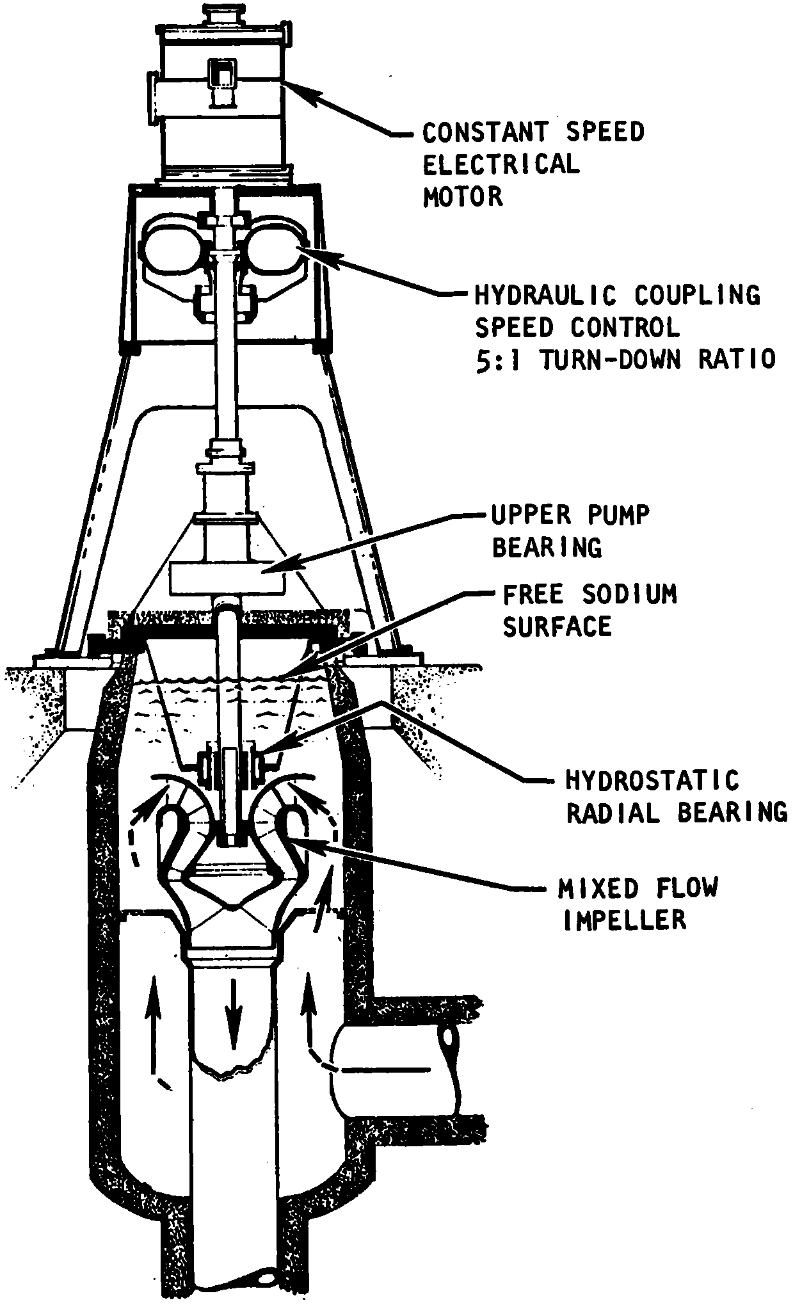
7-7694-212-7



PFR PRIMARY SODIUM PUMP

70-MA19-48-152

PFR SECONDARY SODIUM PUMP



70-MA1-48-204

OPERATING HISTORY

SYSTEM	MAXIMUM CAPACITY (gpm/ft-HEAD)	DESIGN TEMP (°F)	NUMBER OF UNITS PRIMARY/ SECONDARY	PUMP OPERATING HOURS TOTAL PROJECT	PRINCIPAL EXPERIENCE
FERMI	13,000/310	1000	3/1	94,000	SHAFT SEALS TIGHT CLEARANCES REVERSE THRUST LOAD
HALLAM	7,200/160	7000	3/3	117,000	PUMP FLOODING GAS ENTRAINMENT TIGHT CLEARANCES – THERMAL DISTORTION SHAFT SEALS
PFR	7,100/150	750	1	7,000	INCIPIENT CAVITATION
EBR II	5,500/200	800	2/0	40,000	TIGHT CLEARANCE THERMAL DISTORTION
SCT	3,200/235	1200	1	-	
SRE-PEP	2,700/180	1200	1/1	21,000	
RAPSODIE	1,650/105	1200	1	24,000	
FFTF	12,000/450	1200	-	-	
FBR					
(P)	42,200/550	1060	3	-	
(S)	47,200/374	700	3	-	

SRE PUMP PROBLEMS

- PROBLEM
  - GAS ENTRAINMENT IN OVERFLOW RETURN TO PUMP SUCTION THROUGH DIP LEG
- REASON
  - VELOCITY IN DIP LEG TOO HIGH TO PERMIT GAS SEPARATION IN DIP LEG
- CORRECTIVE ACTION
  - INSTALLED FLOW CONTROL VALVE BETWEEN DIP LEG AND PUMP SUCTION TO CONTROL RATE OF SODIUM FLOW TO PUMP SUCTION THEREBY REDUCING SODIUM VELOCITY

HALLAM PUMP PROBLEMS

- PROBLEM
  - GAS ENTRAINMENT AND THERMAL DISTORTION OF SECONDARY SODIUM PUMPS
- REASON
  - SODIUM VELOCITY IN SECONDARY EXPANSION TANK TOO HIGH AND HOLES ON BACK SIDE OF IMPELLER TO LARGE
  - FREE CONVECTION PATH OBSTRUCTED BY ADJACENT VENT PIPING
- CORRECTIVE ACTION
  - SEPARATED PUMP AND EXPANSION TANK SUCH THAT PUMP FLOW DID NOT GO THROUGH EXPANSION TANK AND PLUGGED HALF THE HOLES IN THE IMPELLER
  - INSTALLED FORCED CONVECTION COOLING AROUND PUMP BARREL

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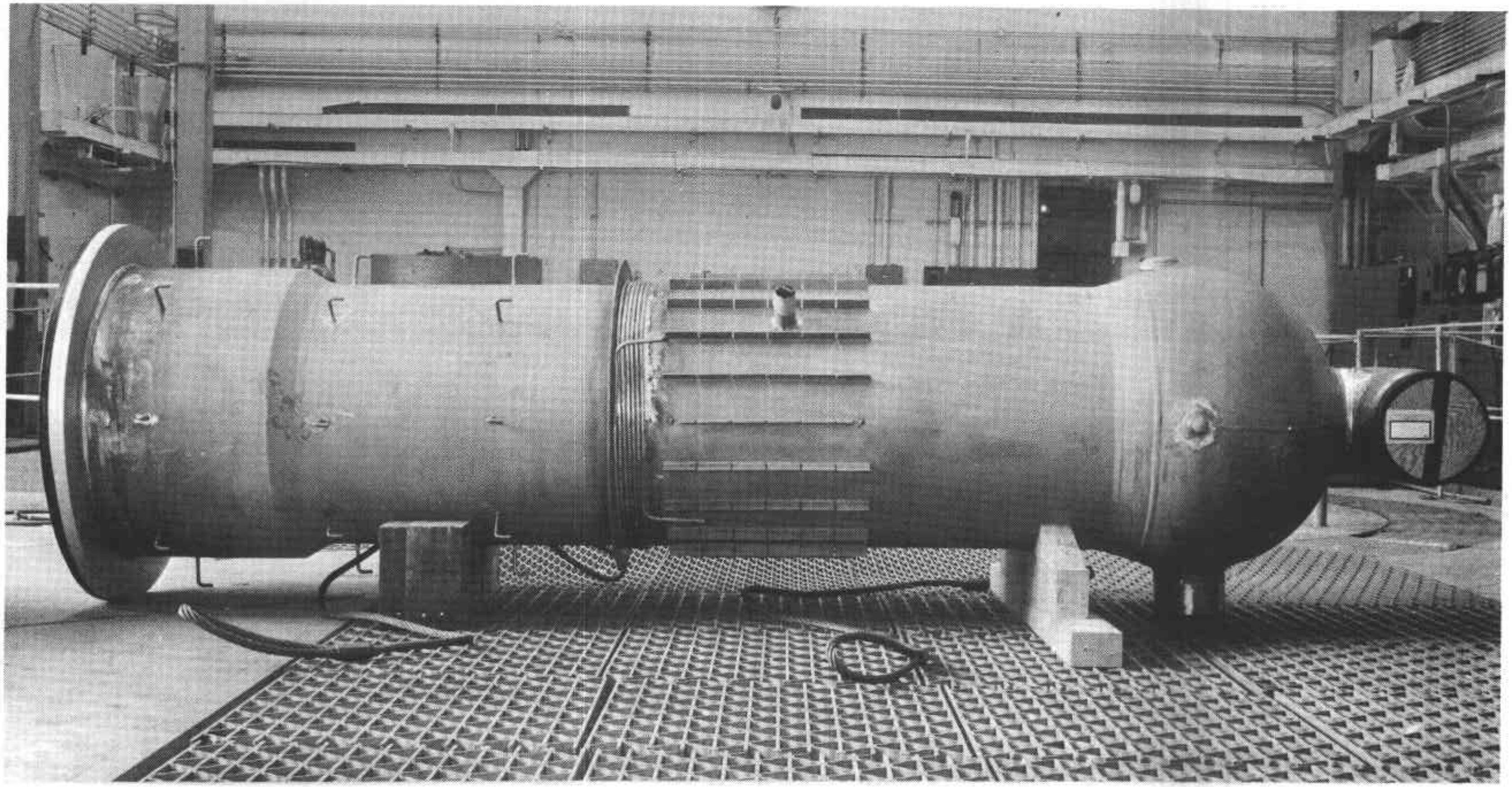
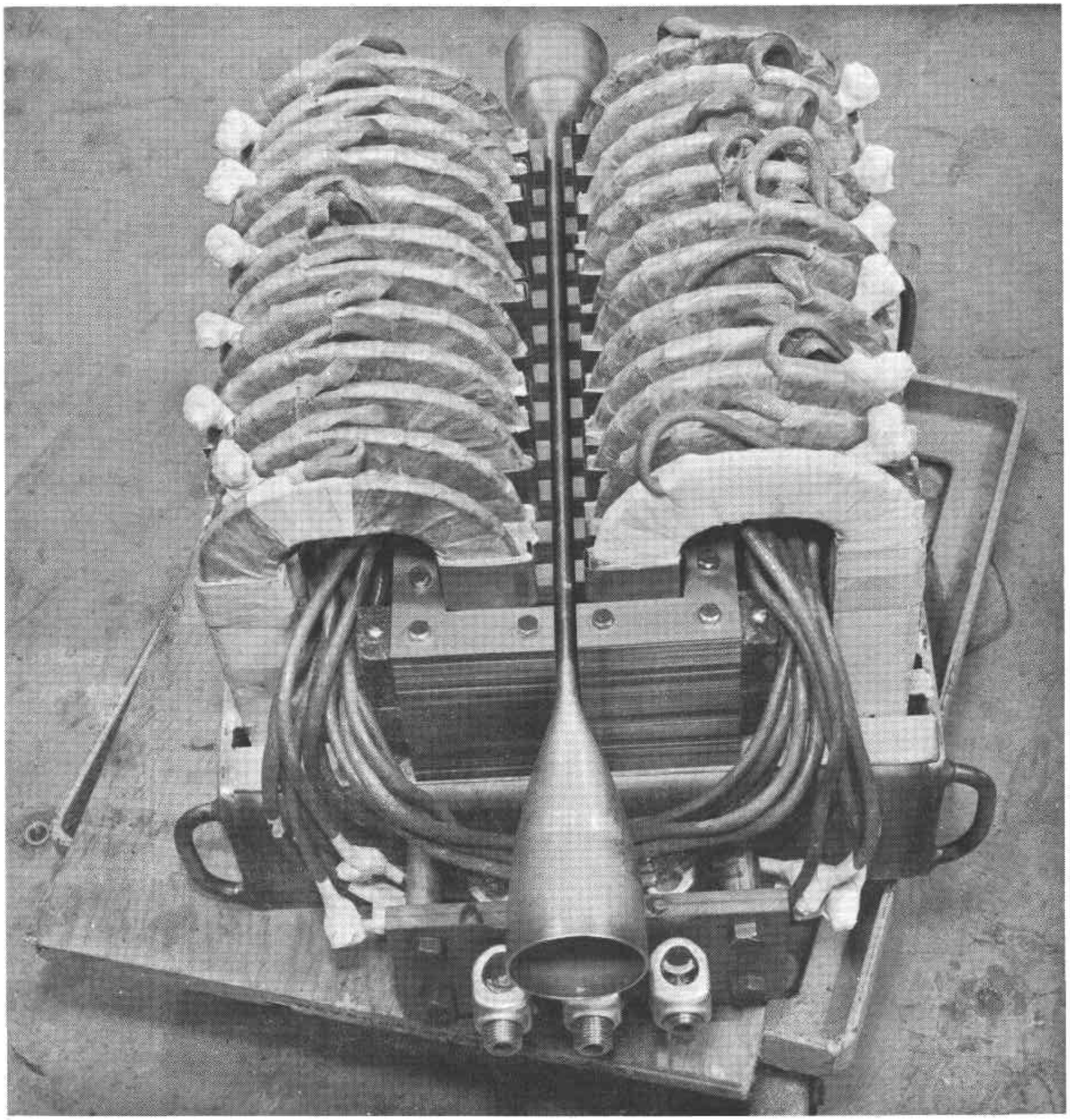
SRE-PEP-MAIN PRIMARY PUMP BARREL



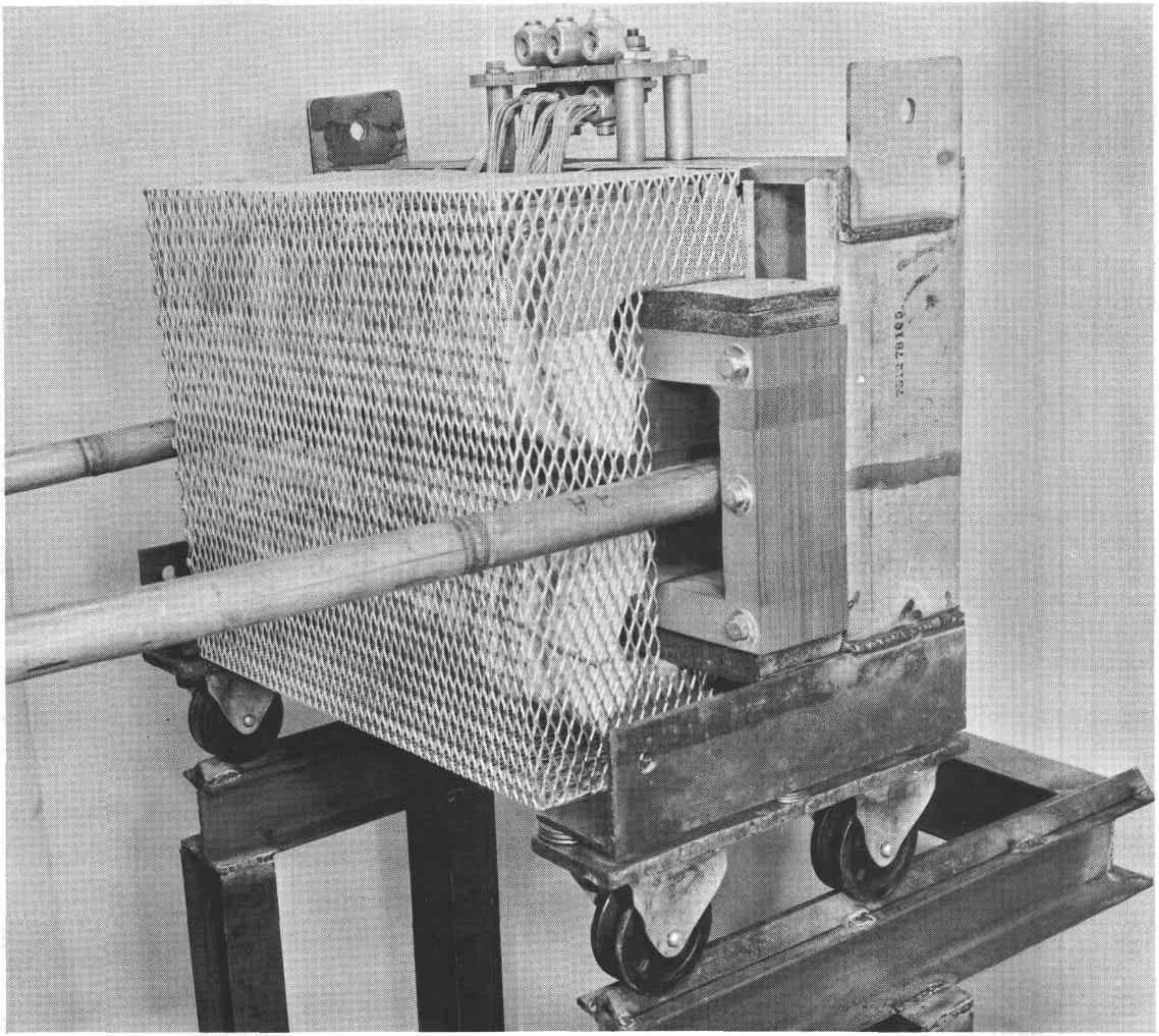
70-MA1-48-221

HALLAM EQUIPMENT TEST PUMP



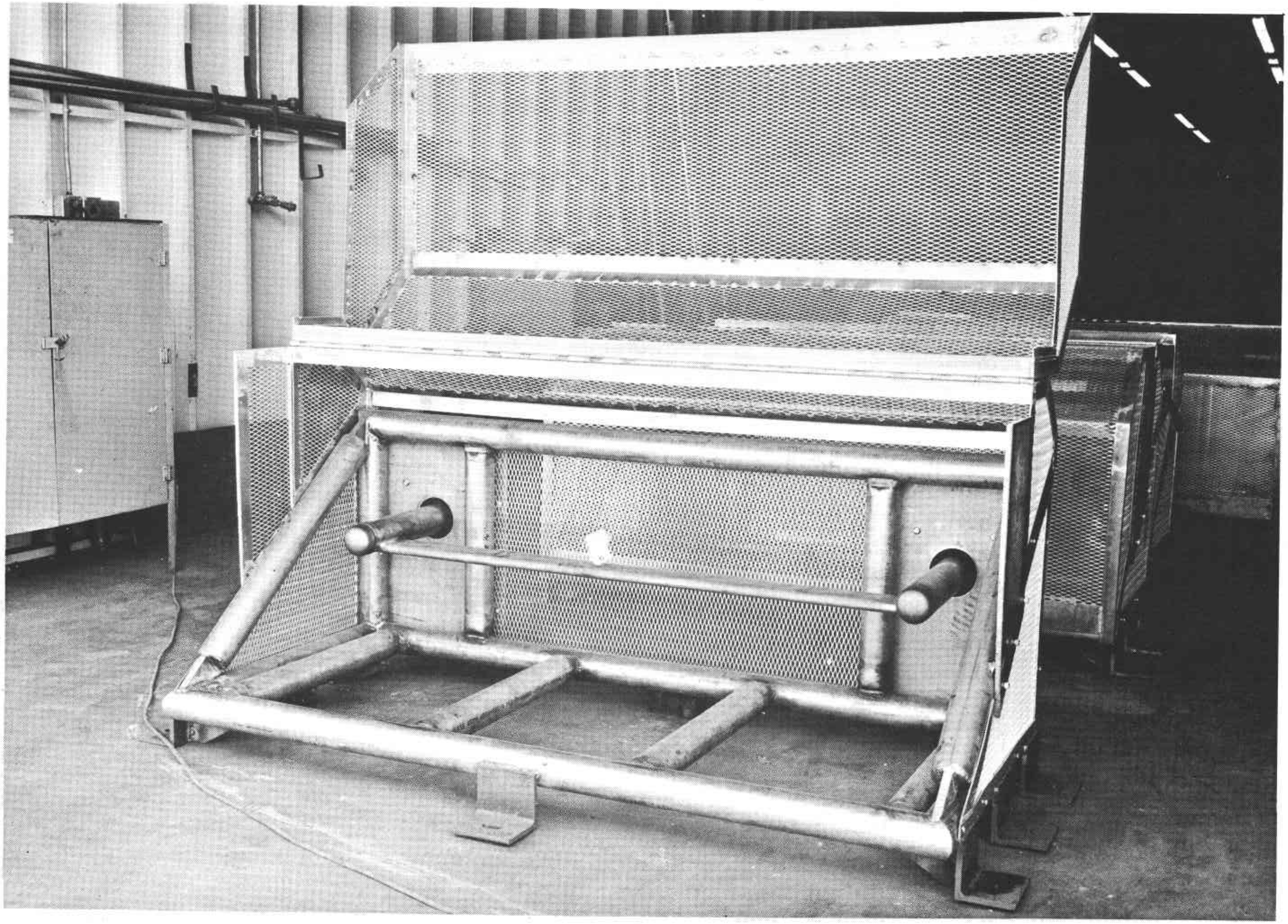
70-MA1-48-180

SNAP 2 ELECTROMAGNETIC PUMP



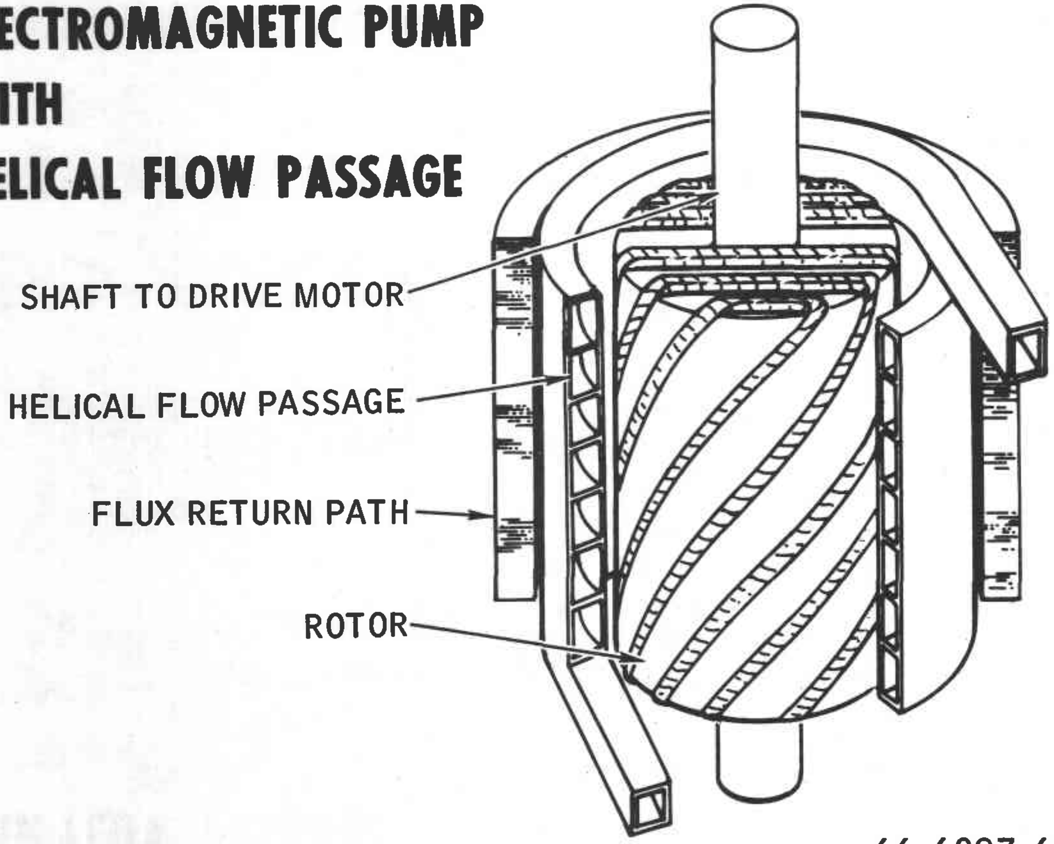
70-MA1-48-179

HALLAM ELECTROMAGNETIC PUMP



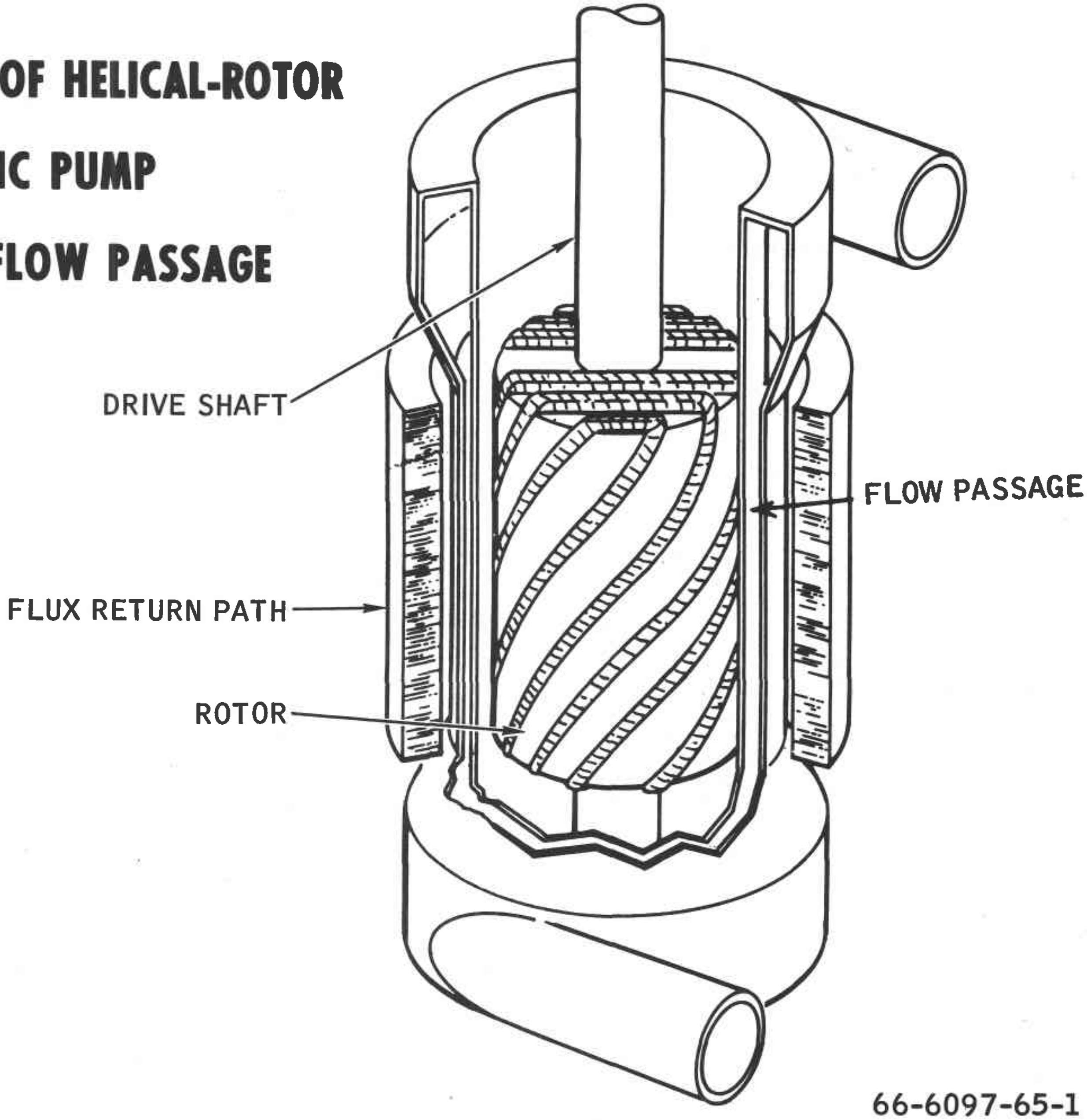
70-MA1-48-181

CUTAWAY VIEW OF HELICAL-ROTOR ELECTROMAGNETIC PUMP WITH HELICAL FLOW PASSAGE



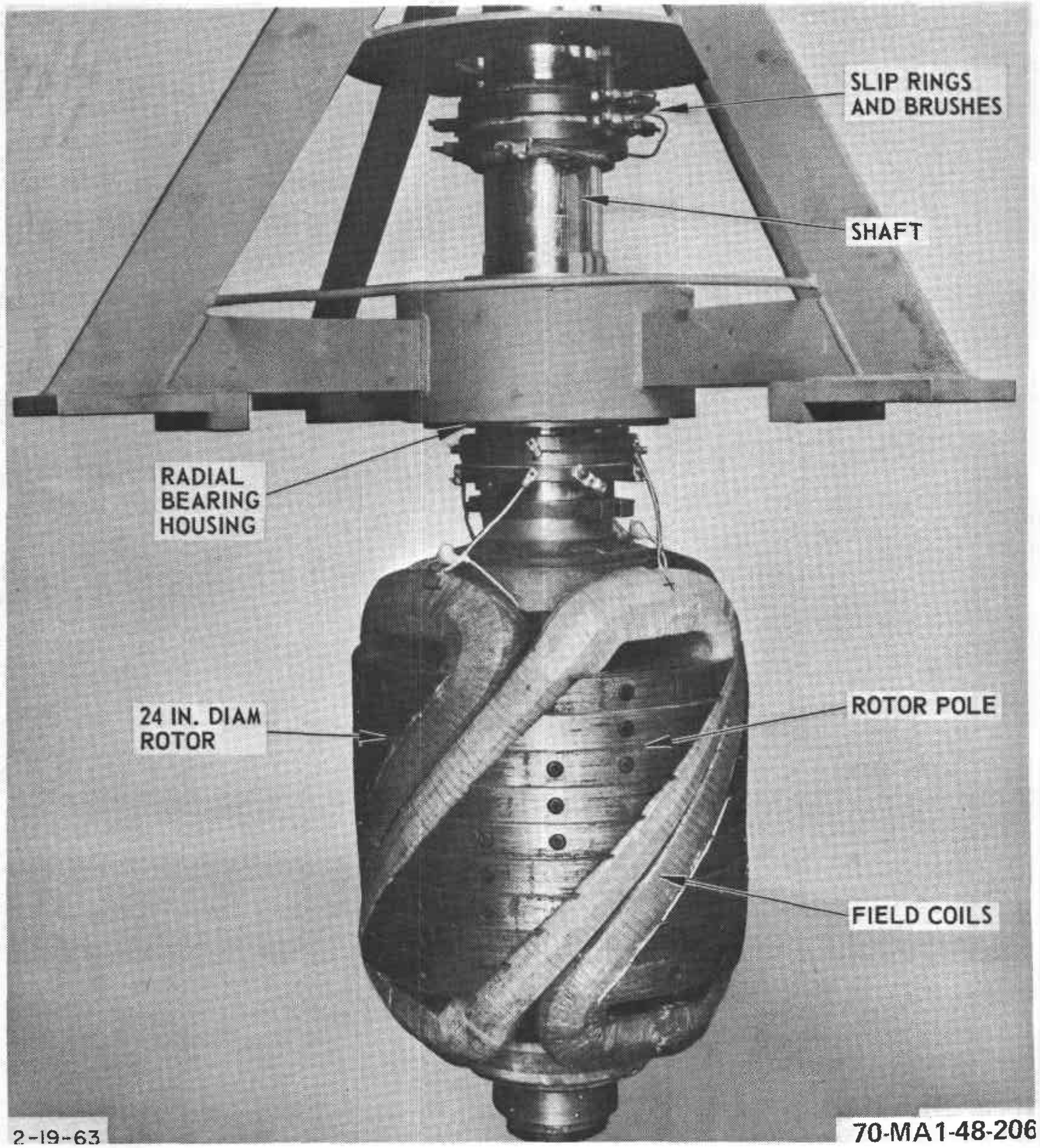
66-6097-65-9

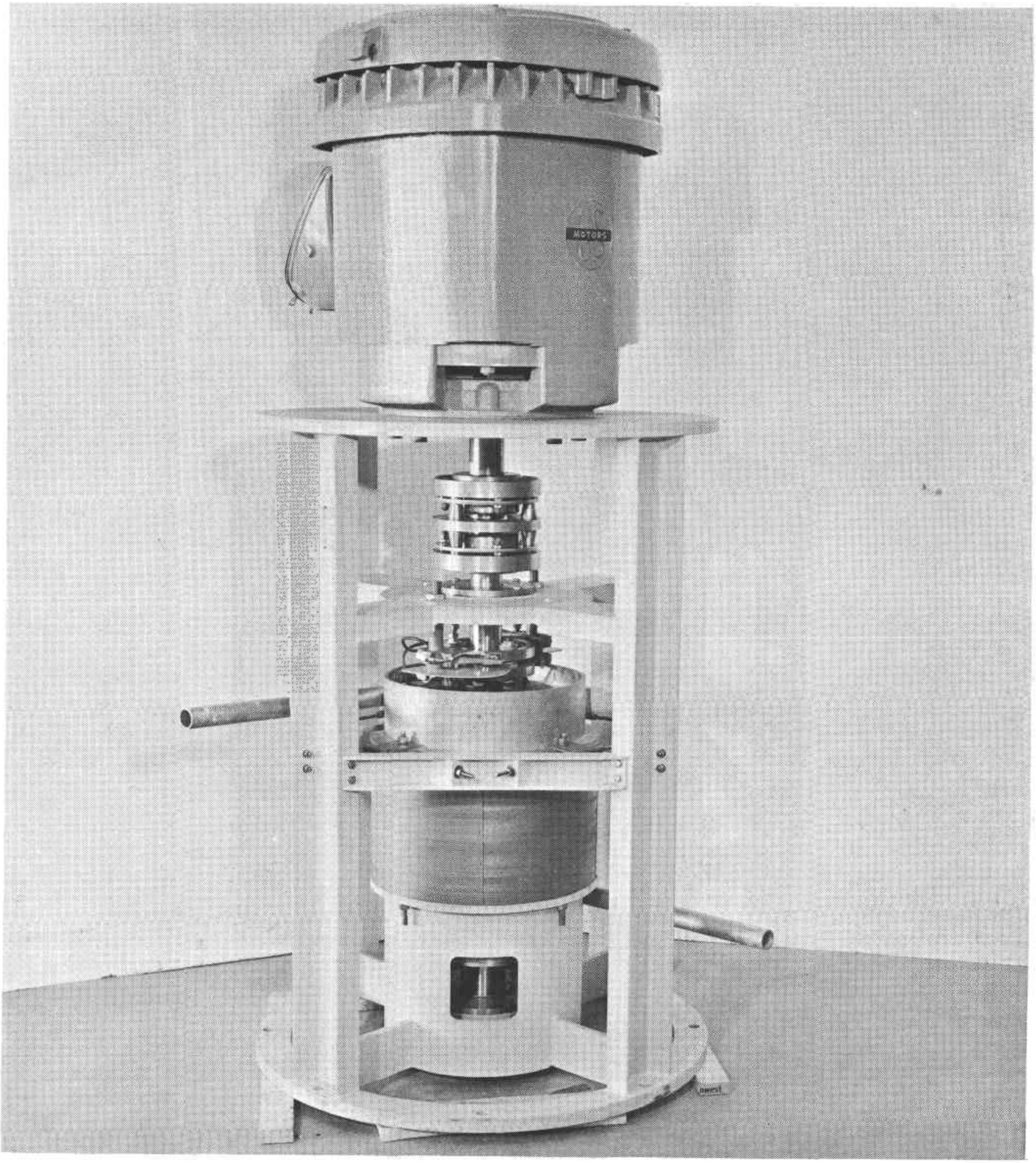
CUTAWAY VIEW OF HELICAL-ROTOR ELECTROMAGNETIC PUMP WITH ANNULAR FLOW PASSAGE



66-6097-65-1

HELICAL ROTOR EM PUMP ROTOR ASSEMBLY





2797-4004

4-1-64

IHX SYSTEM REQUIREMENTS

- TRANSFER HEAT FROM PRIMARY LOOP TO SECONDARY LOOP
    - UNDER NORMAL OPERATING CONDITIONS
    - UNDER ABNORMAL OPERATING CONDITIONS
- PROVIDE FOR ISOLATION OF PRIMARY SODIUM FROM SECONDARY SODIUM
- MUST WITHSTAND EXTERNAL PHYSICAL AND SYSTEM THERMAL TRANSIENTS WITHOUT DAMAGE
- LOW MAINTENANCE

70-MA19-48-131

POTENTIAL PROBLEM AREAS IN THE IHX

- TUBE VIBRATION, PARTICULARLY AT THE ENTRANCE/EXIT REGIONS
- DIFFERENTIAL TUBE EXPANSION DURING PREHEAT
- SATISFACTORY FLOW DISTRIBUTION AT ENTRANCE/EXIT REGIONS
- CAPABILITY FOR TUBE PLUGGING WITHOUT DECONTAMINATION
- POTENTIAL STAGNATION OR REVERSE FLOW DURING LOW FLOW OPERATION
- CAPABILITY FOR IDENTIFYING LEAKING TUBES REMOTELY
- CAPABILITY FOR DECONTAMINATION FOR MAJOR MAINTENANCE

70-MA19-48-159

SUBJECTIVE FACTORS WEIGHED IN SELECTING IHX CONCEPT

- SIZE, SHIPPING, AND WEIGHT LIMITATIONS
- AMENABILITY TO TUBE REPAIR
- ESTIMATED OUTAGE TIME FOR TUBE REPAIR
- AMENABILITY TO PREHEATING
- RELATIVE EASE OF FABRICATION
- OPERATING EXPERIENCE
- RESISTANCE TO THERMAL SHOCK DAMAGE
- EASE OF DECONTAMINATION
- EASE OF REPLACEMENT

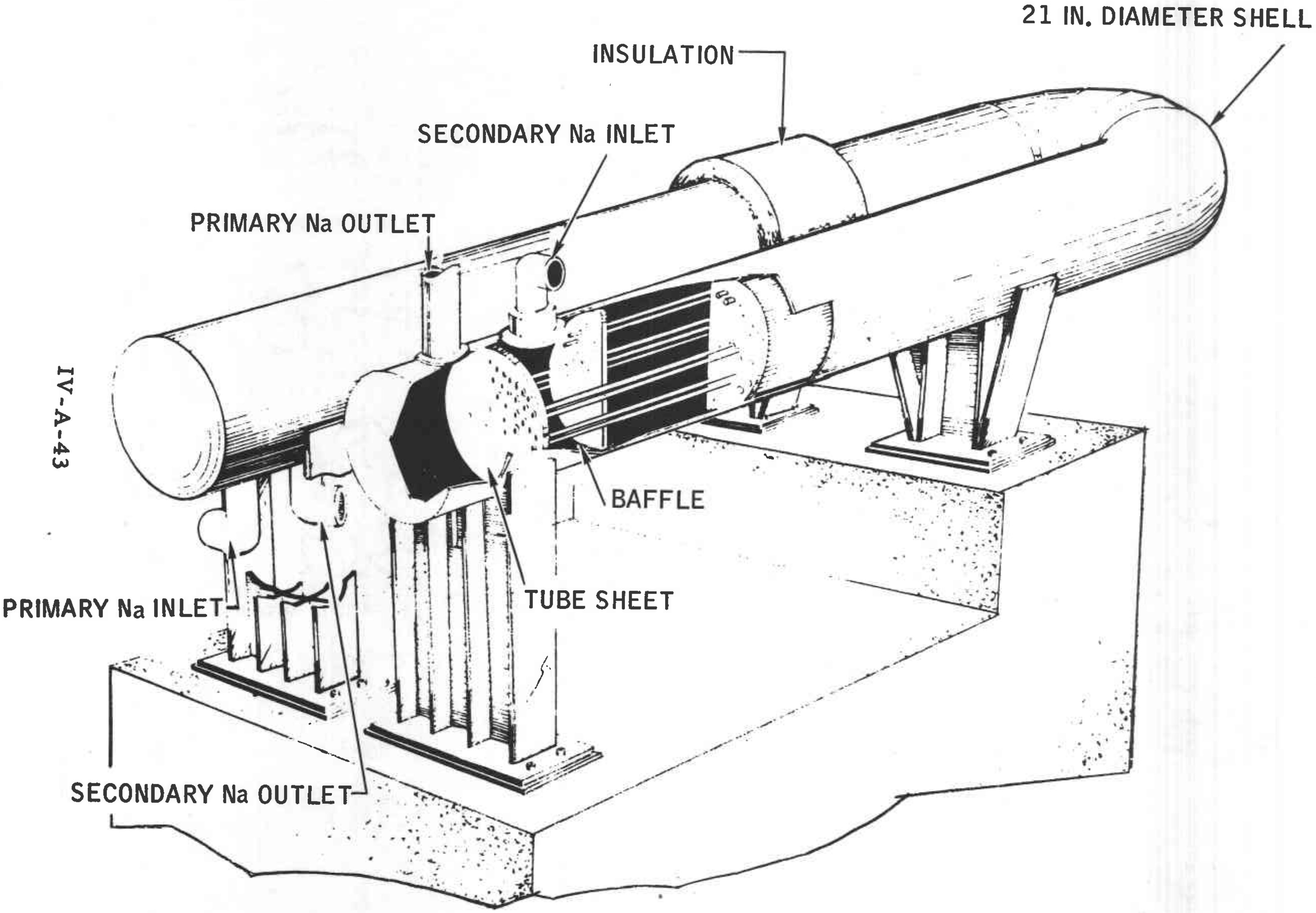
70-MA19-48-132

CONSIDERATIONS INVOLVED IN ESTIMATING IHX FAILURE RATES

- NUMBER OF TUBES
- EXPANSION JOINT FAILURES (IF USED)
- SHELL SEAM WELD LENGTH
- GENERAL CORROSION (FUNCTION OF A&t)
- CORROSION AT INCLUSIONS, CRACKS AND DEFECTS
- STRAIGHT VS BENT TUBES
- POTENTIAL VIBRATION/FATIGUE FAILURE
- NOZZLE WELD FAILURES
- TUBE SHEET CRACKS
- FLANGED JOINT LEAKAGE
- FATIGUE FAILURE IN SHELL BENDS
- BAFFLE TIE-ROD FAILURE
- NUMBER OF BAFFLE-TUBE CONTACT POINTS

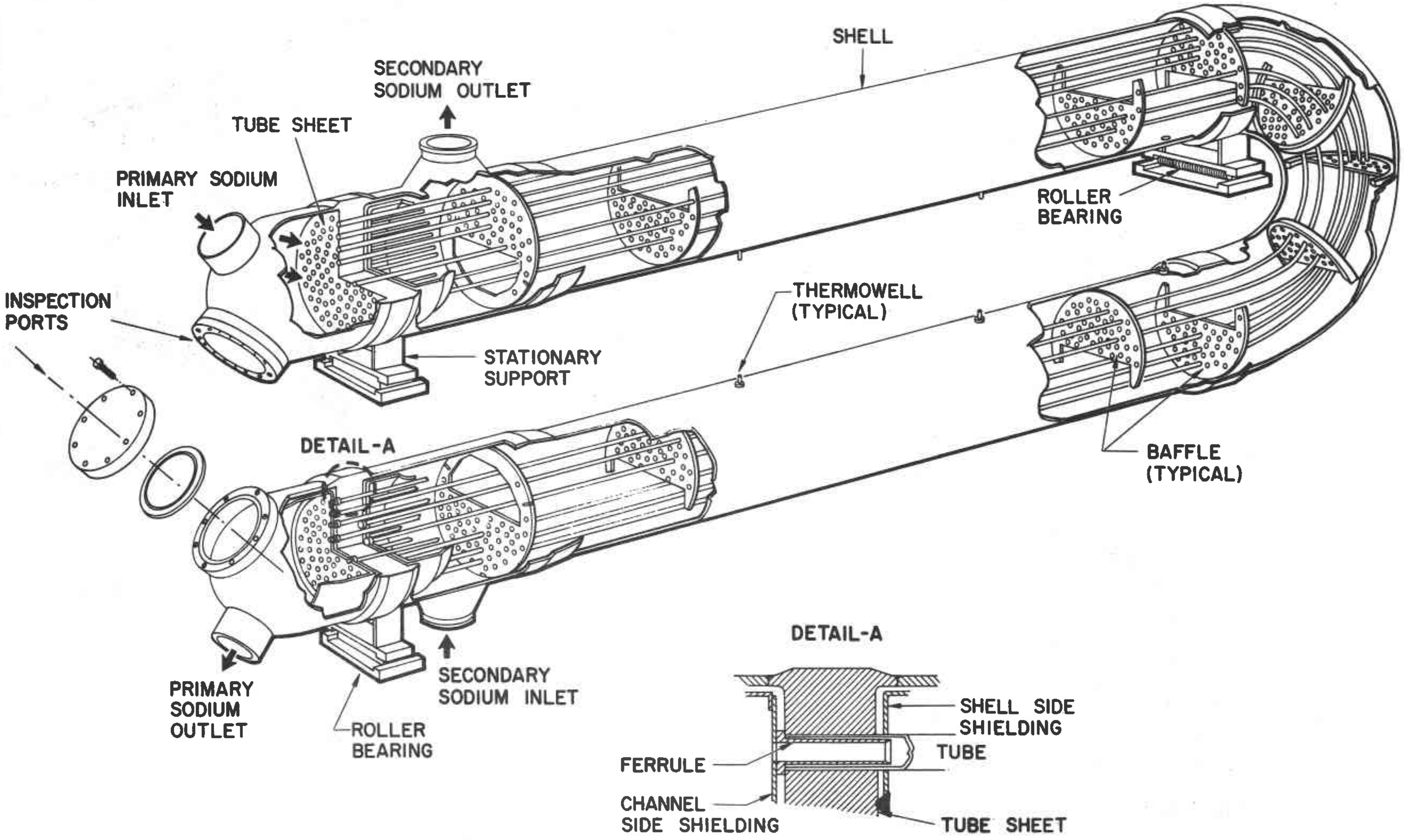
70-MA19-48-134

SRE MAIN INTERMEDIATE HEAT EXCHANGER



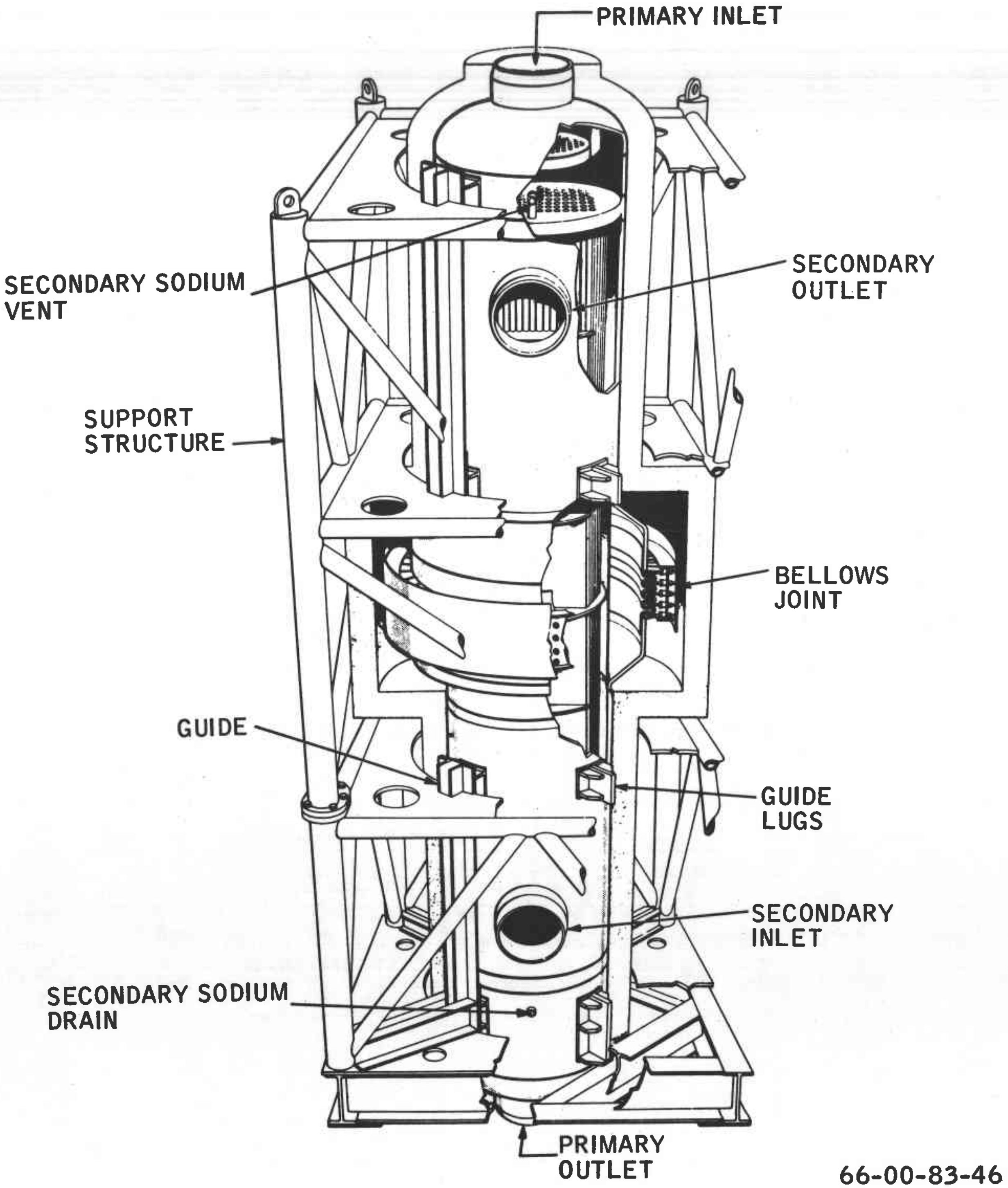
8-J31-007-171

MAIN INTERMEDIATE HEAT EXCHANGER

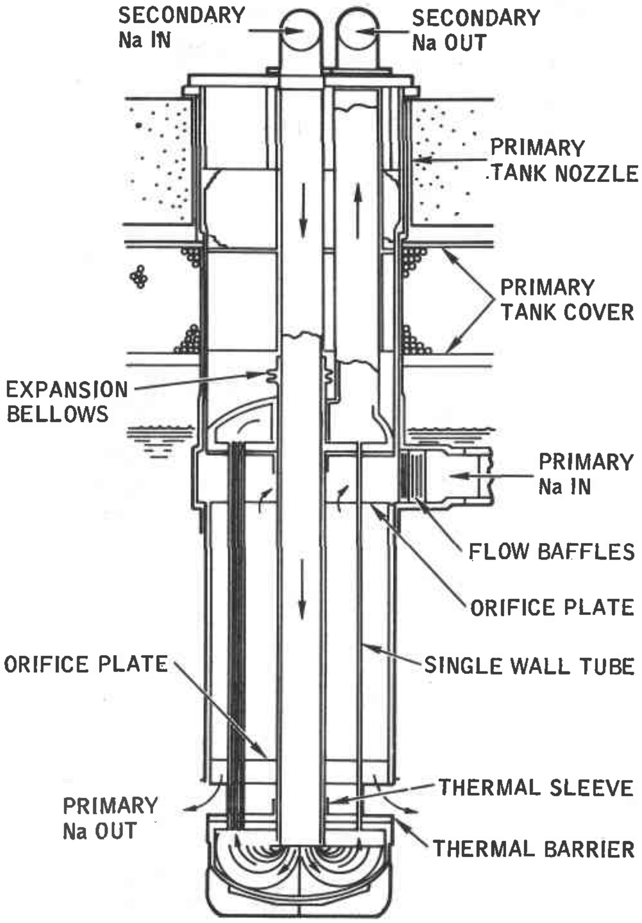


10/10/61

INTERMEDIATE HEAT EXCHANGER

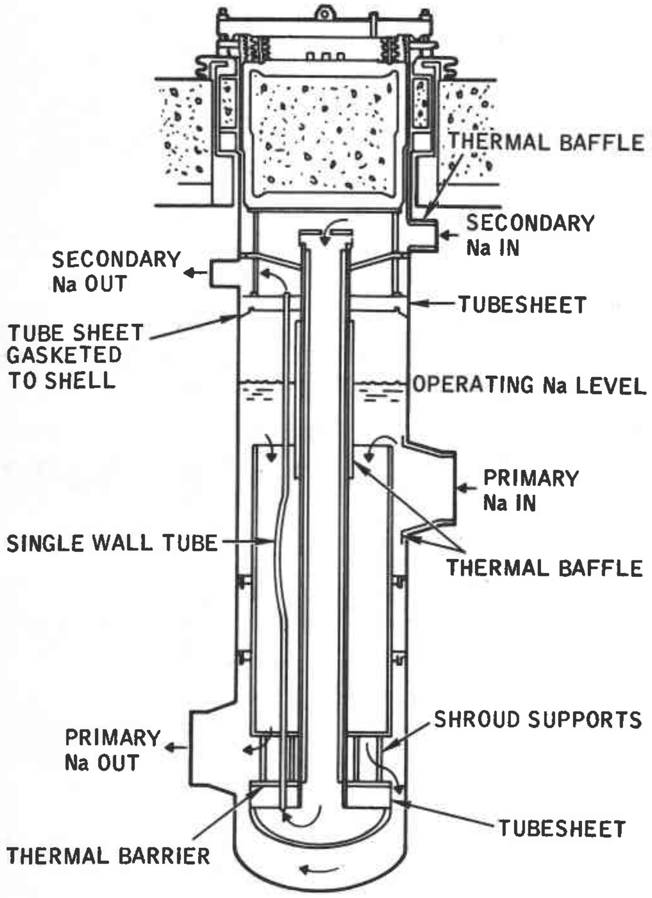


66-00-83-46

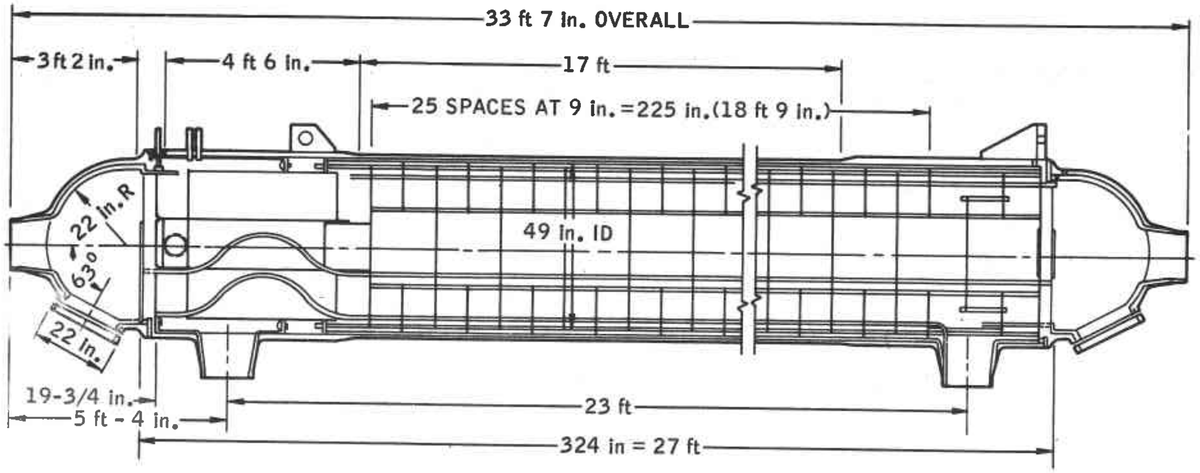

SECONDARY
Na IN
SECONDARY
Na OUT
PRIMARY
TANK NOZZLE
PRIMARY
TANK COVER
EXPANSION
BELLOWS
PRIMARY
Na IN
FLOW BAFFLES
ORIFICE PLATE
ORIFICE PLATE
SINGLE WALL TUBE
THERMAL SLEEVE
PRIMARY
Na OUT
THERMAL BARRIER

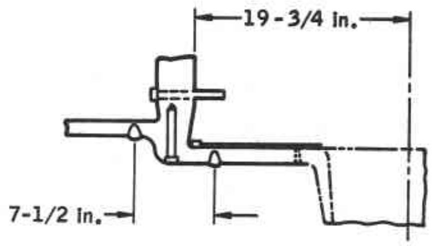
7-7694-208-36

FERMI-TYPE INTERMEDIATE HEAT EXCHANGER



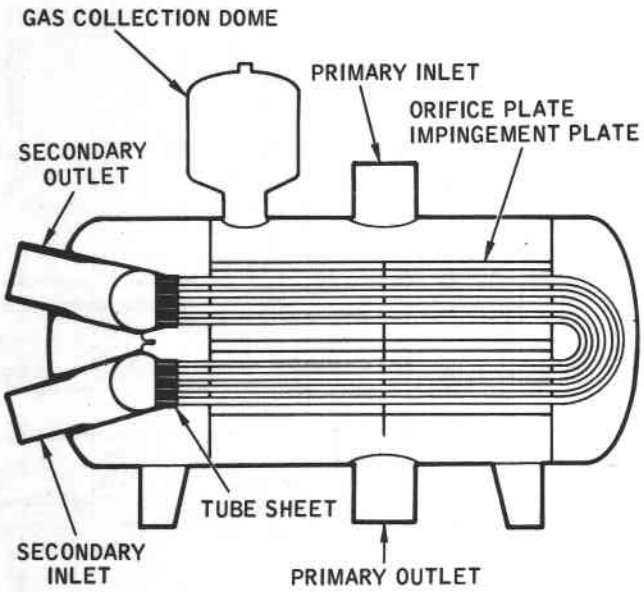
ALCO SINE-WAVE INTERMEDIATE HEAT EXCHANGER (SCTI)



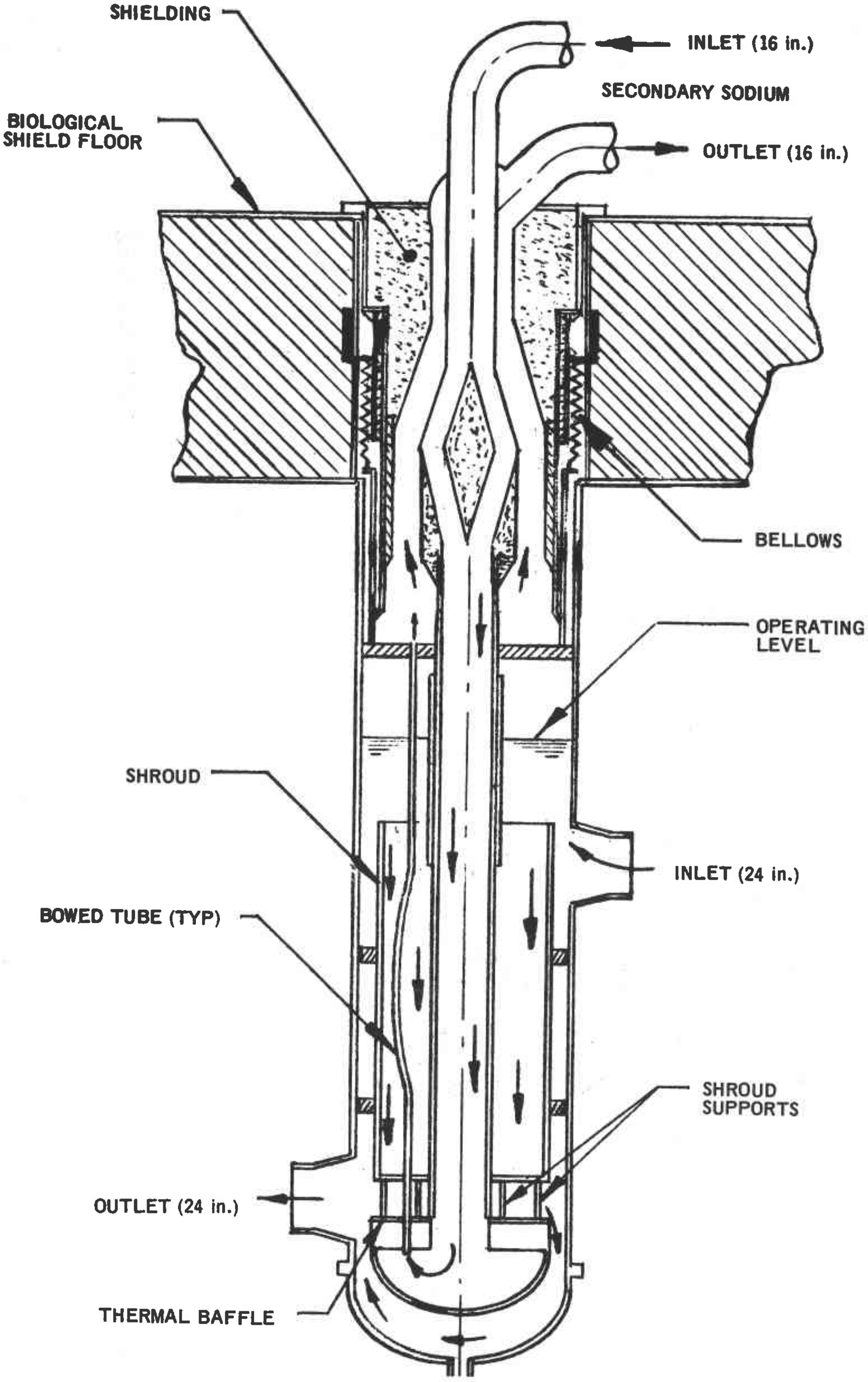


7-7694-208-14

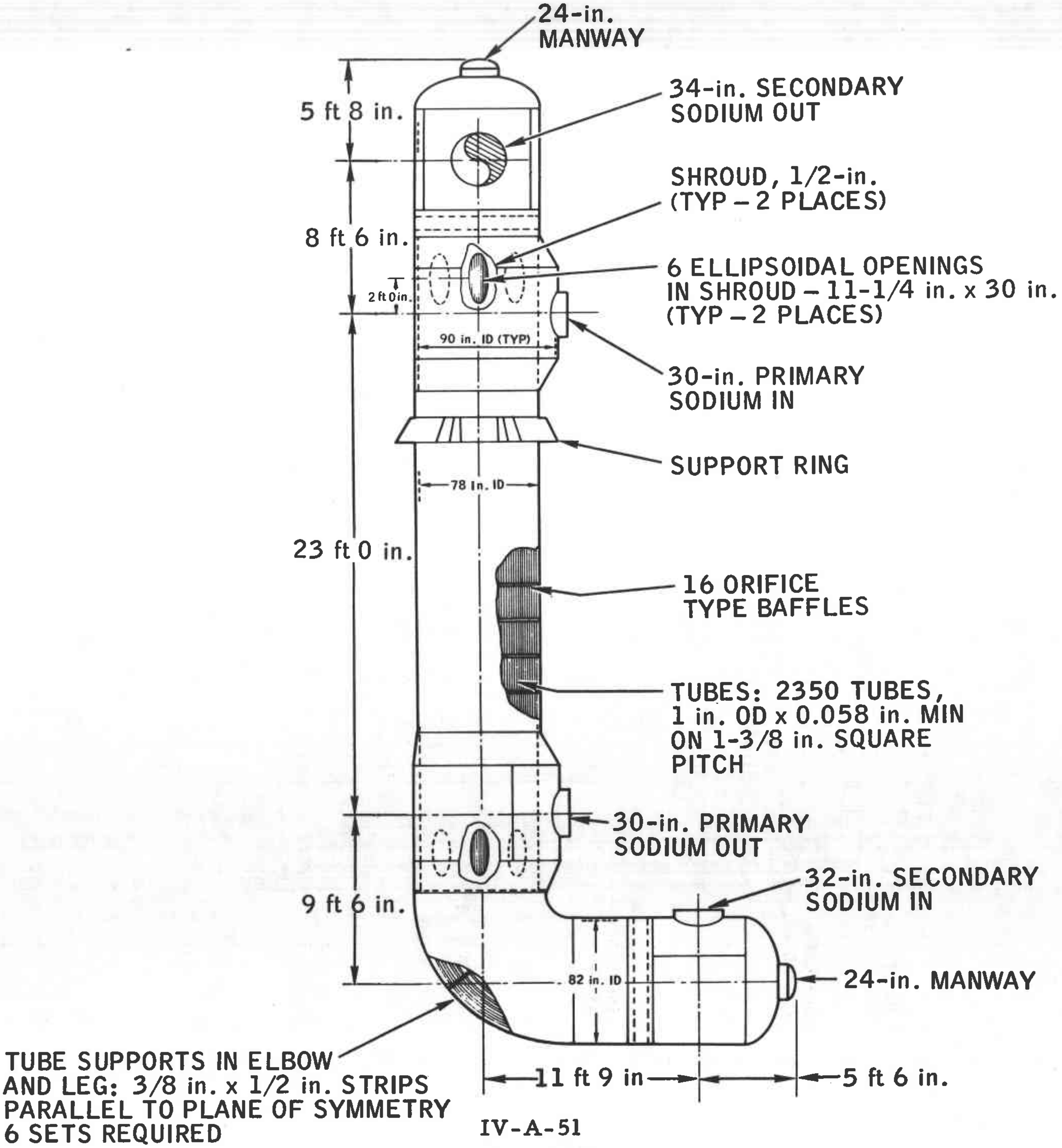
SEFOR INTERMEDIATE HEAT EXCHANGER



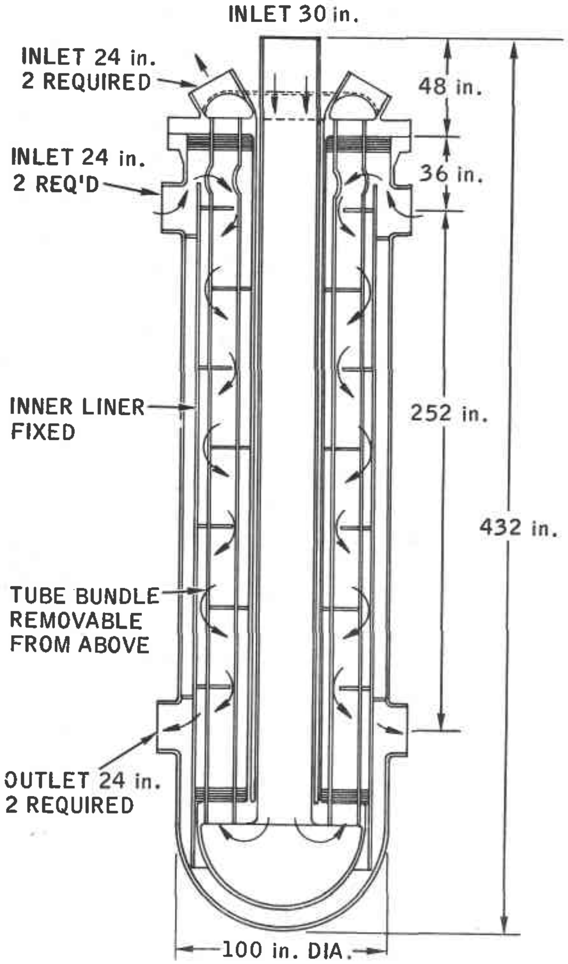
70-MA1-48-186


SHIELDING
INLET (16 in.)
SECONDARY SODIUM
BIOLOGICAL SHIELD FLOOR
OUTLET (16 in.)
BELLOWS
OPERATING LEVEL
SHROUD
INLET (24 in.)
BOWED TUBE (TYP)
SHROUD SUPPORTS
OUTLET (24 in.)
THERMAL BAFFLE

INTERMEDIATE HEAT EXCHANGER



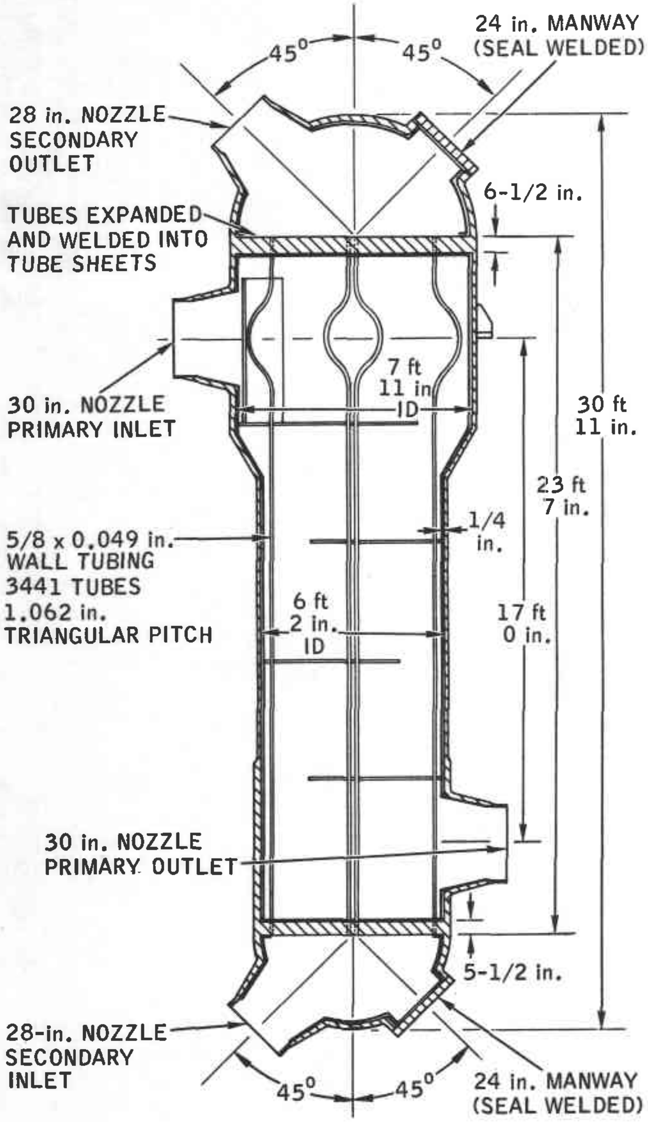
WESTINGHOUSE INTERMEDIATE HEAT EXCHANGER



TYPE		COUNTERFLOW, VERTICAL, SHELL AND TUBE
UNIT RATING		540 Mwt
OVERALL LENGTH		36 ft
OVERALL DIAMETER		8.33 ft
NUMBER OF TUBES		5400
EFFECTIVE HT AREA		20,200 ft^2
EFFECTIVE OVERALL HEAT TRANSFER COEFFICIENT		1430 Btu/hr-ft^2 °F
SHELL SIDE:		
	FLUID	SODIUM
	INLET TEMP	1000°F
	OUTLET TEMP	770°F
TUBE SIDE:		
	FLUID	SODIUM
	INLET	665°F
	OUTLET TEMP	965°F

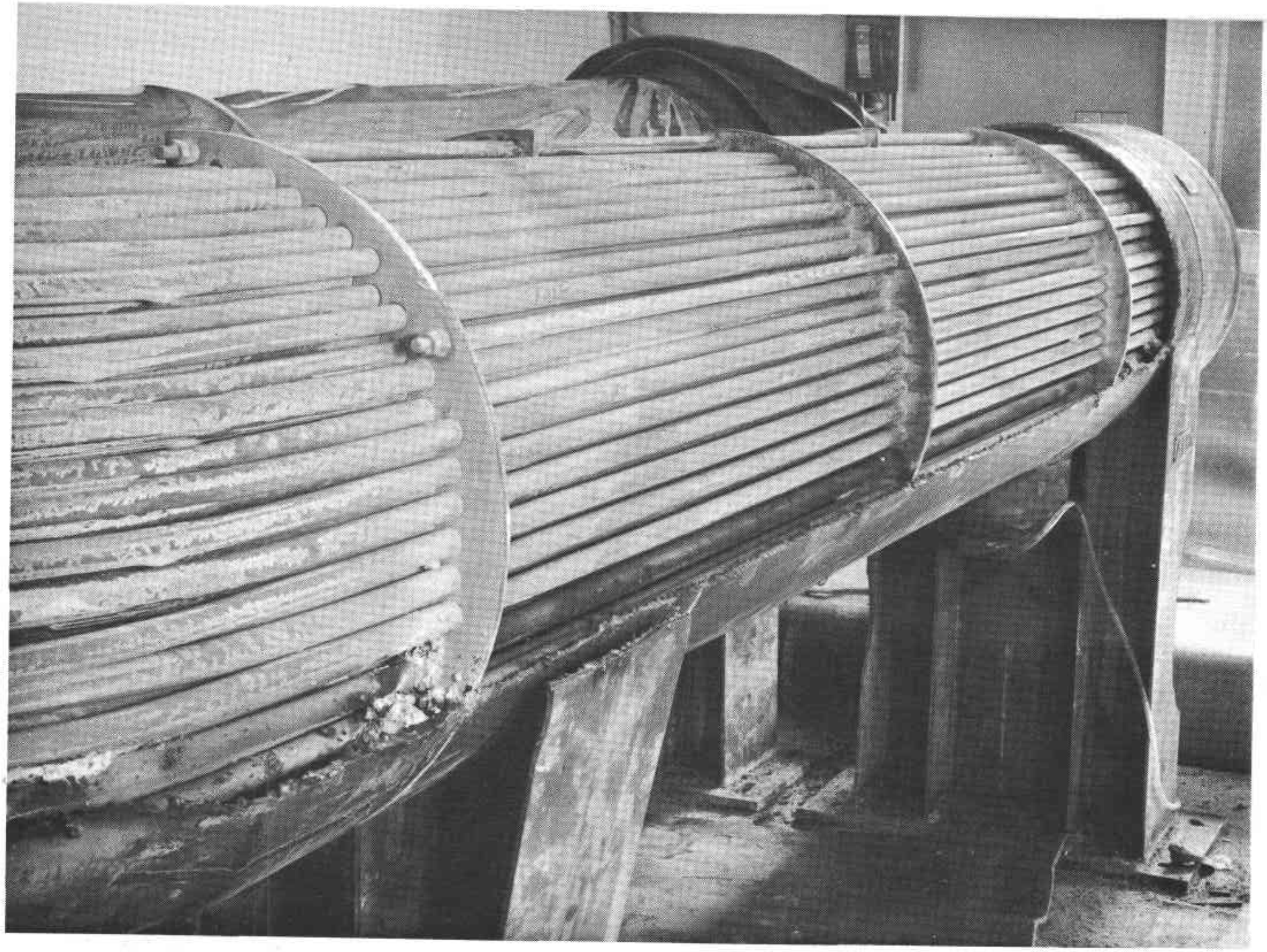
7-7694-208-52

COMBUSTION ENGINEERING SINE-WAVE INTERMEDIATE HEAT EXCHANGER



70-MA1-48-185

SRE INTERMEDIATE HEAT EXCHANGER



70-MA1-48-182

SRE INTERMEDIATE HEAT EXCHANGER

- PROBLEM
  - REDUCED THERMAL PERFORMANCE AND SHELL DISTORTION DUE TO NONUNIFORM TEMPERATURE DISTRIBUTION AT LOW FLOW
- REASON
  - SODIUM BYPASSING BETWEEN SHELL AND TUBE BAFFLES AND SODIUM STRATIFICATION AT LOW FLOW
- CORRECTIVE ACTION
  - REPLACED IHX WITH VERTICAL U TUBE HEAT EXCHANGER AND IMPROVED BAFFLE DESIGN

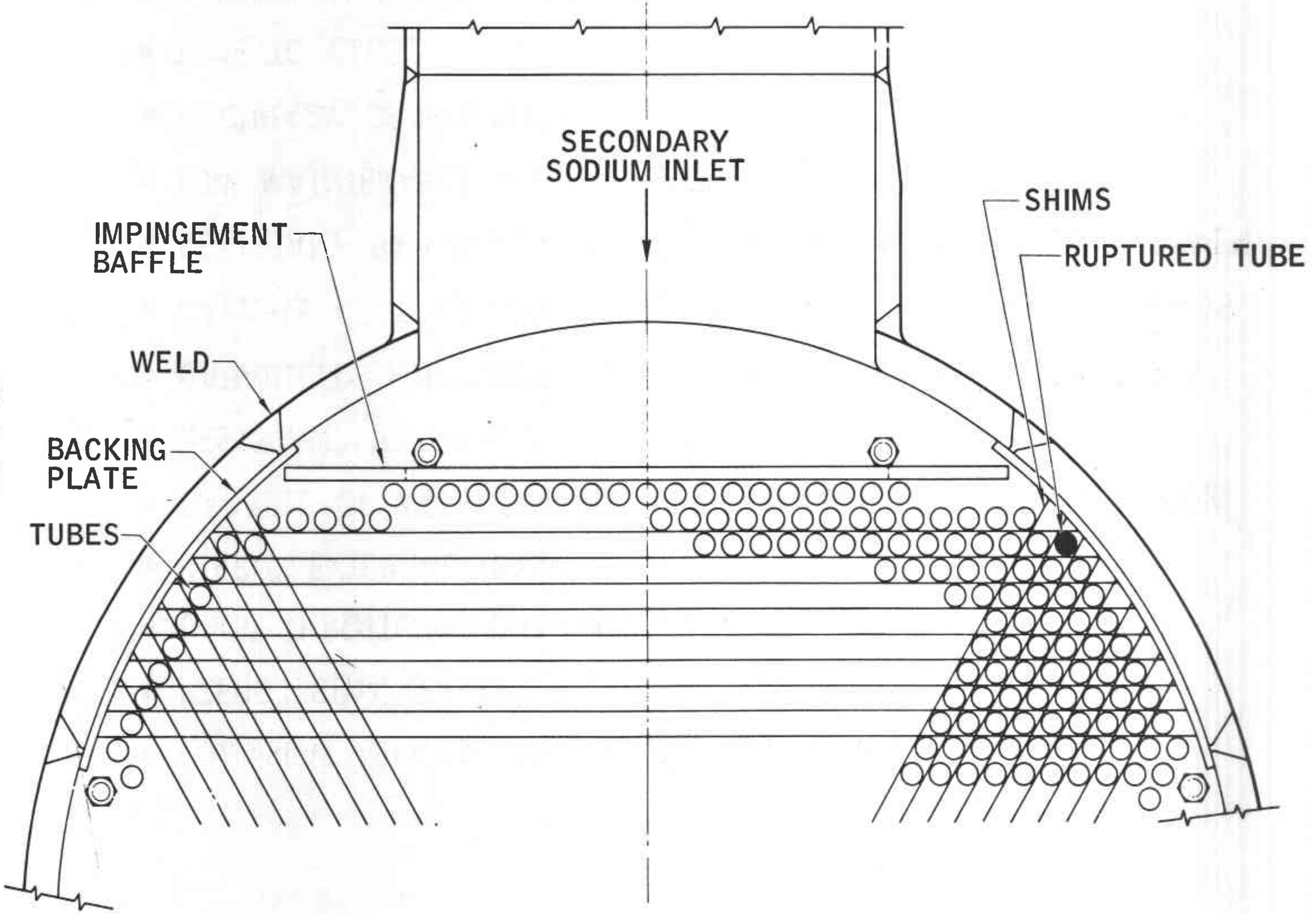
70-MA19-48-124

HALLAM INTERMEDIATE HEAT EXCHANGER

- PROBLEM
  - LEAKING TUBE IN UNIT 1A
- REASON
  - HIGH VELOCITY SODIUM ADJACENT TO IMPINGEMENT BAFFLE AT INLET OF SHELL SIDE OF IHX CAUSED TUBE VIBRATION ~42 cps
- CORRECTIVE ACTION
  - ADDED 60 mil SHIMS 7/8 in. WIDE IN INLET REGION TO INCREASE NATURAL FREQUENCY TO ~ 217 cps

8-J31-007-178

HALLAM INTERMEDIATE HEAT EXCHANGER TUBE BUNDLE



POTENTIAL VALVE REQUIREMENTS/CHARACTERISTICS

- LOW SEAT LEAKAGE/CONTROLLED SEAT LEAKAGE
- "ZERO" SEAT LEAKAGE
- GOOD THROTTLING CHARACTERISTICS
- "ZERO" EXTERNAL LEAKAGE
- CAPABLE OF WITHSTANDING PIPE REACTIONS WITHOUT BINDING
- RESISTANT TO THERMAL DISTORTION
- CAPABILITY FOR TIGHT SHUT-OFF AT VARIABLE TEMPERATURES
- CAPABLE OF THROTTLING SERVICE AT HIGH DIFFERENTIAL HEADS
- RESISTANT TO CORROSION, GAULING, WEAR IN THE ENVIRONMENT
- LOW MAINTENANCE REQUIREMENTS
- ACCURACY OF POSITIONING
- TIME TO CLOSE
- EMERGENCY POWER REQUIREMENTS

70-MA19-48-137

VALVE TEST REQUIREMENTS

- SEAL LEAKAGE
- SEAT LEAKAGE
- VALVE ACTUATOR POWER CAPABILITY
- VALVE OPERATING CHARACTERISTICS
- SUSCEPTABILITY TO THERMAL SHOCK DAMAGE
- BODY LEAKAGE
- CLEANLINESS
- ACCURACY OF POSITIONING
- TIME TO CLOSE

70-MA19-48-138

PROBLEMS INVOLVED IN SODIUM VALVE DEVELOPMENT

- PRESENCE OF RADIOACTIVE COOLANT
- POTENTIAL LEAKAGE AT SEATS AND STEMS
- POTENTIAL REACTION WITH ATMOSPHERE (FIRE)
- SELF-WELDING AND GAULING
- EXCESSIVE SPACE AND HEADROOM REQUIREMENTS
- SODIUM HAMMER-SPEED OF CLOSURE
- PENETRATION OF PORES OF METAL BY SODIUM
- COST
- EXPANSION AND THERMAL SHOCK
- MAINTENANCE CONSIDERATIONS (INCLUDING RADIATION AND FIRE HAZARDS
- DRIVE MECHANISMS; EMERGENCY DRIVE POWER
- POSITIONING ACCURACY AND REPRODUCIBILITY
- THERMAL EXPANSION, GROWTH, AND CREEP

70-MA1-48-232

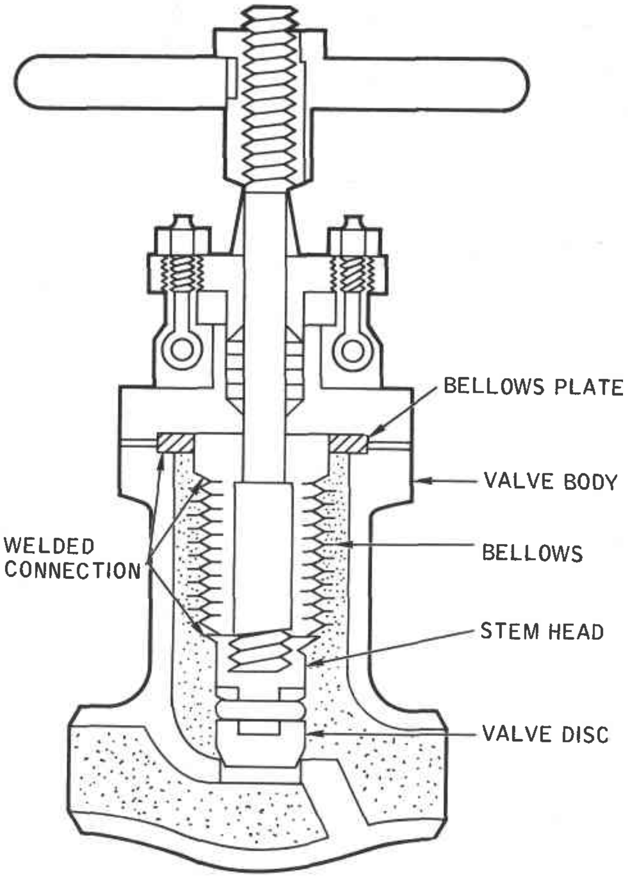
70-MA1-48-233

LARGE VALVES IN LIQUID METAL COOLED REACTORS

REACTOR	VALVE FUNCTION	TOTAL VALVES IN LOOP	SIZE (in.)	STEM SEAL	SERVICE CONDITIONS		
					APPROX. TEMP., (^oF)	APPROX. PRESSURE, psi	APPROX. FLOW, gal/min
EBR-I	BLOCK	15	4,6	DOUBLE BELLOWS	600	20	291
ERB-II	THROTTLE	2	4	CLOSE CLEARANCE	700	56	630
FERMI	THROTTLE	3	6	DOUBLE BELLOWS	600	118	1,000
	CHECK	3	16	NONE	600	118	10,000
HALLAM	BLOCK	9	14,16	FREEZE SEAL	950	57	6,750
	CHECK	3	16	NONE	610	37	6,750
SRE	BLOCK	9	6	BELLOWS AND FREEZE SEAL	850		
SRE-PEP	BLOCK	4	4,6	BELLOWS AND FREEZE SEAL	1160	47	1,540
	THROTTLE	1	8	TORQUE TUBE	650	19	1,420

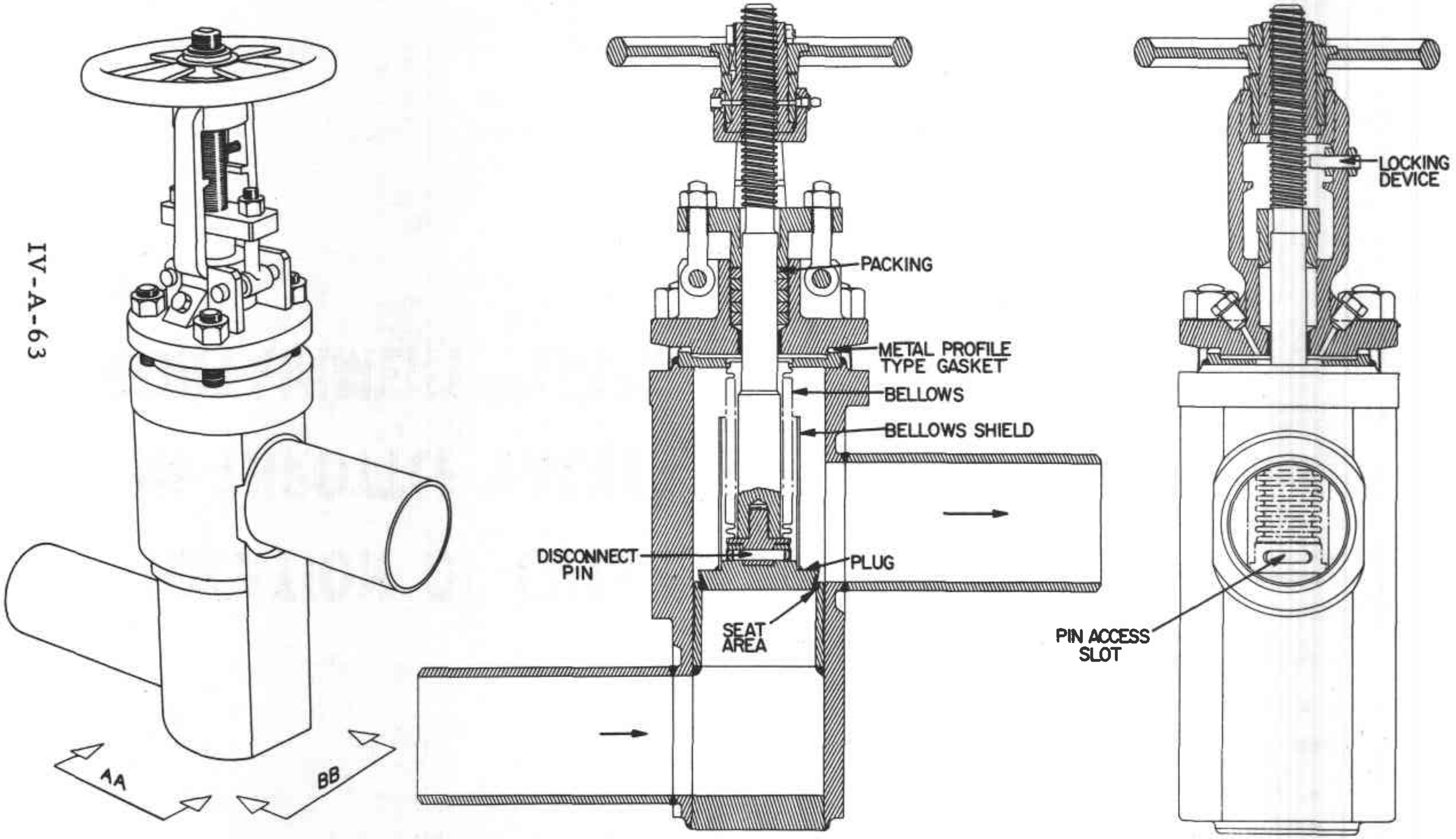
NOTE: ALL VALVES HAD STAINLESS STEEL BODIES

70-MA1-48-243


BELLOWS PLATE
VALVE BODY
WELDED CONNECTION
BELLOWS
STEM HEAD
VALVE DISC

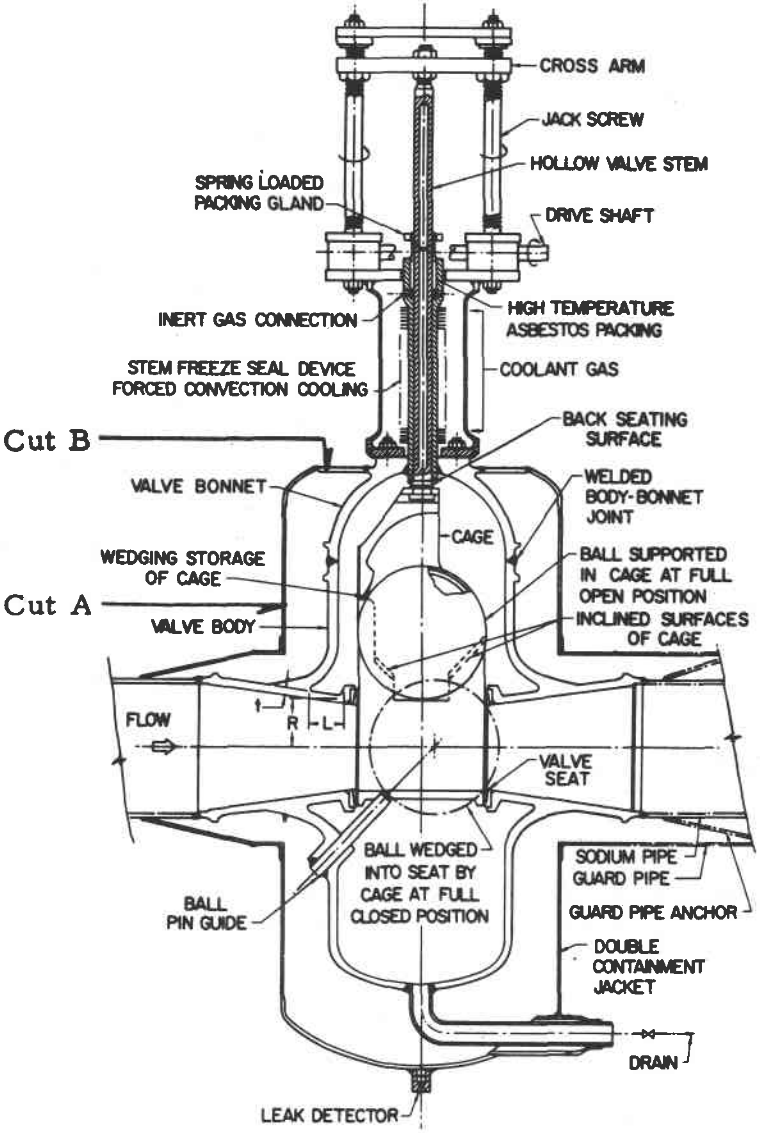
7-7694-215-37

BELLOWS SEAL VALVES



66-3623-107-2

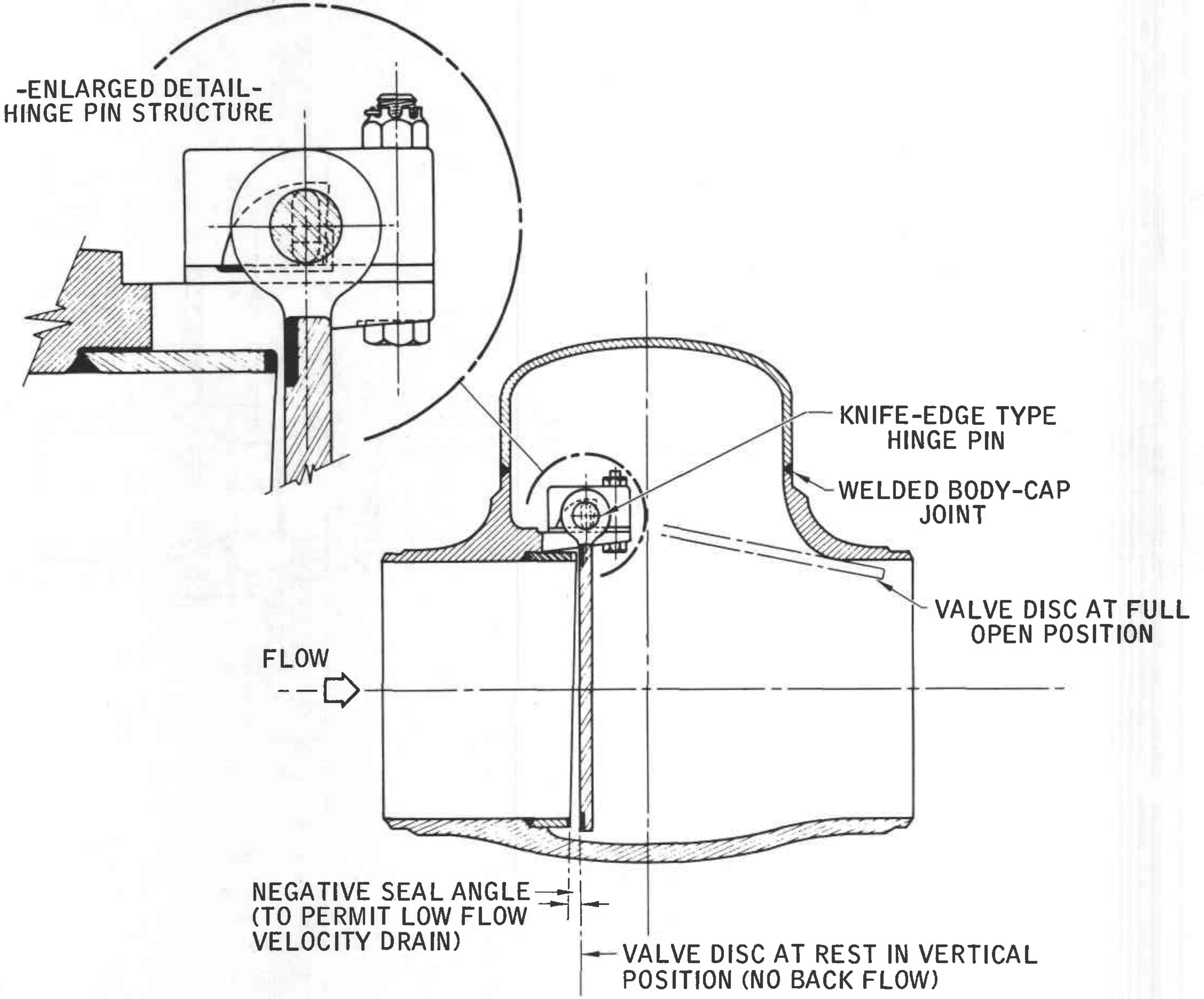
LOCATION OF CUTS IN THROTTLE VALVE CONTAINMENT VESSEL



PRIMARY SODIUM THROTTLING VALVE

66-3623-107-3

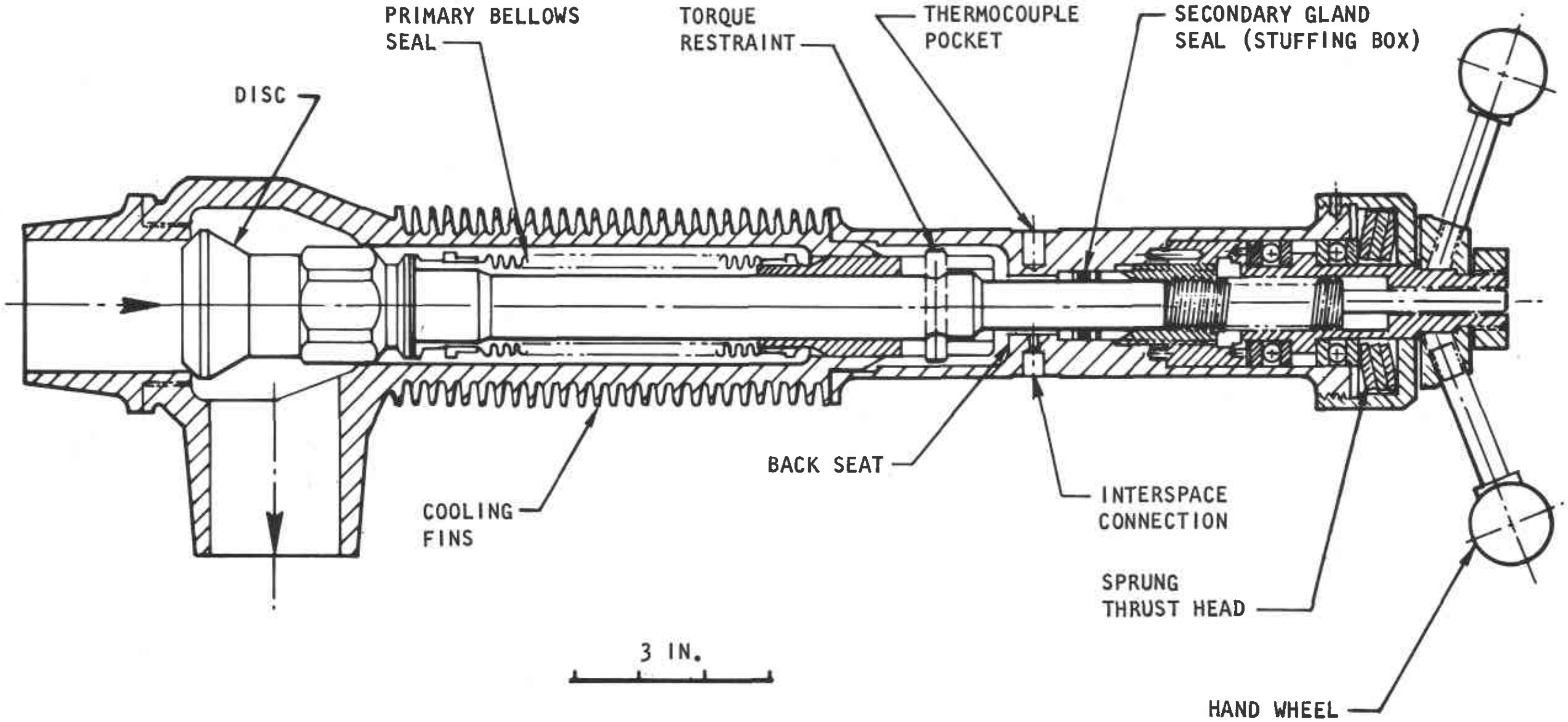
500-Mwe FBR PRIMARY SODIUM CHECK VALVE



7-6095-132-17

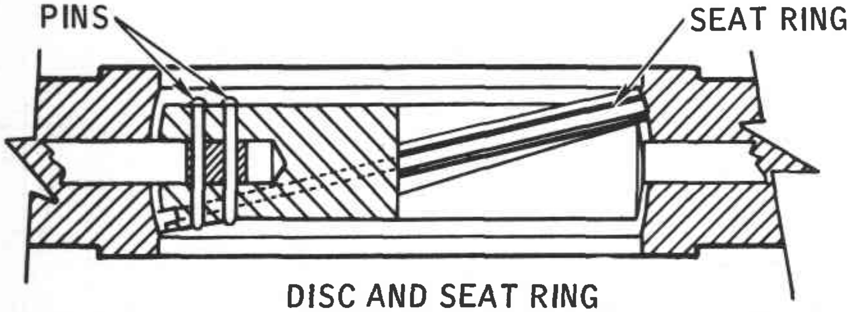
TWO INCH VALVE

(BRITISH DESIGN)

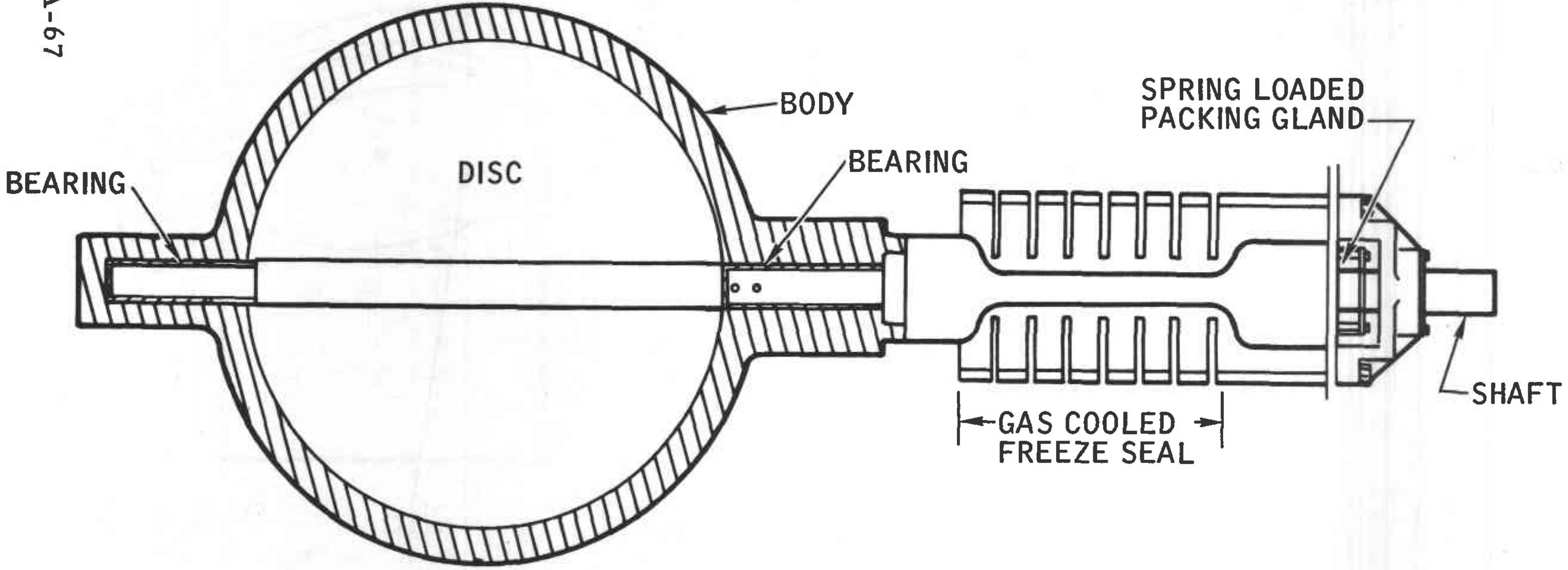


70-MA19-48-151

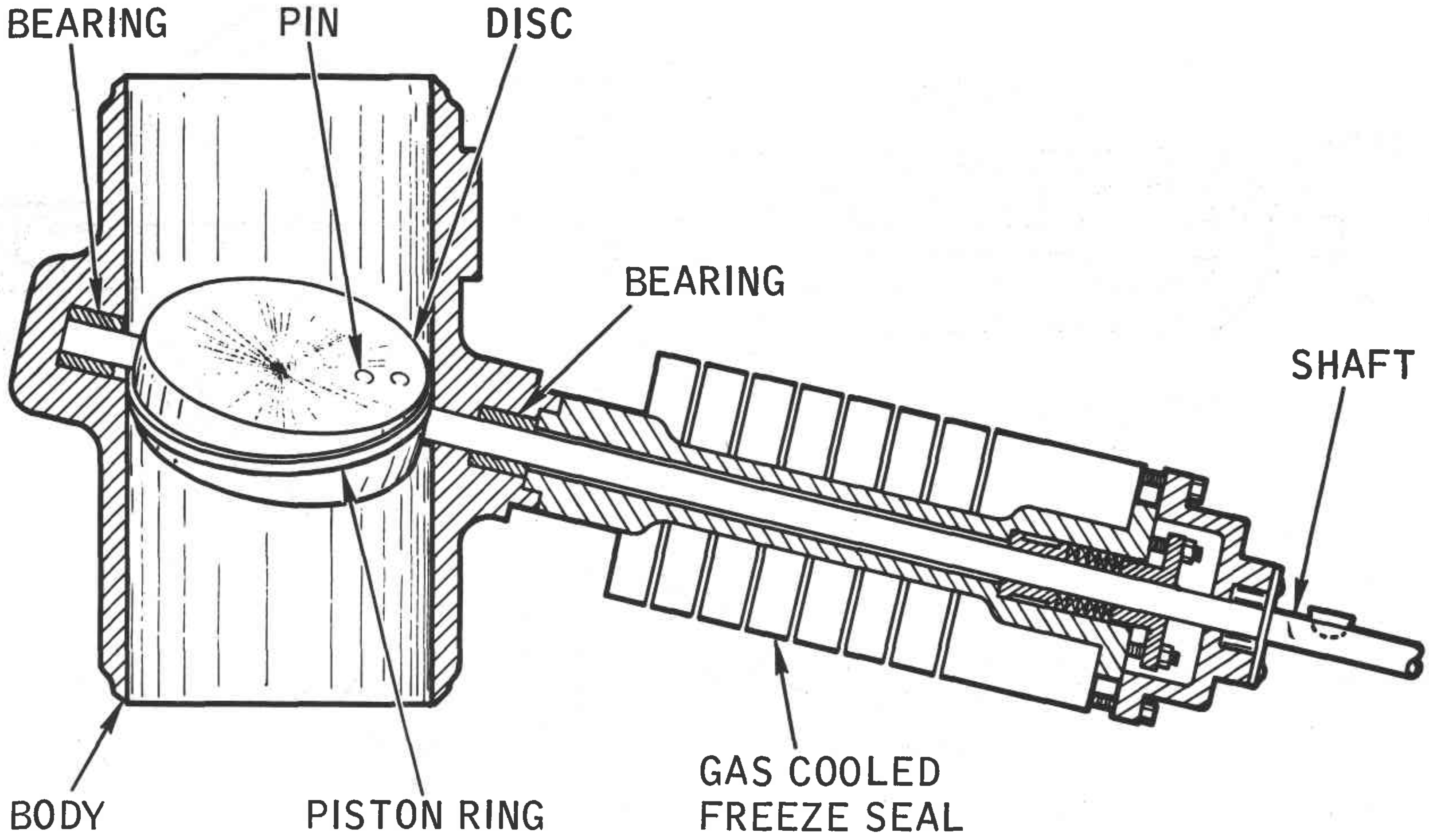
SODIUM BUTTERFLY VALVE
(VALVE BODY)



DISC AND SEAT RING



7-6095-132-1

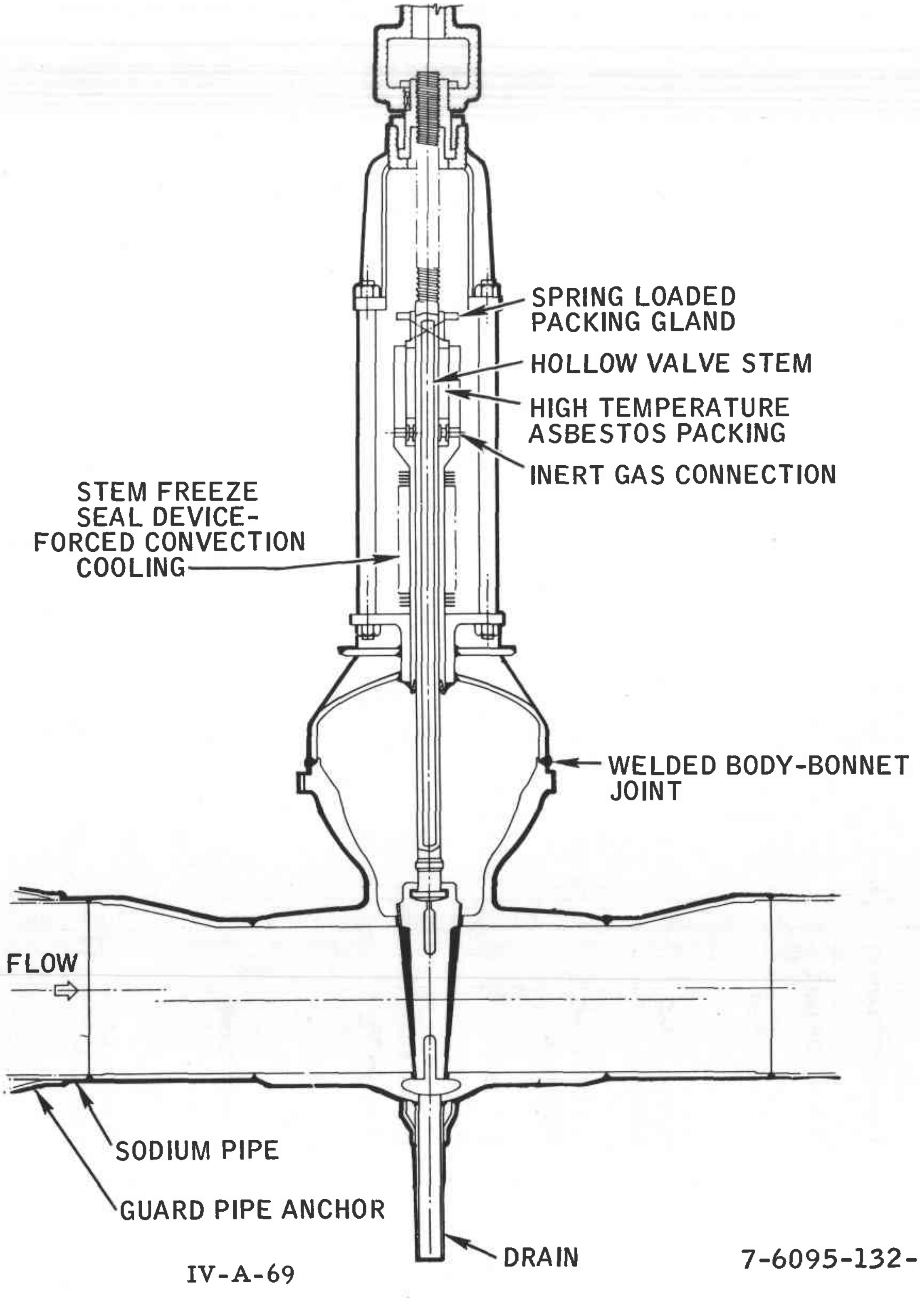


3-5-68

7-7694-213-12

500-Mwe FBR

PRIMARY SODIUM BLOCKING VALVE



7-6095-132-16

TYPICAL EXPECTED TRANSIENTS FOR DESIGN

TRANSIENT NAME	EXPECTED NUMBER 30 YEARS	LOCATION HOT OR COLD LEG	TEMPERATURE CONDITIONS (°F)			
			INITIAL	FINAL	NET	RATE
INITIAL PREHEAT	3	BOTH	70	350	+280	+3/hr
RISE TO POWER	3	COLD	350	760	+410	+50/30 M
		HOT	350	1060	+710	+50/30 M
NORMAL LOAD INCREASE	9000	COLD	674	760	+ 86	+2.3/ M
		HOT	974	1060	+ 86	+2.3/ M
PARTIAL LOAD REJECTION	720	COLD	760	726	– 34	– 34/1.2 M
		HOT	1060	1020	– 34	–34/1.2 M
REFUELING SHUTDOWN	180	COLD	760	500	–260	–23/30 M
		HOT	1060	500	–560	–50/30 M
SPURIOUS REACTOR TRIP	575	COLD	760	600	–160	–19.3/30 M
		HOT	1060	600	–460	–190/8 S 0/10 S +145/30 S –50/30 M
LOSS OF FLOW	10 TO 30	COLD	760	730	–30	–40/M; +10/M
		HOT	1060	1060	0	+83/5 S –83/20 S
CONTROL ROD WITHDRAWL	1	COLD	760	600	–160	–18.2/30 M
		HOT	1060	600	–460	+48/4S –190/8 S 0/10 S +122/30 S –50/30 M

70-MA1-48-249

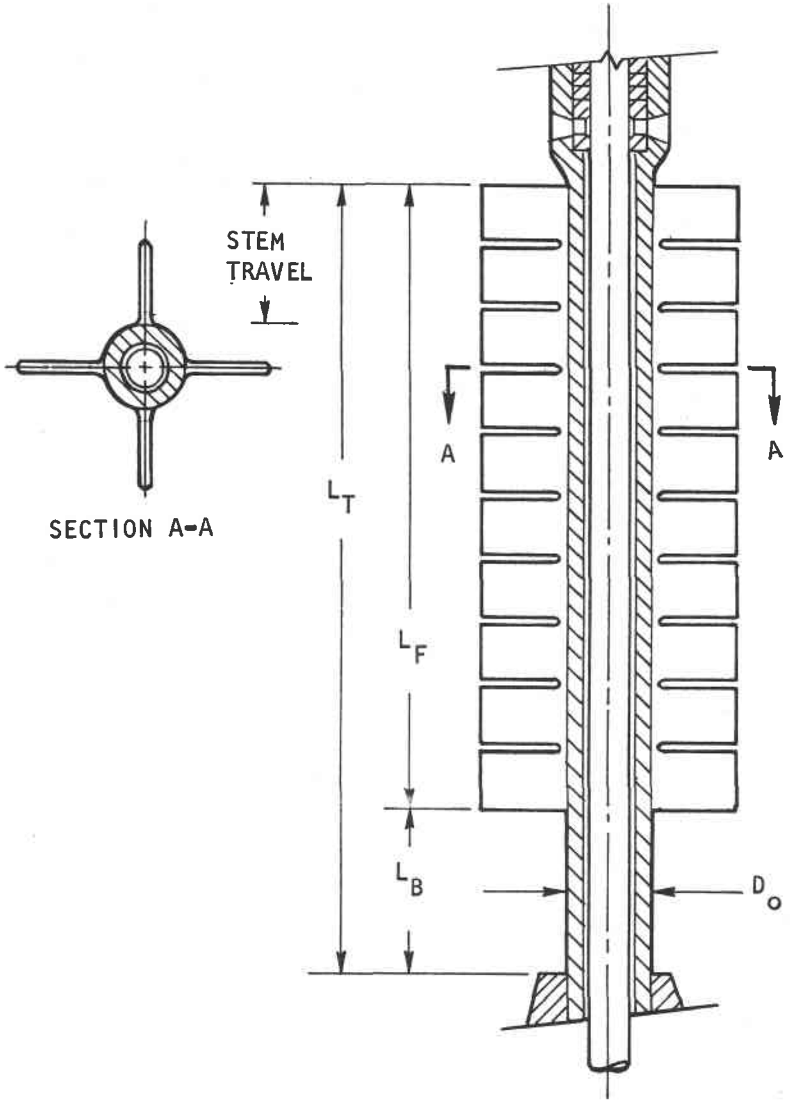
TYPICAL VALVE DESIGN DATA SHEET

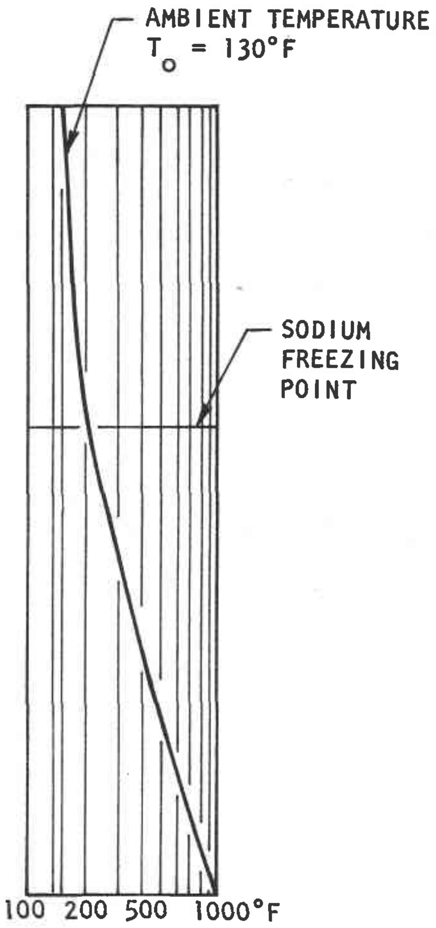
ITEM	BLOCKING VALVE	THROTTLING VALVE	CHECK VALVE
TYPE	SPLIT WEDGE GATE	BUTTERFLY	SWING DISC
LOCATION	REACTOR INLET	REACTOR INLET	REACTOR INLET
OPERATING TEMPERATURE	1060°F	760°F	760°F
NOMINAL OPERATING PRESSURE	120 psig	120 psig	120 psig
FLOW RATE	15.6×10^6 lb/hr	15.6×10^6 lb/hr	15.6×10^6 lb/hr
VALVE SIZE	30 in.	30 in.	30 in.
INTERNAL (SEAT) LEAKAGE	2×10^{-3} ft^3/hr MAX. @ 50 psi ΔP	NA	NA
PRESSURE DROP AT RATED FLOW	0.5 psi MAS.	5 psi MAX.	1 psi MAX.
FLOW CONTROL RANGE	NA	0% to 25% OF RATED FLOW*	NA
ACTUATOR	PNEUMATIC OR MOTOR	PNEUMATIC OR MOTOR	NA
CLOSURE SPEED	1 TO 2 in./sec	15%/sec	NA
STEM SEAL	GAS COOLED FREEZE SEAL	GAS COOLED FREEZE SEAL	NA

*ABOVE 25% OF RATED LOOP FLOW, THE VARIABLE SPEED PUMP DRIVES CONTROL LOOP FLOW RATES

70-MA1-48-244

FREEZE SEAL TEMPERATURE PROFILE





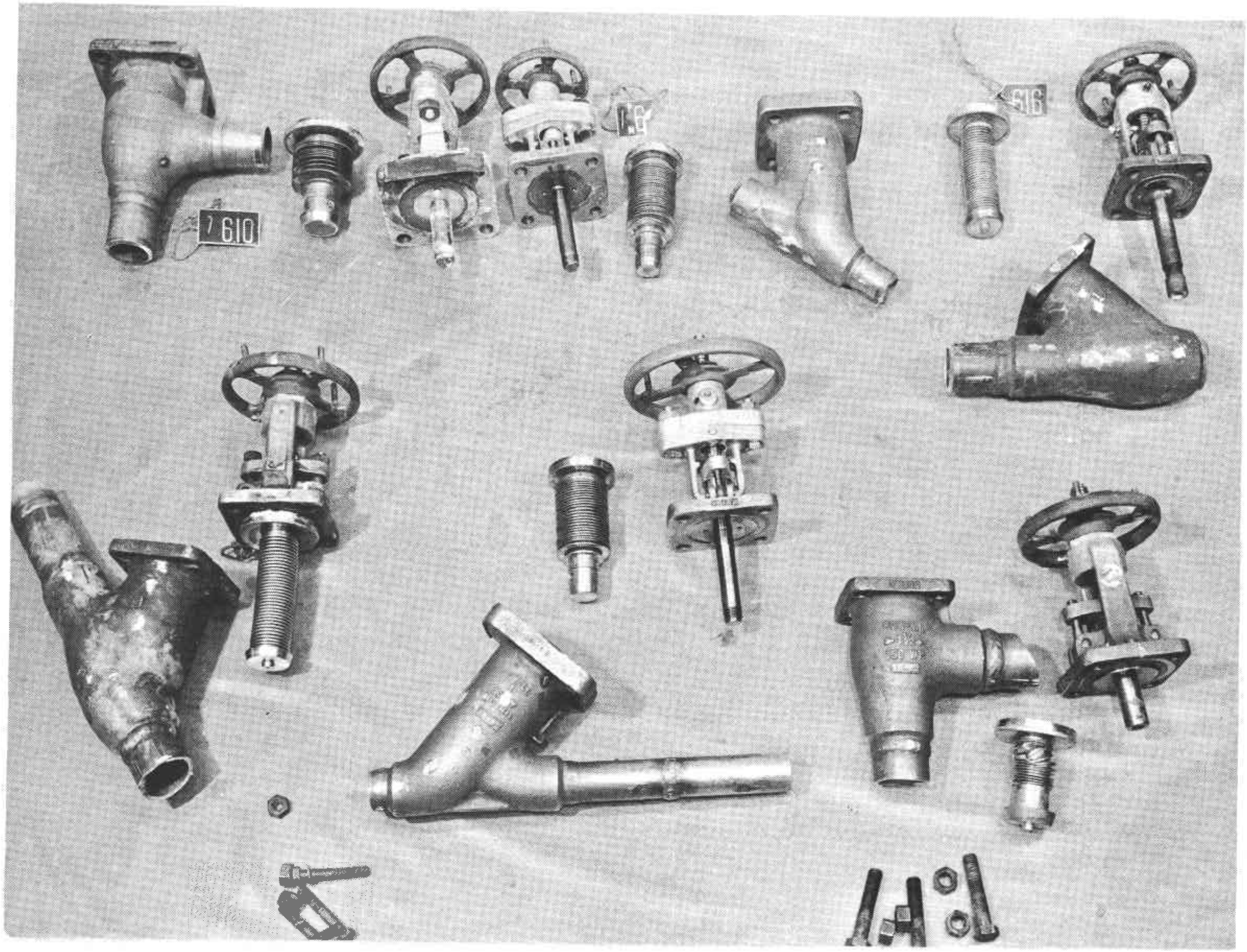
SEMI-LOG PLOT OF PREDICTED STEM TEMPERATURE

70-MA1-48-242

DAMAGED VALVE BELLOWS-SRE

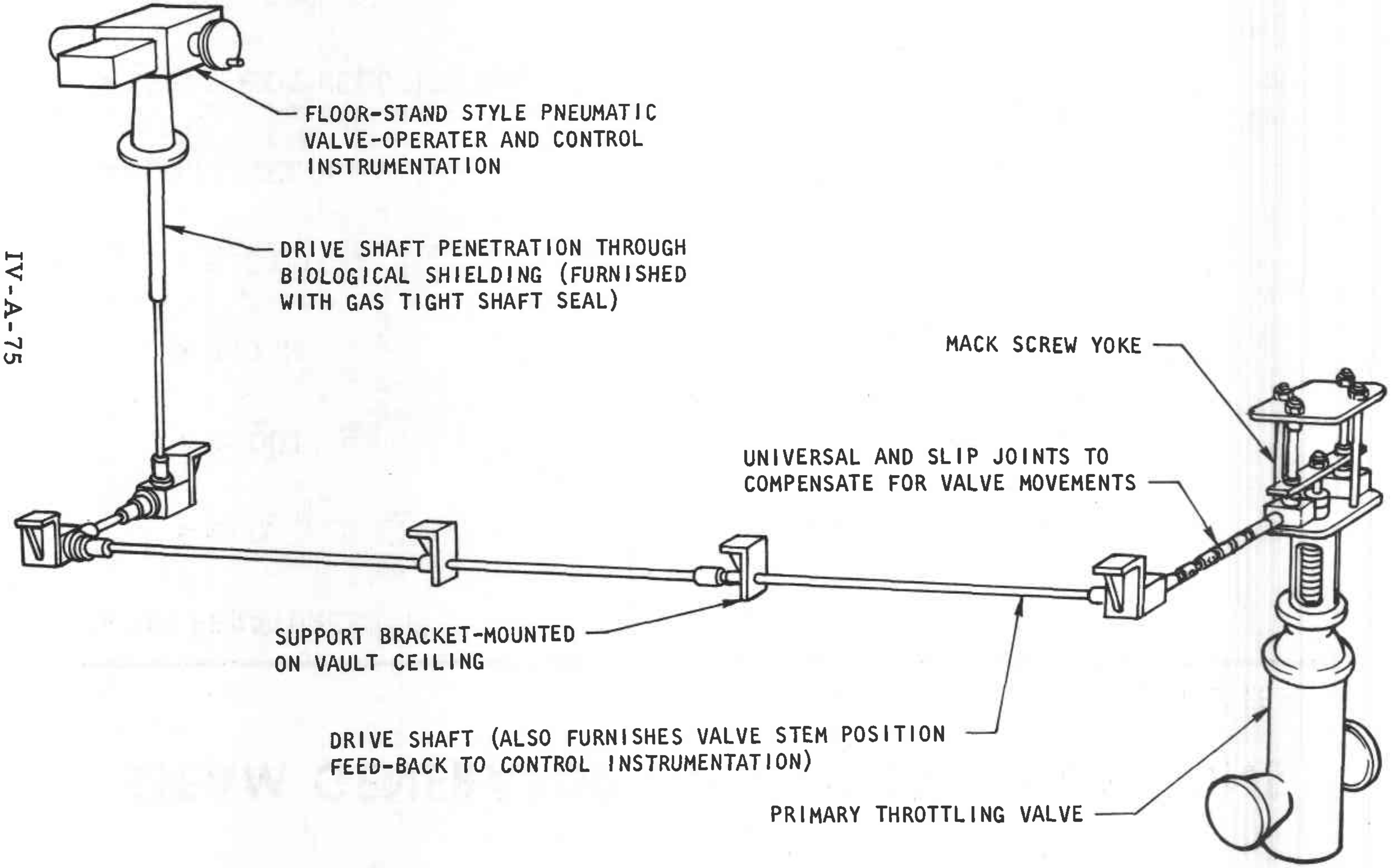
70-MA1-48-219

DAMAGED BELLOWS-SEALED VALVES-SRE



70-MA1-48-223

REMOTE VALVE OPERATOR AND DRIVE SHAFTING



70-MA1-48-240

STEAM GENERATOR OPERATING CONDITIONS

	EVAPORATOR	SUPERHEATER
• TEMPERATURES (°F)		
▪ Na IN	855	950
▪ Na OUT	700	855
▪ H_2O IN	470	715
▪ H_2O OUT	715	905
• SODIUM VELOCITY (fps)	8.5	11.0
• STEAM EXIT VELOCITY (fps)	37.4	173
• PRESSURE DROP (psi)		
▪ H_2O	44	245
▪ Na	21	29

8-JY15-117-9

STEAM GENERATOR CONCEPT SELECTION

	ADVANTAGE	
	UNITIZED	MODULAR
LEAK DETECTION SENSITIVITY		+
LEAK EFFECTS SEVERITY		+
AVAILABILITY, MAINTAINABILITY		+
DESIGN SIMPLICITY, INSPECTABILITY		+
NUMBER OF POTENTIAL SUPPLIERS		+
ACCOMMODATE FULL SCALE TESTS		+
CAPITAL COST	+	

7-A8-179-13A

MATERIAL SELECTION TRADE-OFFS

AUSTENITIC STAINLESS	VS	INCOLOY 800	VS	FERRITIC
● STRESS CORROSION RISK		● LACK OF STEAM EXPERIENCE ● COST PENALTY		● REDUCED TEMPERATURE COST PENALTY

CONCLUSION: FERRITIC PREFERRED BASED ON RISK REDUCTION

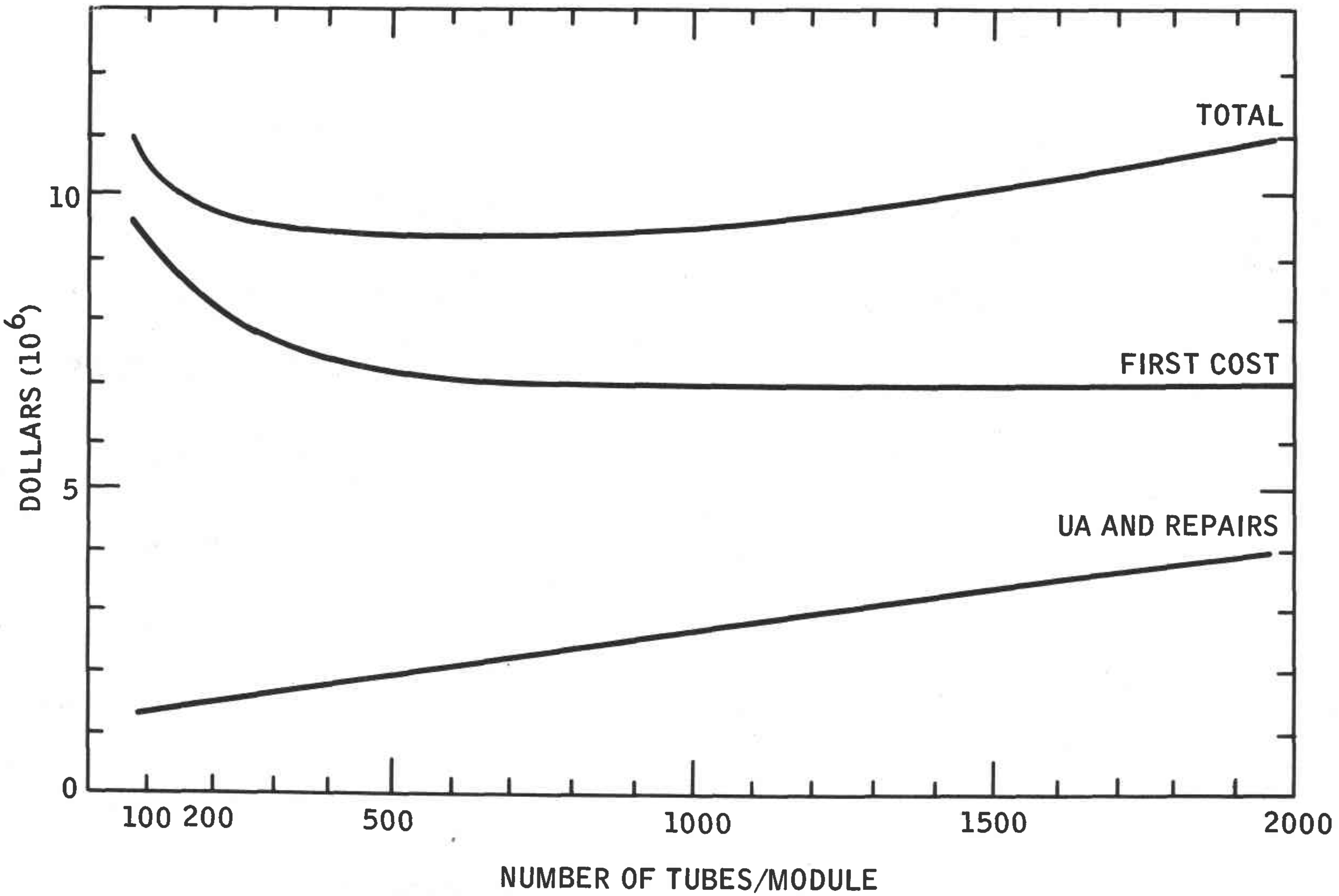
7-A8-179-16

MODULE SIZE STUDY

- FIRST COSTS
  - UNITS (PLUS SPARES)
  - Na, H_2O, RELIEF PIPING
  - BUILDING
  - INSTRUMENTS AND MISCELLANEOUS
- UNAVAILABILITY AND REPAIR COSTS (30 yr)
  - TUBE FAILURE RATES 2×10^{-9} AND 2×10^{-8}/TUBE HOUR
  - LEAKS CORRECTED BY
    - REPAIRS
    - REPLACEMENT WITH SPARES ON HAND
    - REPLACEMENT WITH UNIT ORDERED AFTER FAILURE

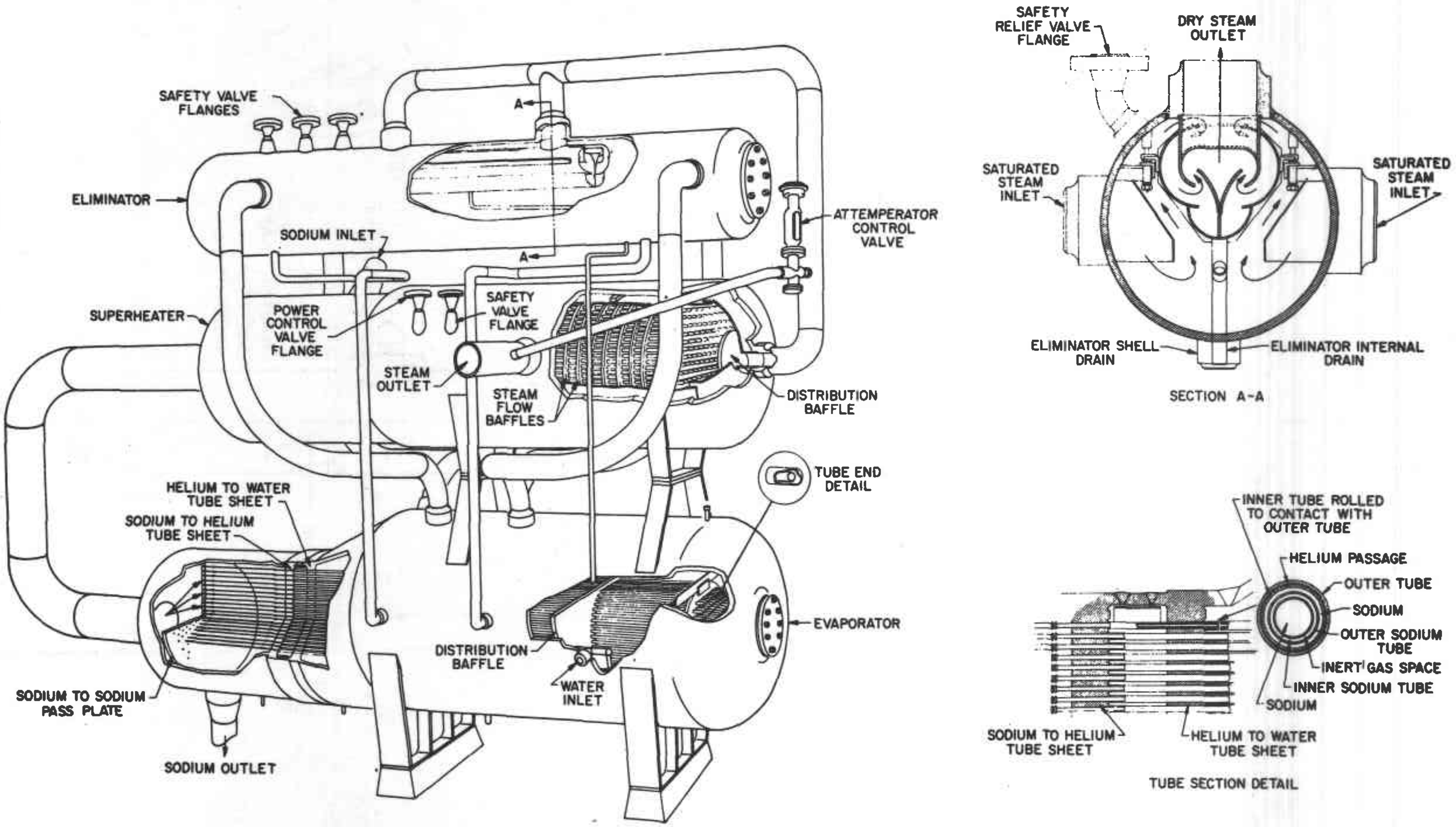
8-JY15-117-6

STEAM GENERATOR COST vs SIZE



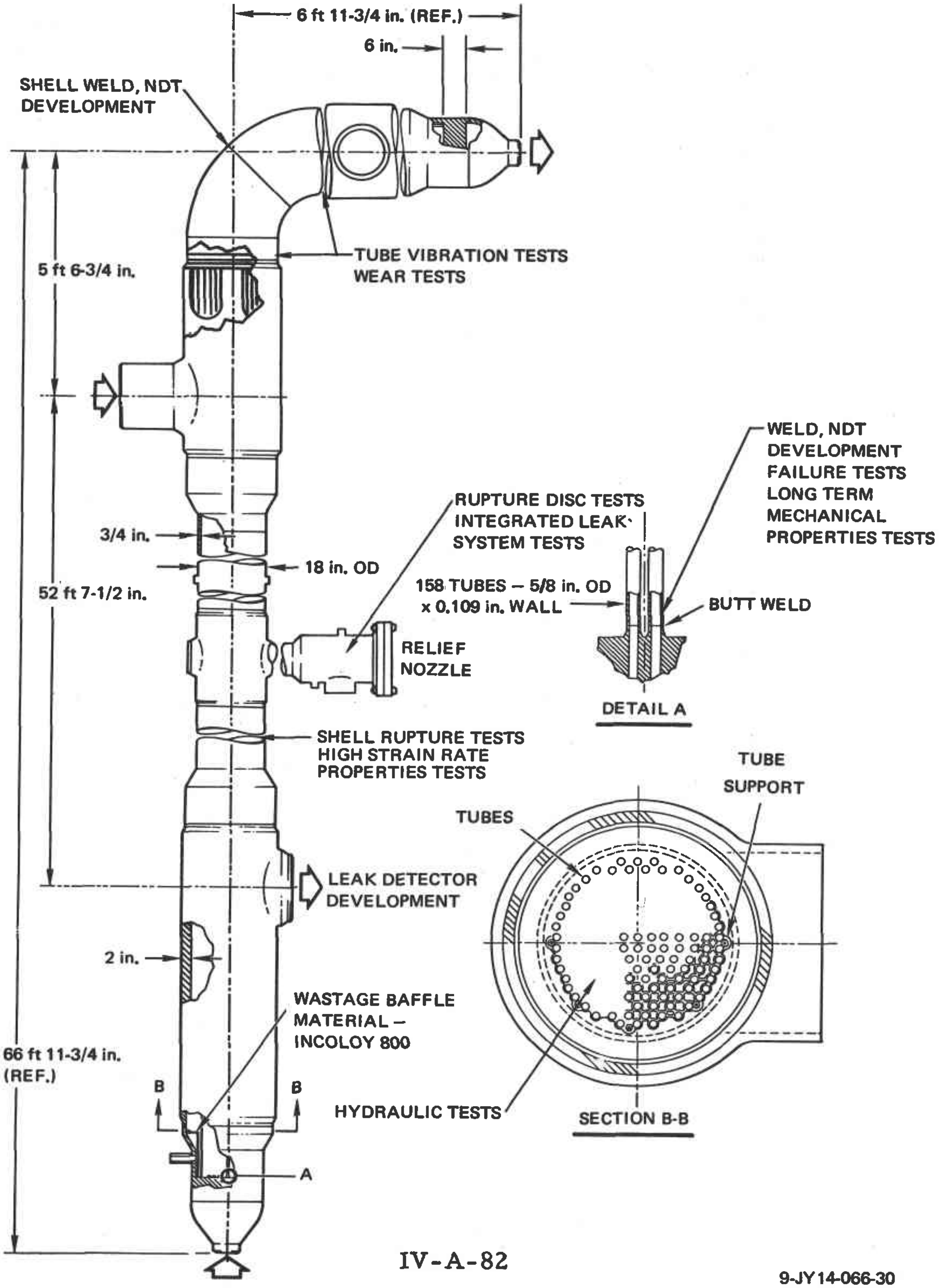
8-JY15-117-22

HALLAM STEAM GENERATOR



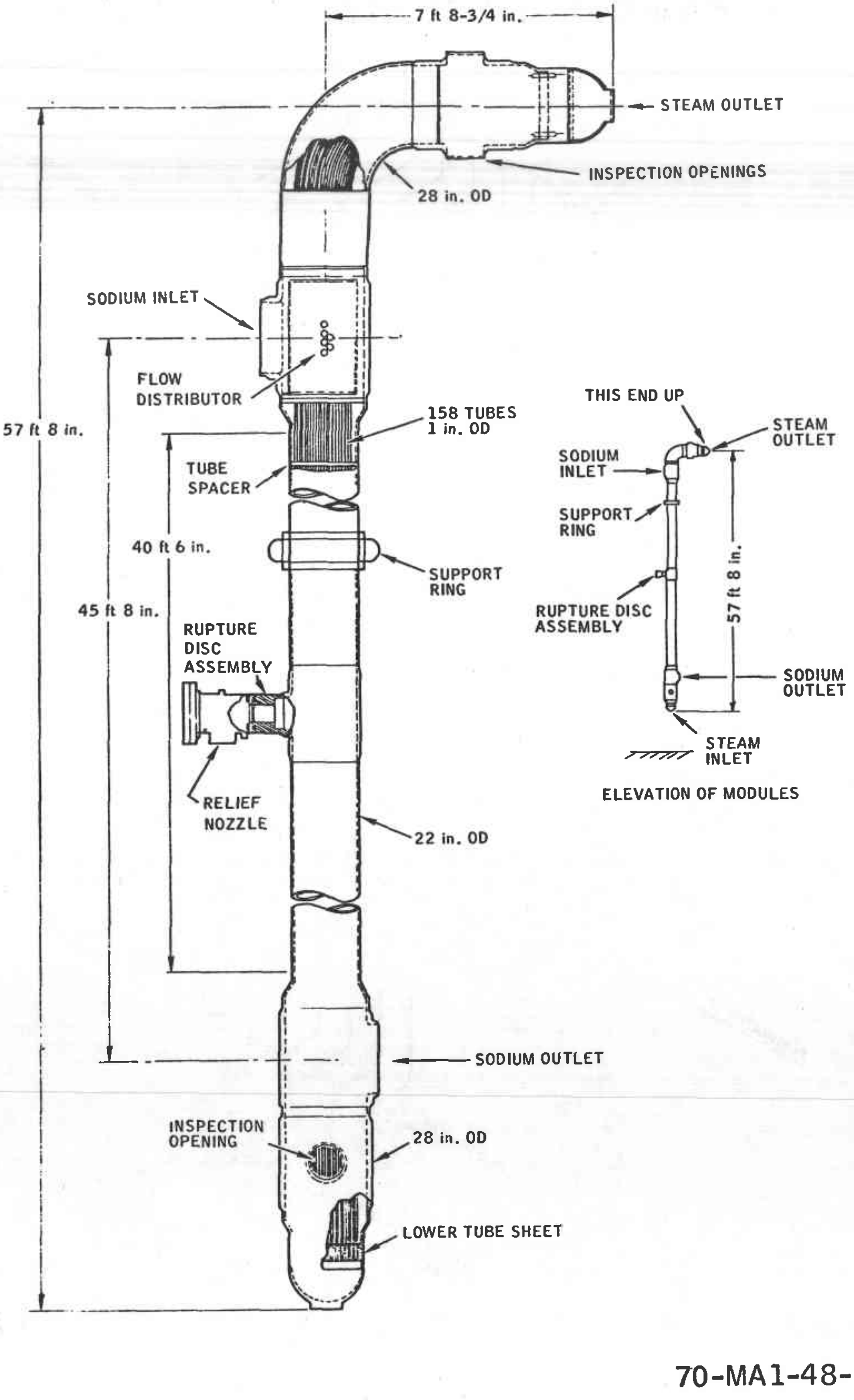
Steam Generator

EVAPORATOR/SUPERHEATER MODULE



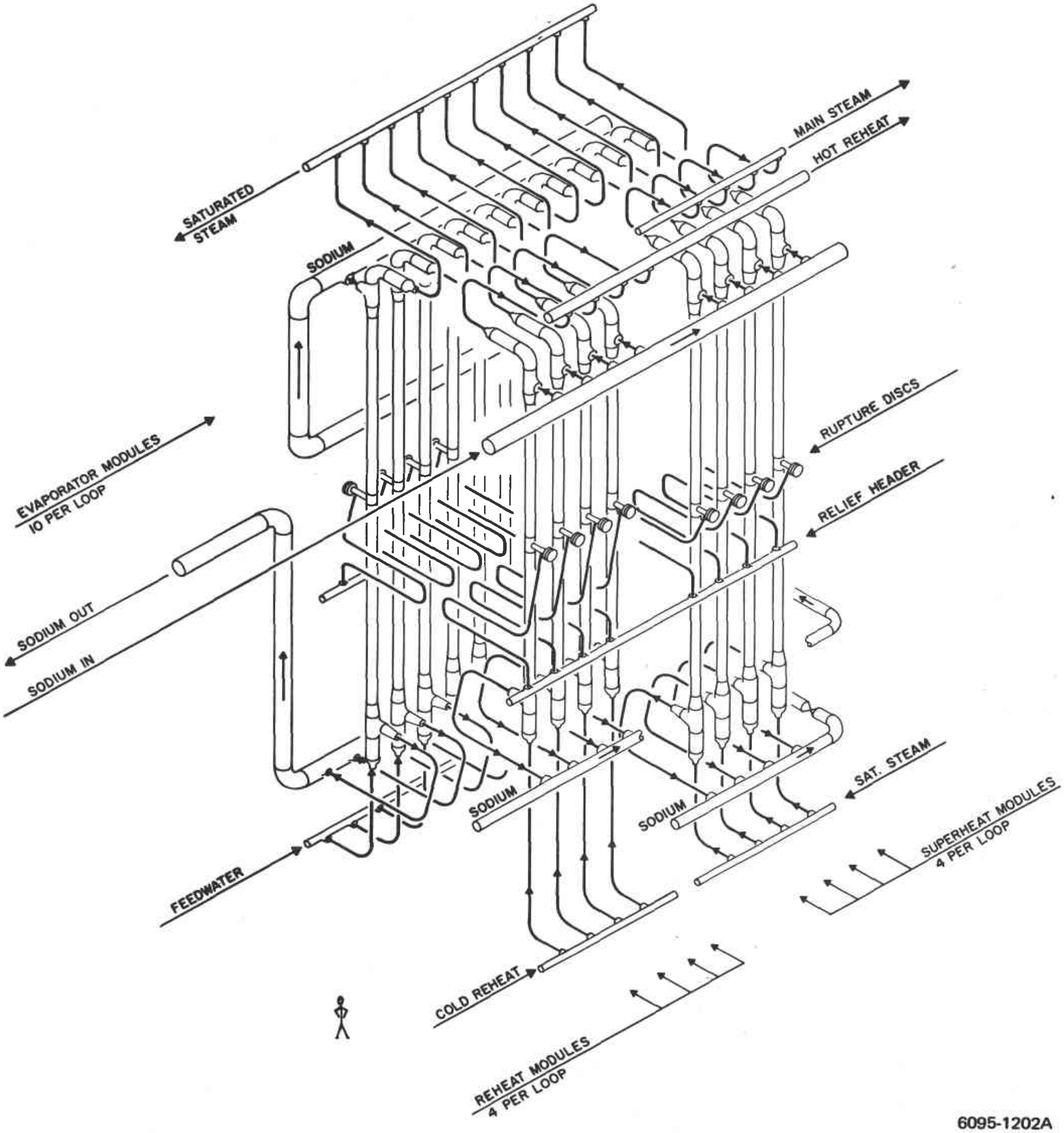
9-JY14-066-30

MODULAR STEAM GENERATOR



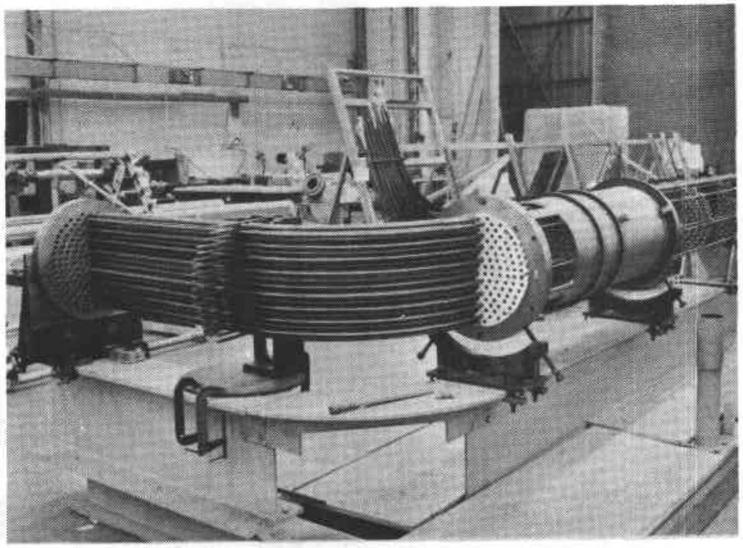
70-MA1-48-187

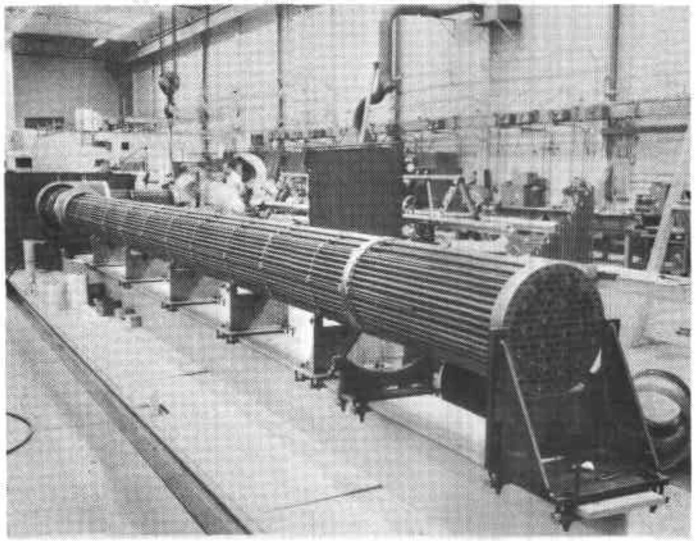
MODULAR STEAM GENERATOR ARRANGEMENT

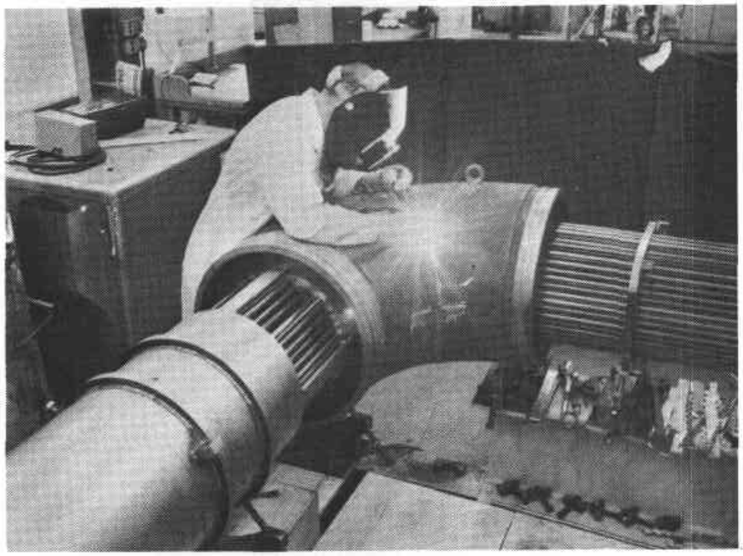


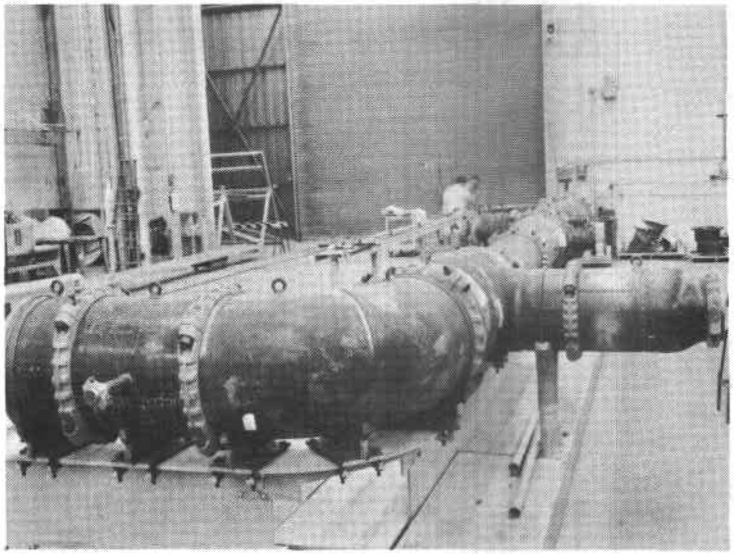
6095-1202A

STEAM GENERATOR TEST MODULE



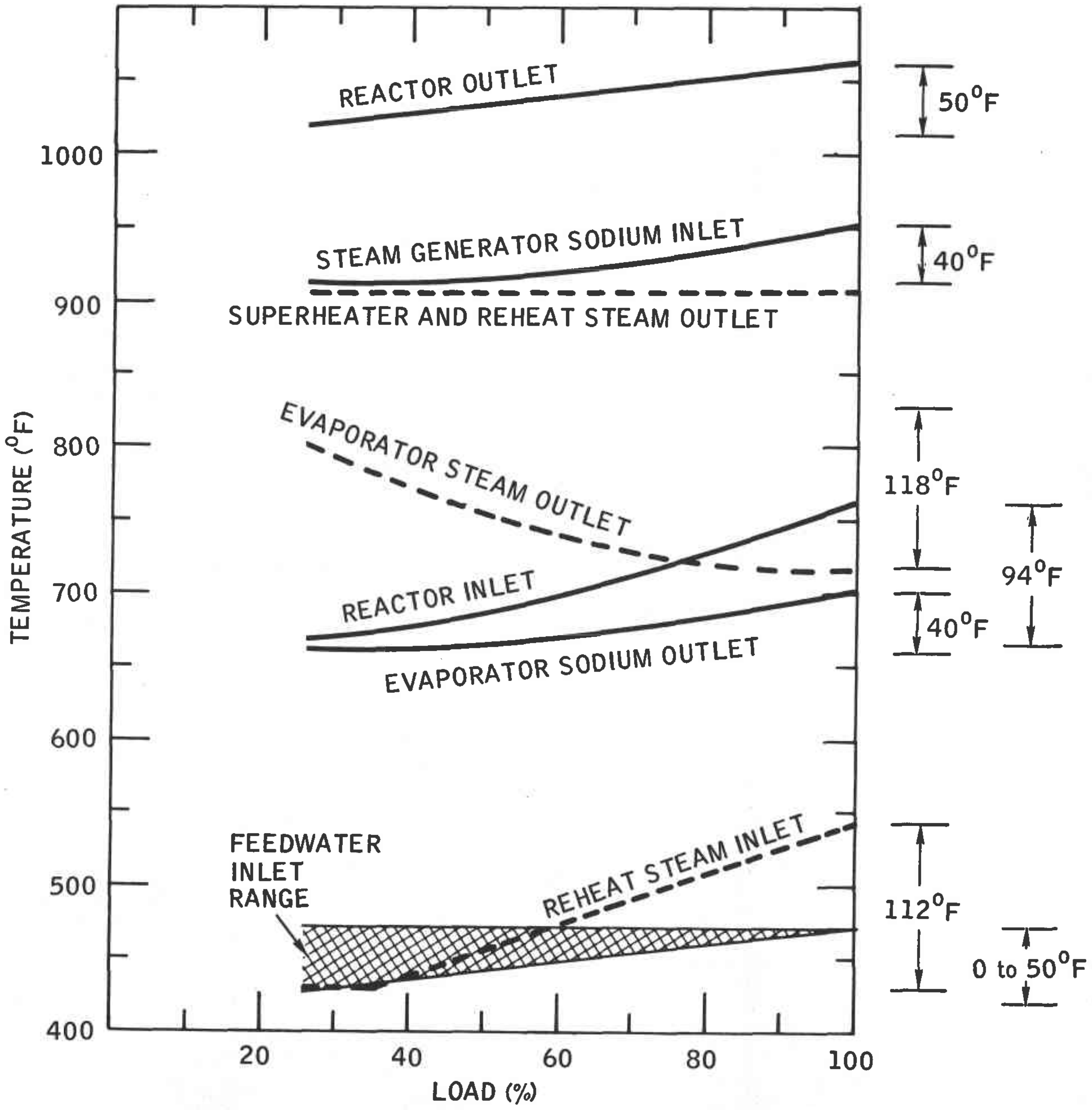






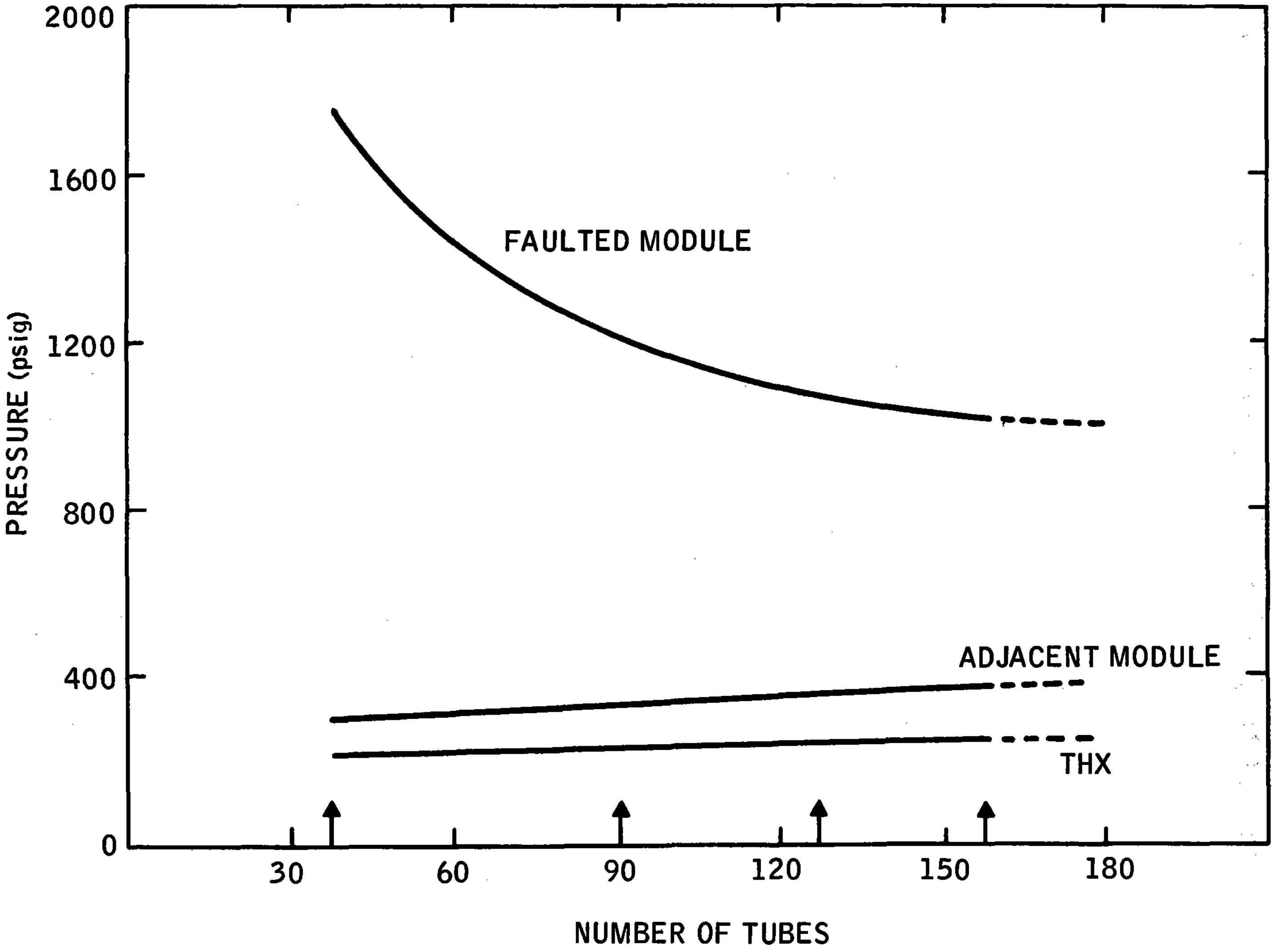
9-JU5-066-12

TEMPERATURE PROGRAM 500 Mwe FBR



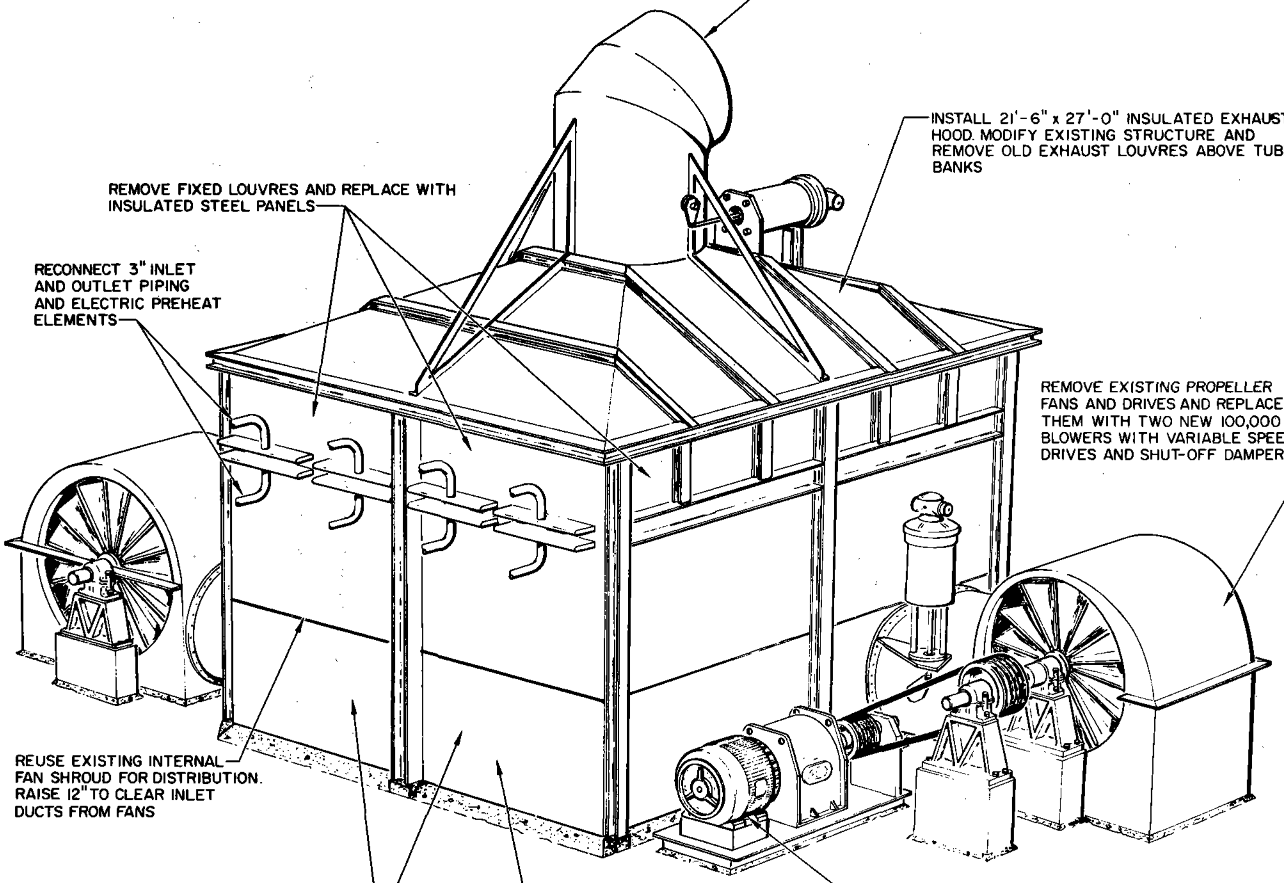
9-JA28-015-18

PEAK PRESSURES FROM TUBE FAILURE
(INITIAL PRESSURE 200 psig)



8-JY15-117-8

SRE – PEP
MAIN AIR BLAST HEAT EXCHANGER



INSTALL 10'-0" DIA. EXHAUST STACK WITH PNEUMATIC ACTIVATED DAMPER AND DIRECT STACK AWAY FROM BUILDINGS

INSTALL 21'-6" x 27'-0" INSULATED EXHAUST HOOD. MODIFY EXISTING STRUCTURE AND REMOVE OLD EXHAUST LOUVRES ABOVE TUBE BANKS

REMOVE FIXED LOUVRES AND REPLACE WITH INSULATED STEEL PANELS

RECONNECT 3" INLET AND OUTLET PIPING AND ELECTRIC PREHEAT ELEMENTS

REMOVE EXISTING PROPELLER FANS AND DRIVES AND REPLACE THEM WITH TWO NEW 100,000 cfm BLOWERS WITH VARIABLE SPEED DRIVES AND SHUT-OFF DAMPERS

REUSE EXISTING INTERNAL FAN SHROUD FOR DISTRIBUTION. RAISE 12" TO CLEAR INLET DUCTS FROM FANS

CONNECT FAN DRIVES TO STARTERS AND 4160v, 3 PHASE SYSTEM

REMOVE MECHANICAL LOUVRES AND REPLACE WITH FABRICATED STEEL PANELS ON FOUR SIDES

PROVIDE INERT GAS BLANKET SYSTEM TO FLOOD EXCHANGER

7519-1501A

SRE MAIN AIR COOLED HEAT EXCHANGER

- CAPACITY .... 20 Mwt
- SURFACE 1 in. FIN TUBES .... 34,000 ft^2
- FAN VARIABLE SPEED PROPELLER .... 2 - 50 hp
- OPERATING CONDITIONS
  - SODIUM INLET (°F) 900
  - SODIUM OUTLET (°F) 440
  - AIR INLET (°F) 100
  - AIR FLOW (cfm) 200,000
- PROBLEM
  - POOR TEMPERATURE CONTROL DURING PREHEAT AND LOW FLOW
- REASON
  - EXCESSIVE AIR LEAKAGE OF AIR LOUVERS FOR AIR CONTROL
- CORRECTIVE ACTION
  - UNIT NOT REQUIRED BECAUSE OF EXCELLENT PERFORMANCE OF STEAM GENERATOR AND TURBINE PLANT
- SRE-PEP
  - THE UNIT WAS TO BE REBUILT TO BE COMPLETELY ENCLOSED AND USE BLOWERS WITH POSITIVE CONTROL OF AIR FLOW
- PROPOSED PEP OPERATING CONDITIONS
  - SODIUM INLET (°F) 1150
  - SODIUM OUTLET (°F) 600
  - AIR INLET (°F) 100
  - AIR FLOW (cfm) 200,000

FFTF-DHX PRELIMINARY CONCEPT

TUBE BUNDLE PERFORMANCE:

- TUBE SIDE

TOTAL SODIUM FLOW (lb/hr)	1.52×10^6
FLOW PER TUBE (lb/hr)	2.4×10^4
FLUID VELOCITY (ft/sec)	8
FLUID PRESSURE DROP (psi)	11.7
INLET TEMPERATURE (°F)	755
OUTLET TEMPERATURE (°F)	515

- AIR SIDE

AIR FLOW (lb/hr)	1.093×10^6
FACE VELOCITY (ft/min.)	640
UNIT MASS FLOW (lb/ft^2-hr)	7.23×10^3
PRESSURE DROP (in. H_2O)	1.81
INLET TEMPERATURE (°F)	110
OUTLET TEMPERATURE (°F)	535

70–F19–019–8

PRELIMINARY CONCEPT

- PRINCIPAL FEATURES:
  - FOUR PARALLEL 33 Mwt MODULES PER LOOP
  - SERPENTINE FIN-TUBE BUNDLE ARRANGED FOR CROSS-COUNTERFLOW
  - VARIABLE SPEED CENTRIFUGAL BLOWERS WITH VARIABLE INLET GUIDE VANES
  - INSULATED TUBE BUNDLE HOUSING, DUCTS, AND AIR SHUTOFF DOORS
  - NORMAL (ELECTRIC) AND EMERGENCY (GAS) HEATING SYSTEMS
  - MONITORING AND WARNING INSTRUMENTATION

TUBE BUNDLE DETAILS

FFTF-DHX PRELIMINARY CONCEPT

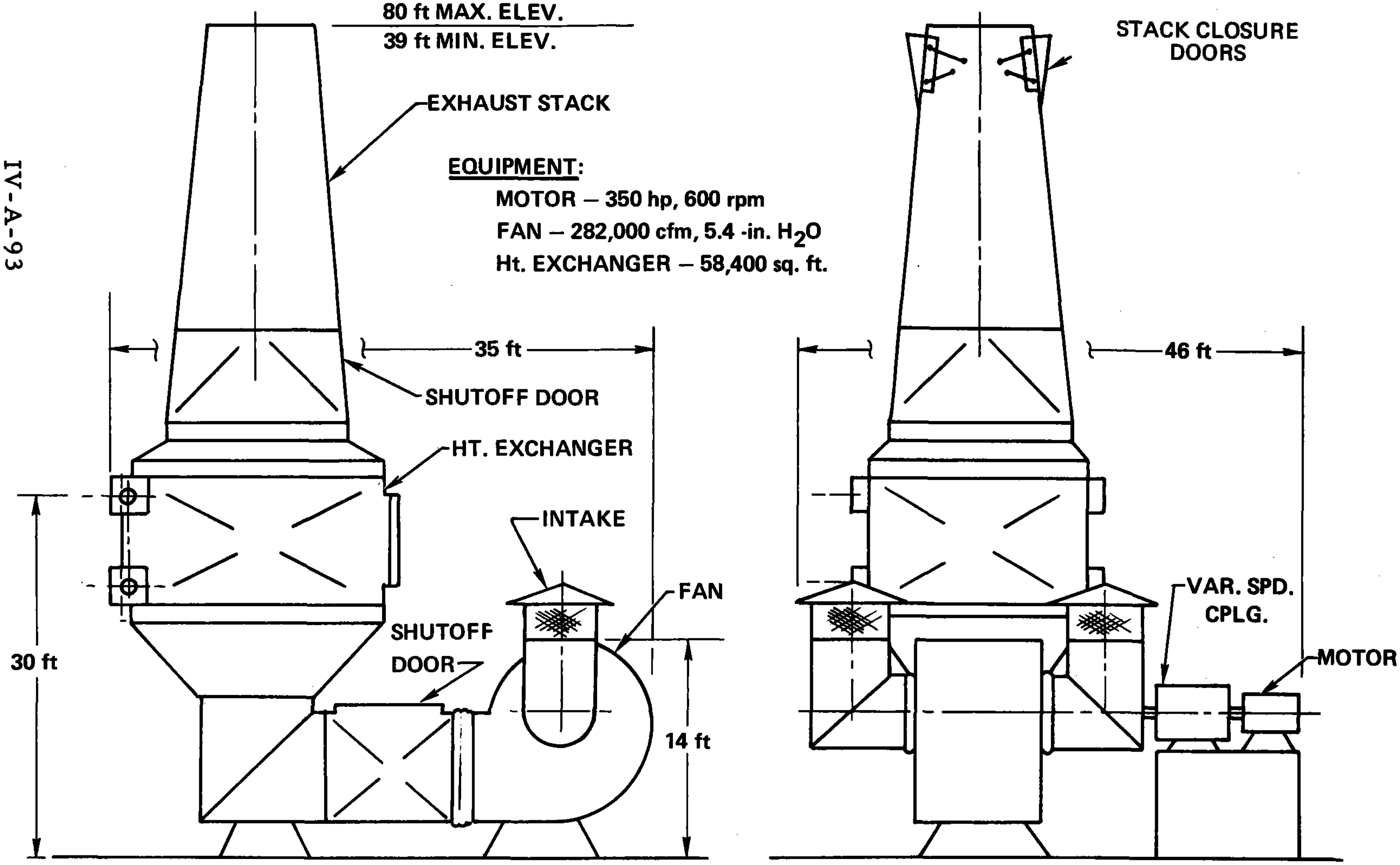
TUBE BUNDLE DETAILS:

NO. OF PARALLEL COILS	63
NO. OF PASSES/COIL	8
NO. OF ROWS/PASS	1
TYPE OF ARRAY	TRIANGULAR
HORIZONTAL PITCH (in.)	3.8
TUBE OD (in.)	1.9
TUBE ID (in.)	1.682
ST. TUBE LENGTH (ft)	20
FIN OD (in.)	3.4
TUBE MATERIAL	TYPE 304 SS
FIN THICKNESS (in.)	0.030
NO. OF FINS/INCH	6
FIN MATERIAL	TYPE 410 SS
EXT. HT. TRANS. AREA (sq. ft)	58,500

NOTE: THESE PARAMETERS WERE USED AS THE BASIS OF CALCULATIONS AND DO NOT REPRESENT OPTIMIZED VALUES

70–F19–019–7

FFTF-DHX PRELIMINARY CONCEPT DHX MODULE ELEVATION

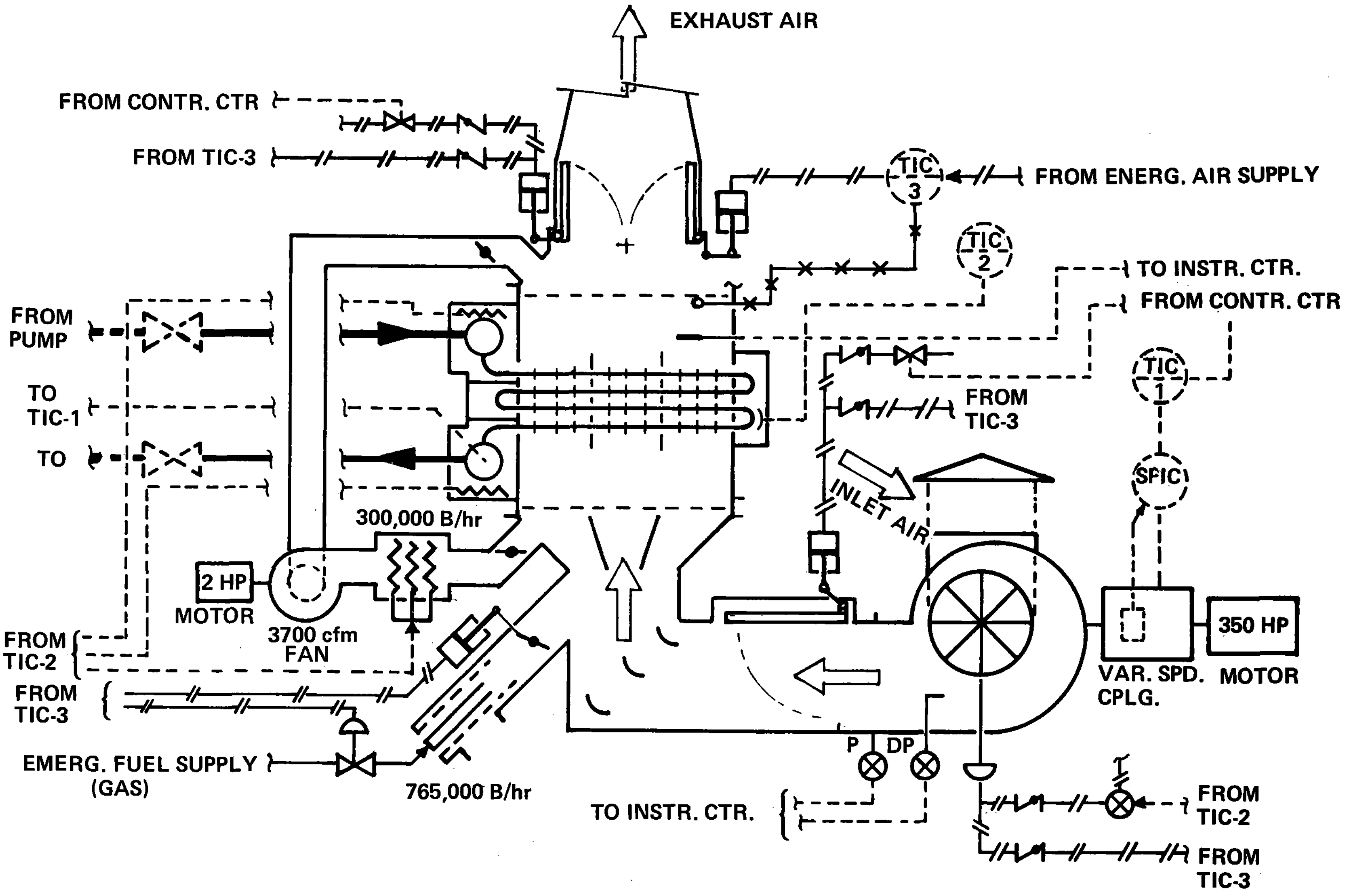


EQUIPMENT:
MOTOR – 350 hp, 600 rpm
FAN – 282,000 cfm, 5.4 -in. H_2O
Ht. EXCHANGER – 58,400 sq. ft.

70–F19–019–5

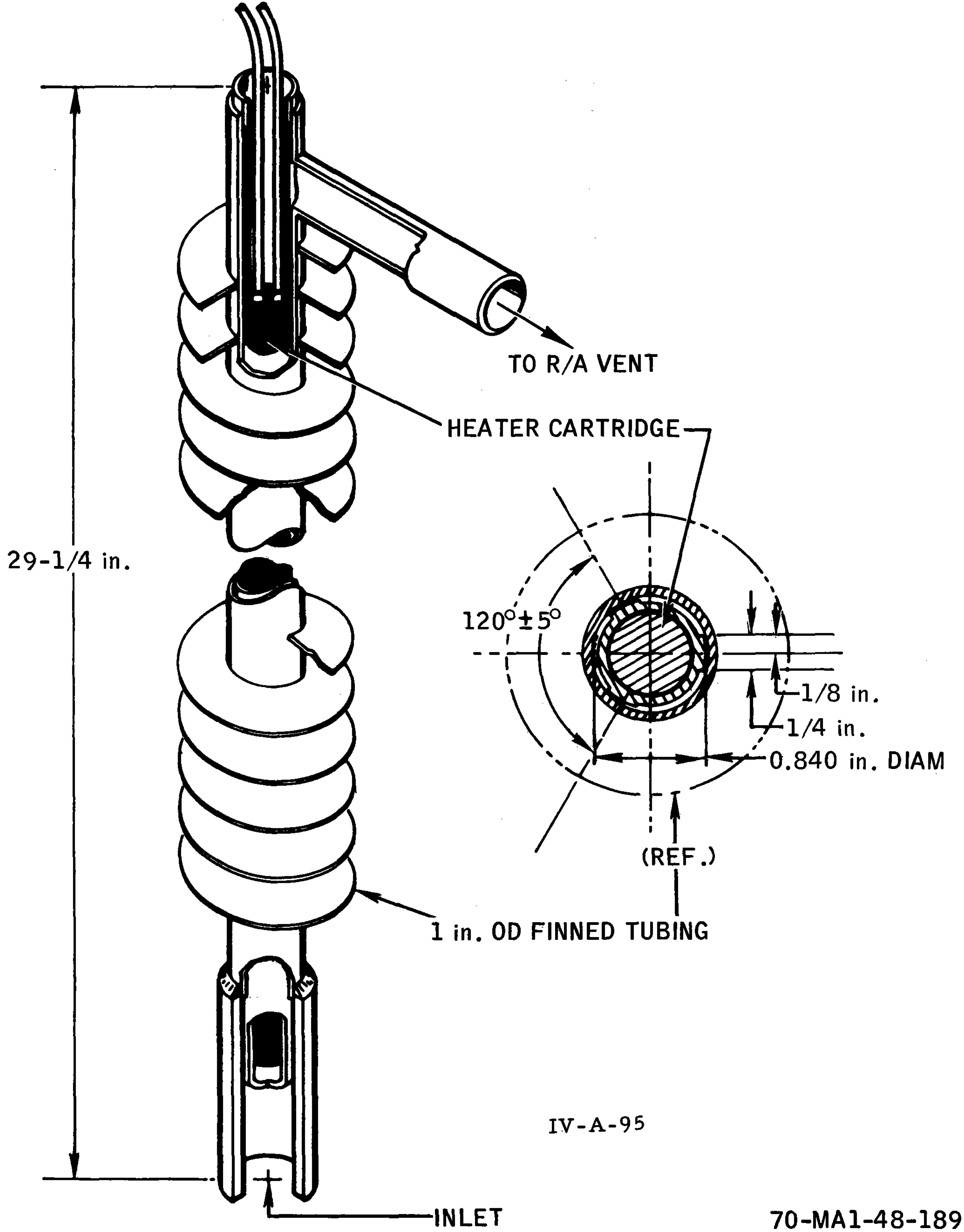
SIMPLIFIED DHX MODULE P&I DIAGRAM

FFTF-DHX PRELIMINARY CONCEPT



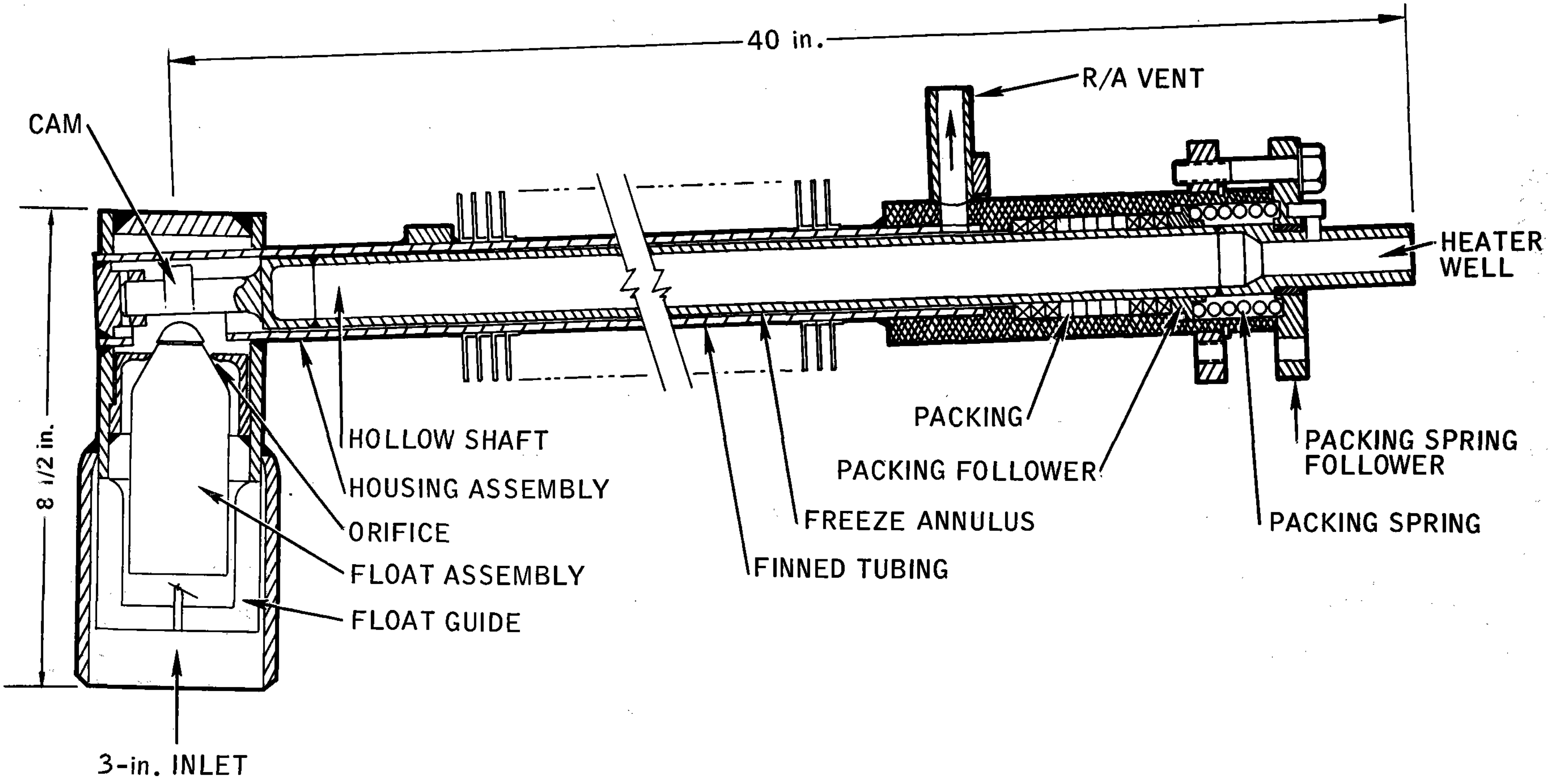
70–F19–019-6

SCTI FREEZE TRAP



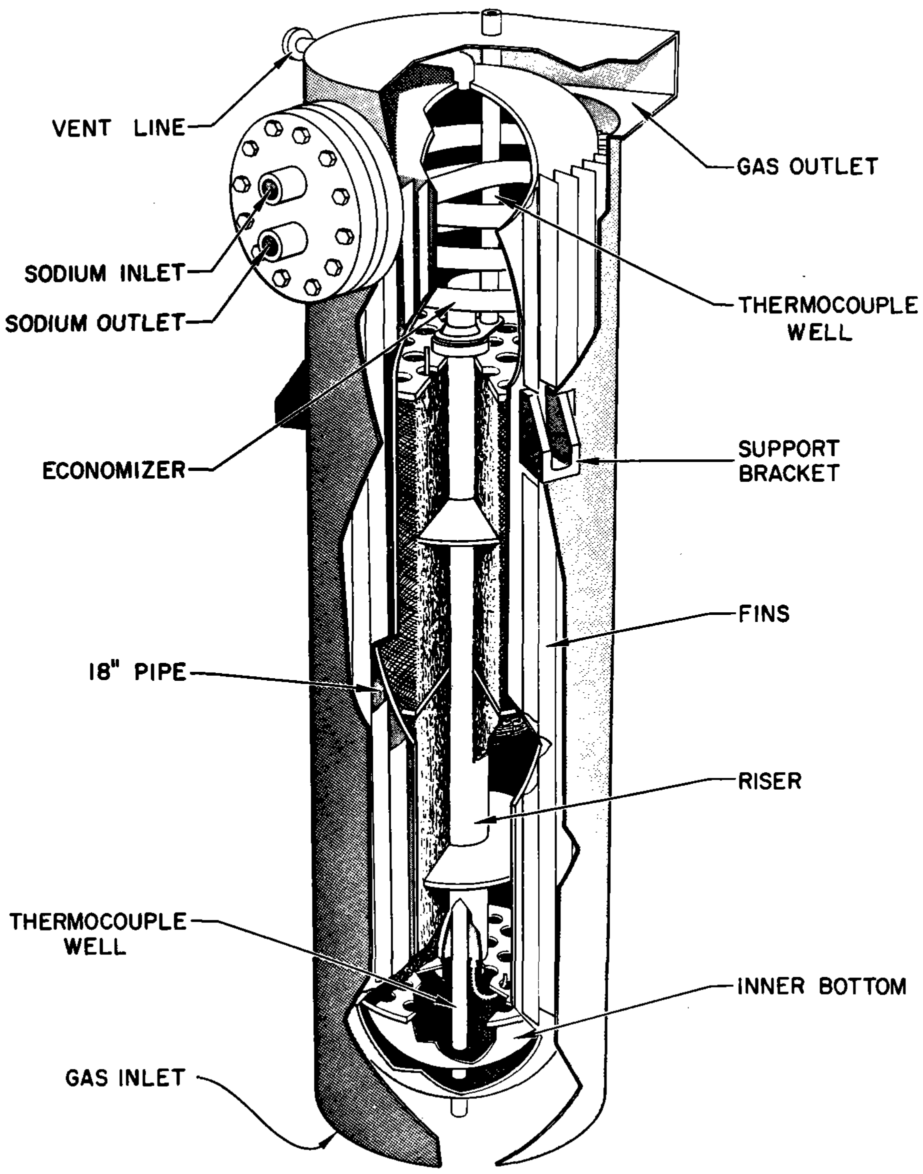
70-MA1-48-189

FREEZE TRAP ASSEMBLY
HNPF



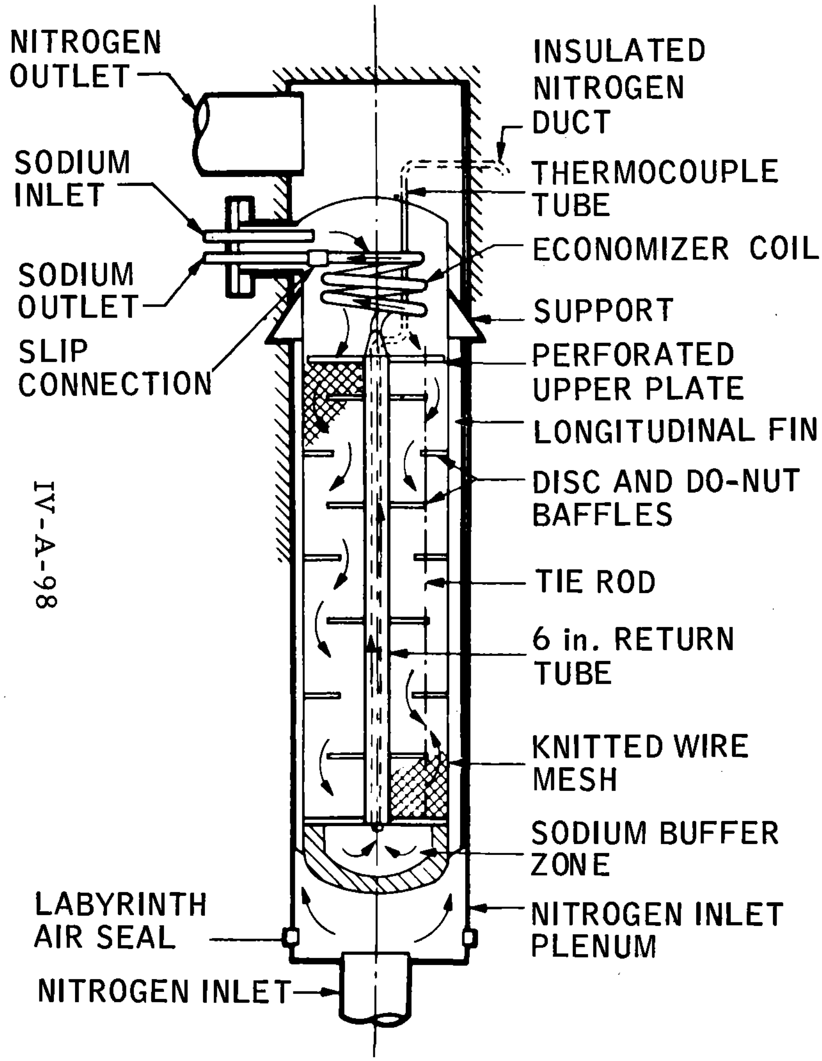
70-MA1-48-229

CIRCULATING COLD TRAP

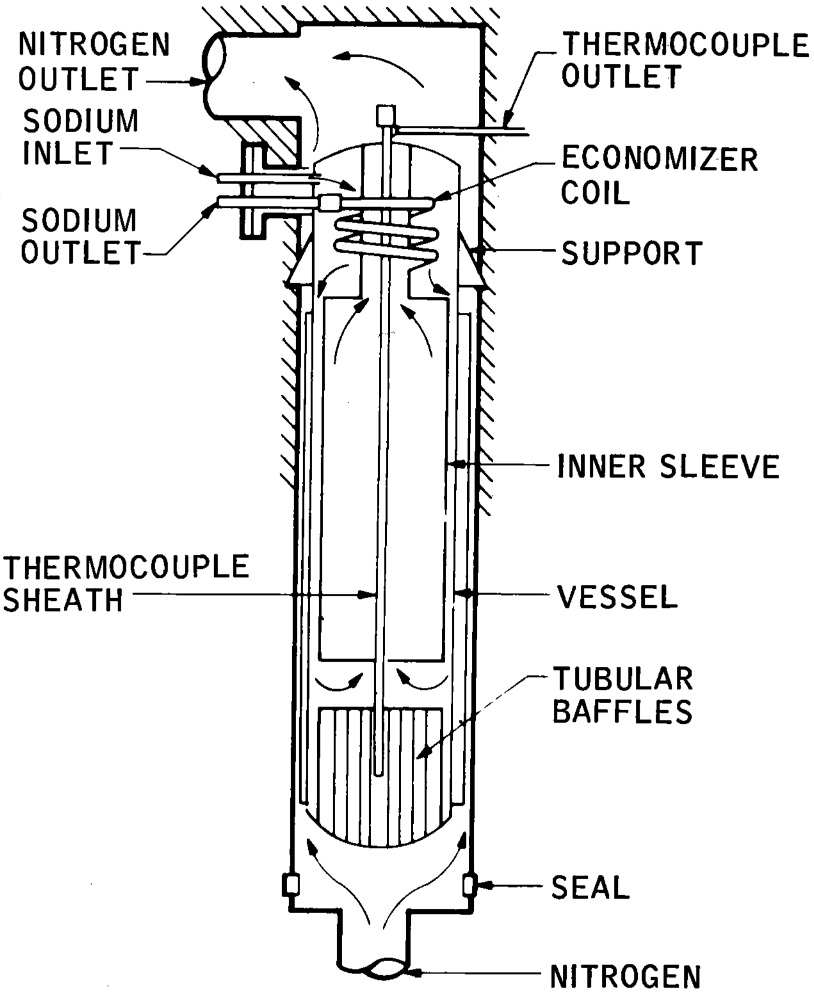


66-00-83-42

HNPF PACKED AND PACKLESS COLD TRAPS



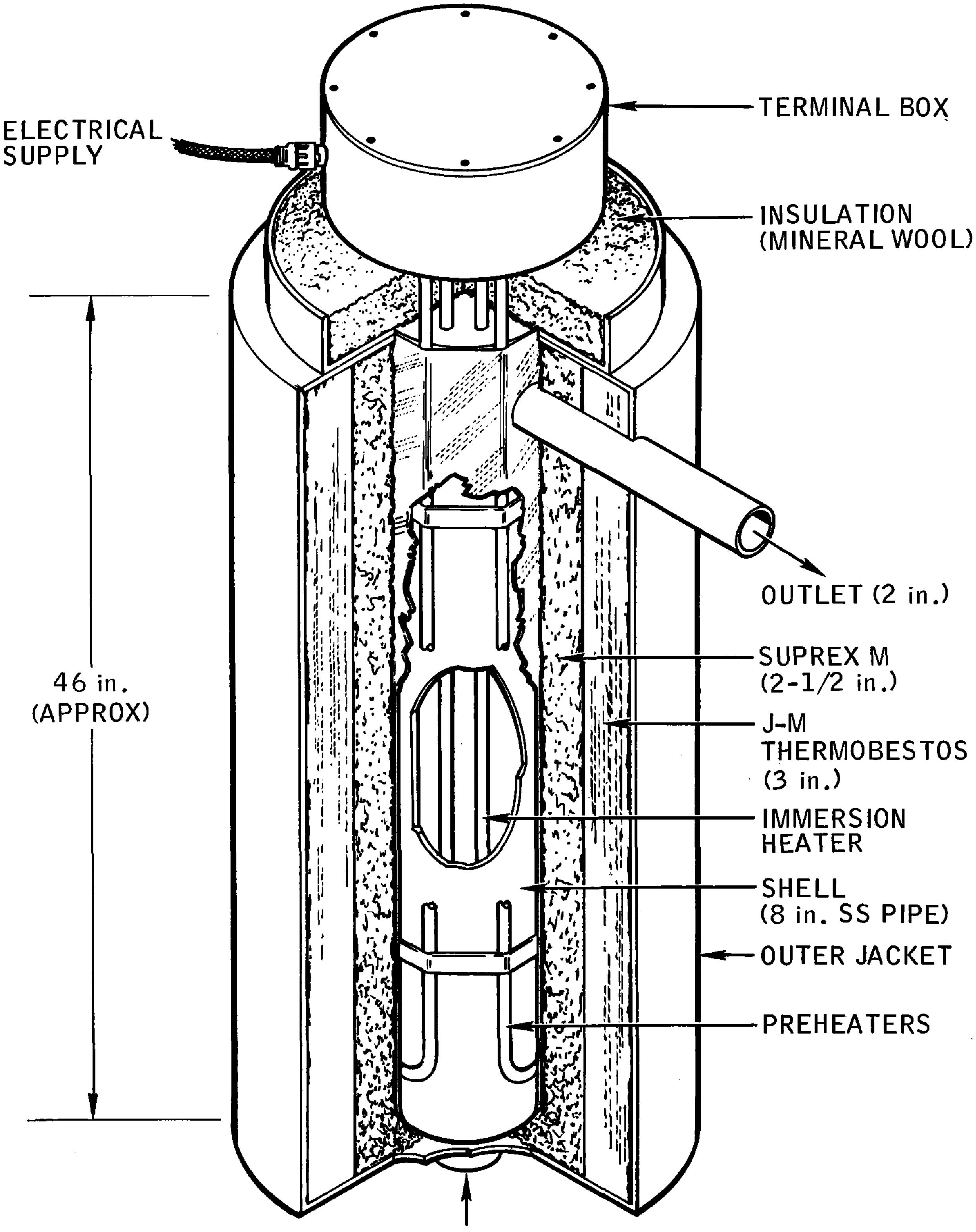
PACKED



PACKLESS

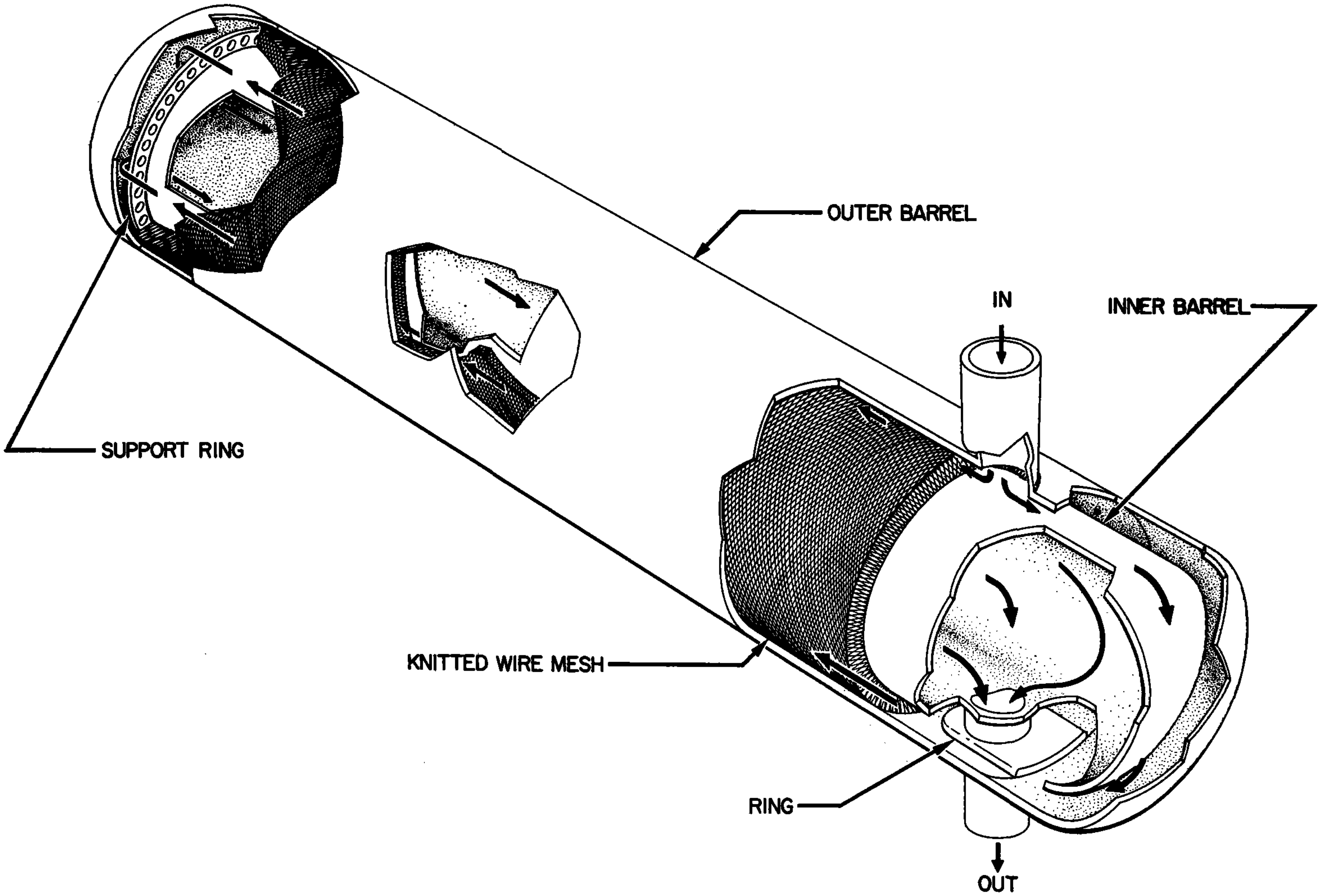
66-00-83-40

IMMERSION HEATER ASSEMBLY



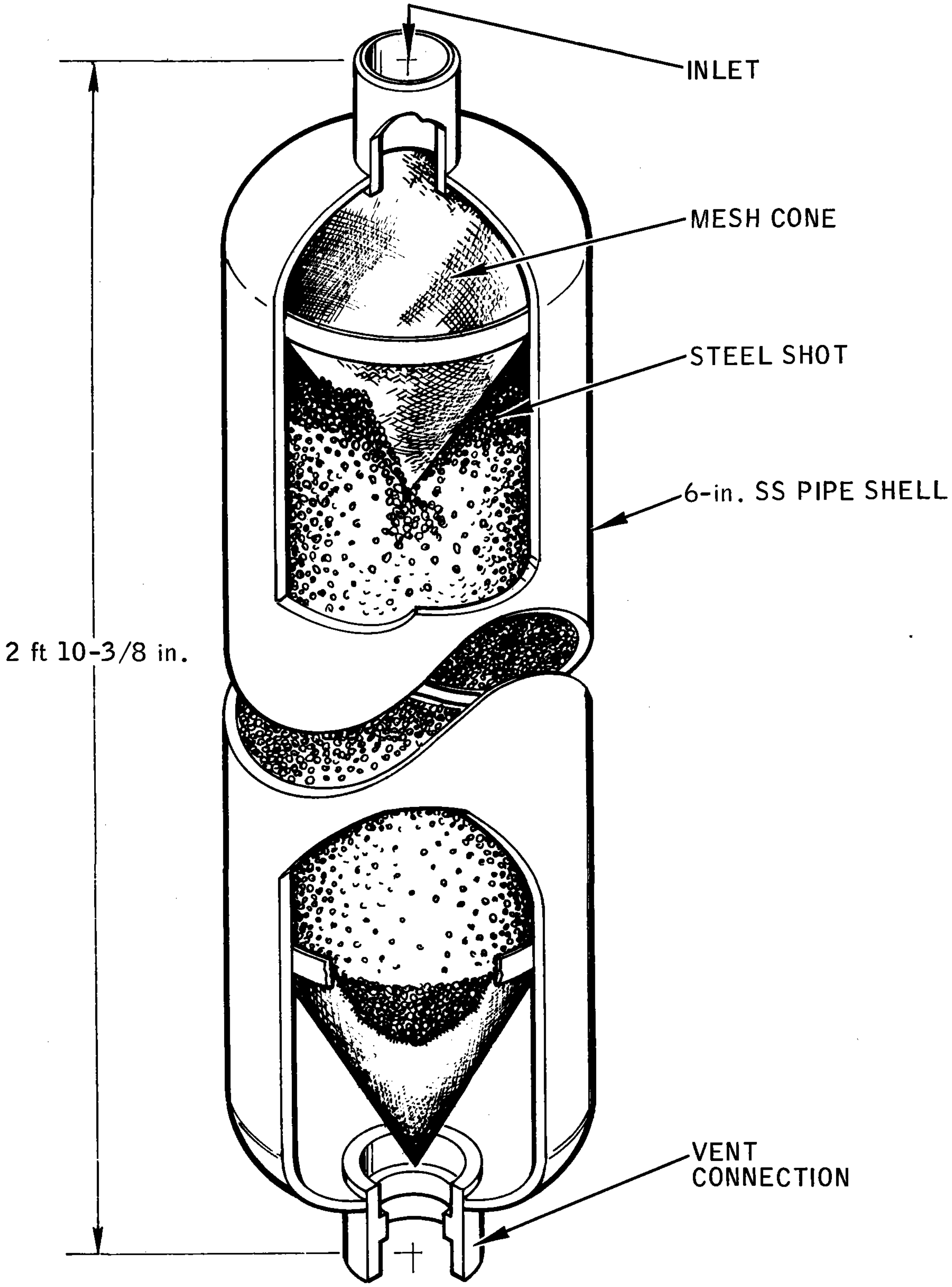
70-MA1-48-230

VAPOR TRAP



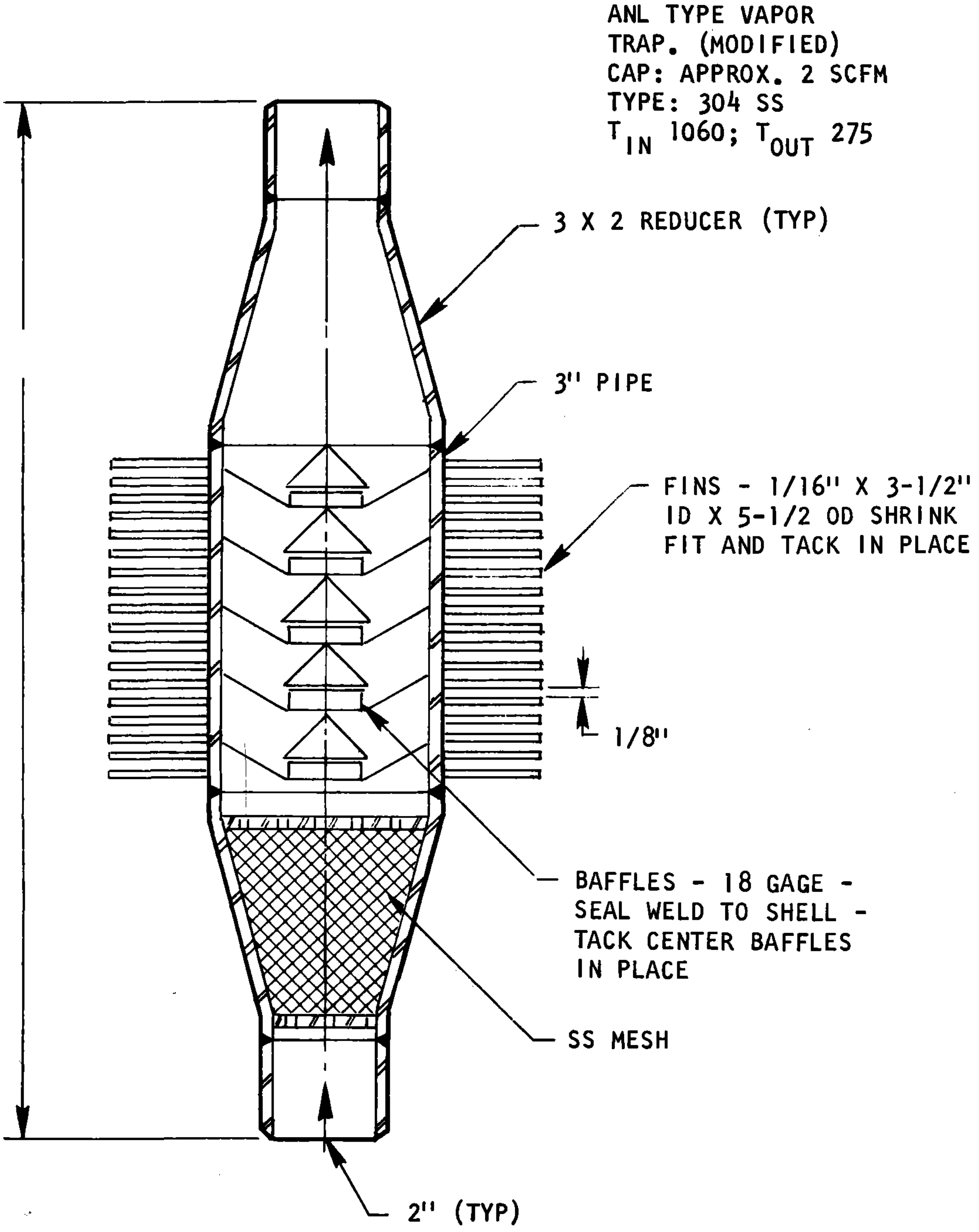
66-3623-107-1

VAPOR TRAP ASSEMBLY



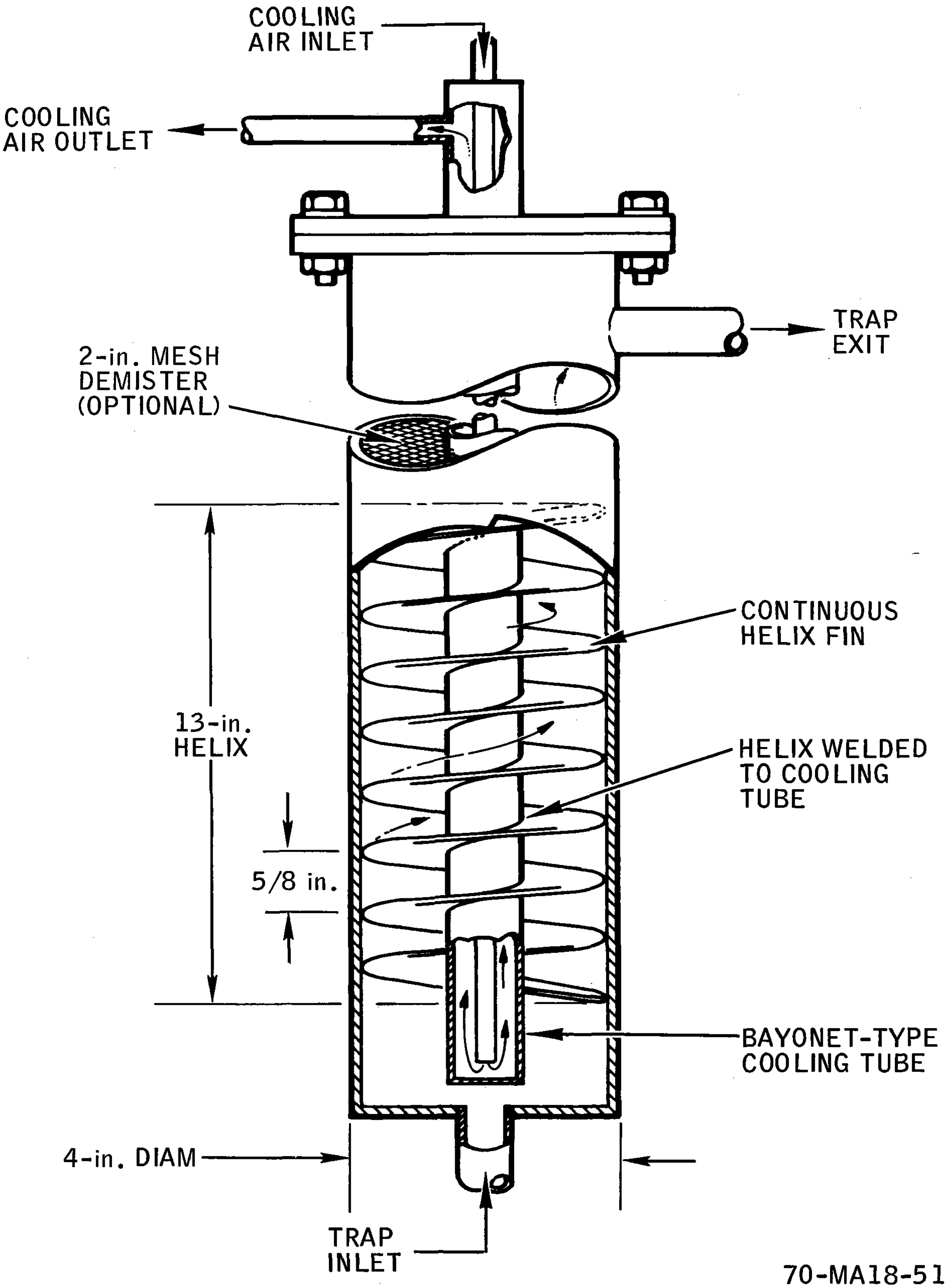
70-MA1-48-190

HIGH VOLUME VAPOR TRAP MODULE



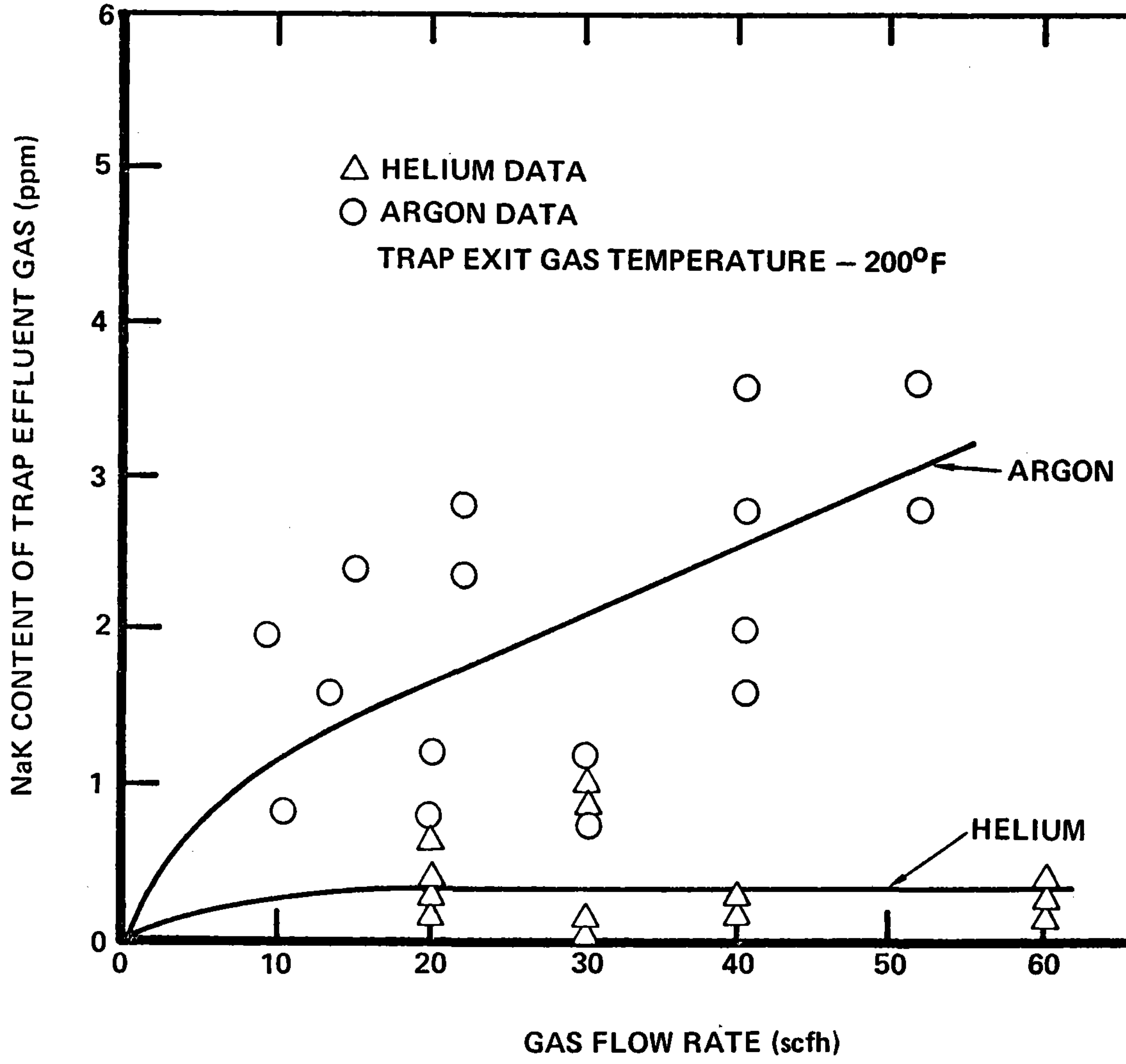
70-MA1-48-116

PRATT AND WHITNEY VAPOR TRAP



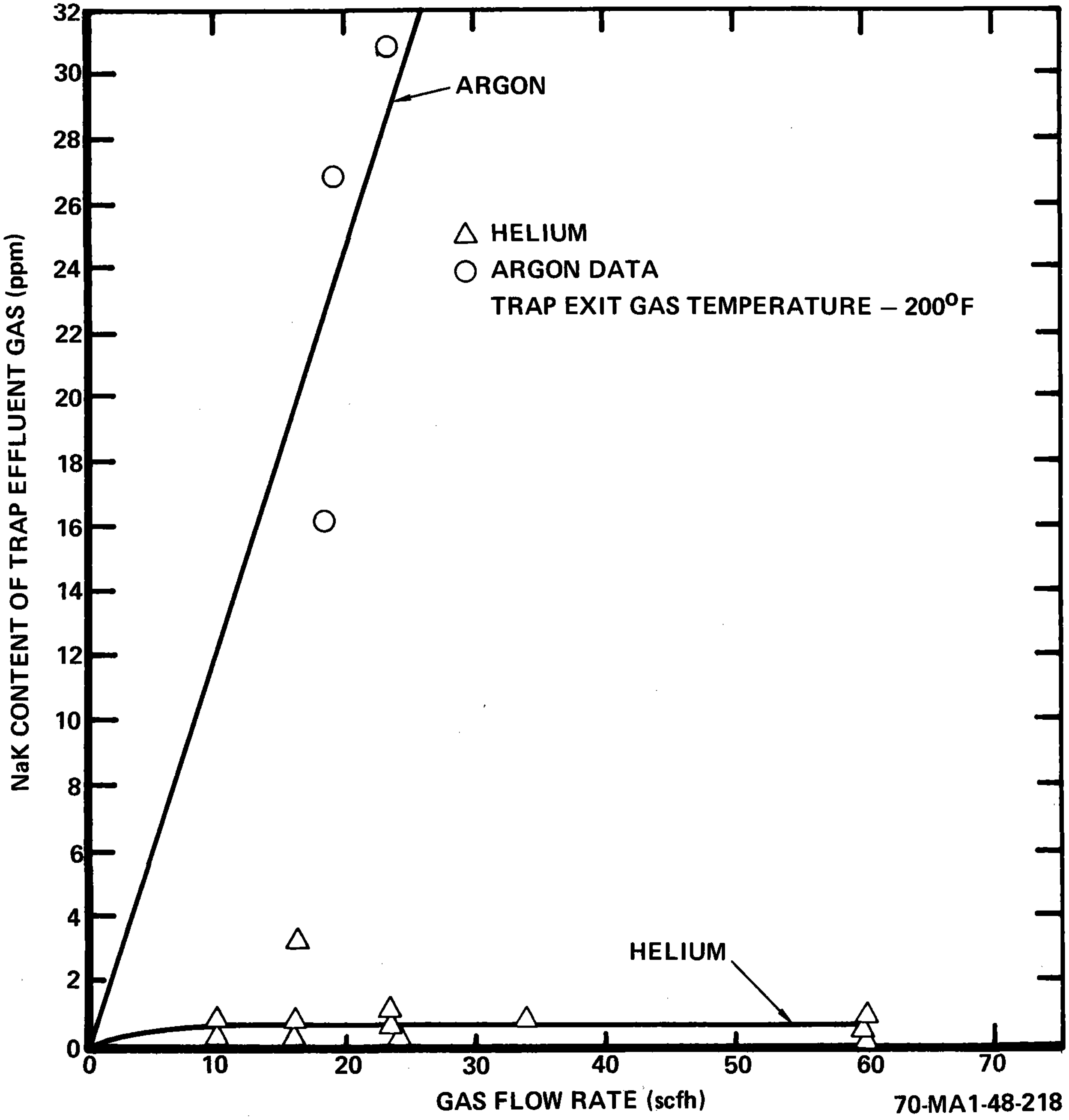
70-MA18-51-163

PERFORMANCE OF NaK VAPOR TRAP IV WITH HELIUM AND ARGON AT 400°F INLET



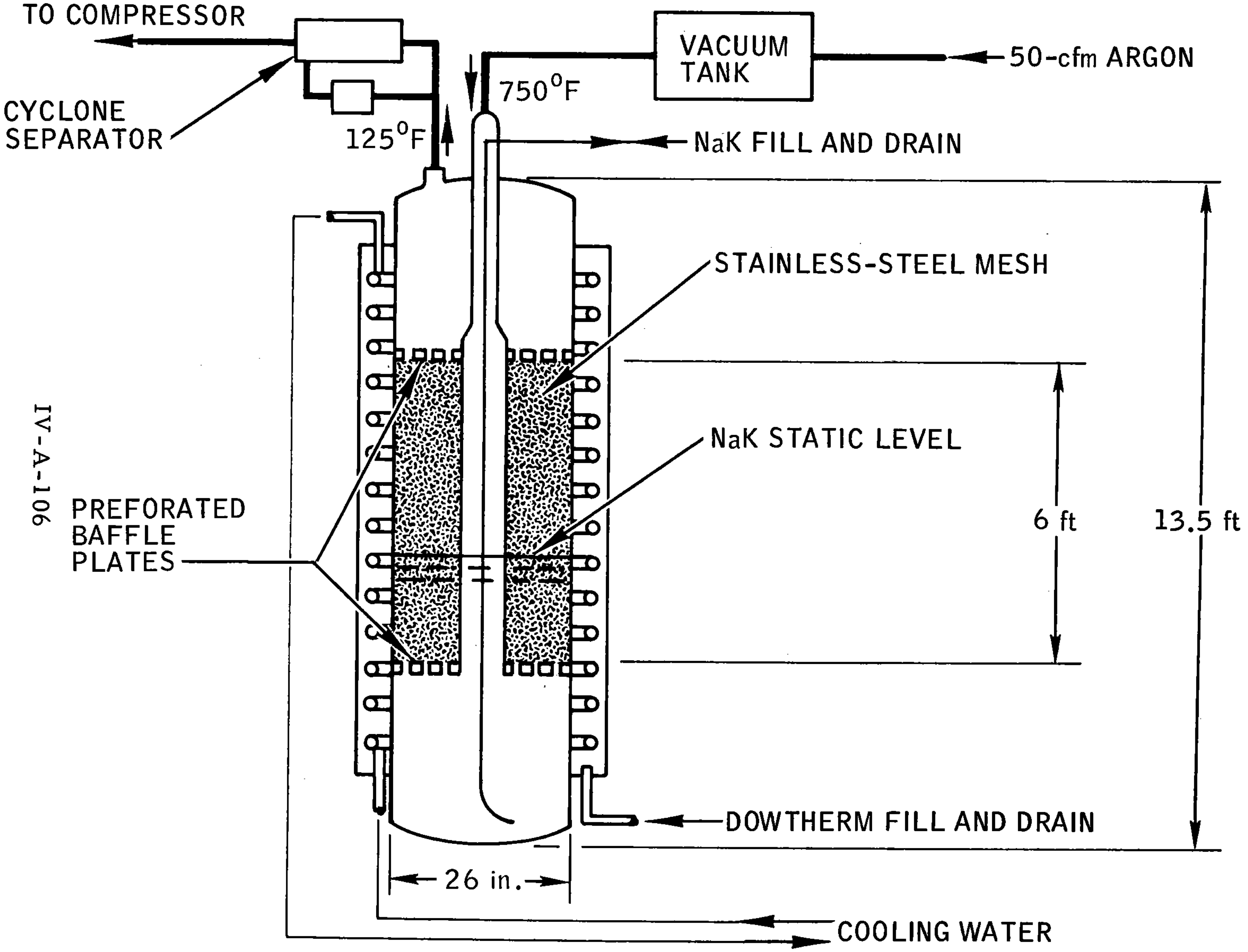
70-MA1-48-217

PERFORMANCE OF NaK VAPOR TRAP IV WITH HELIUM AND ARGON AT 700°F INLET



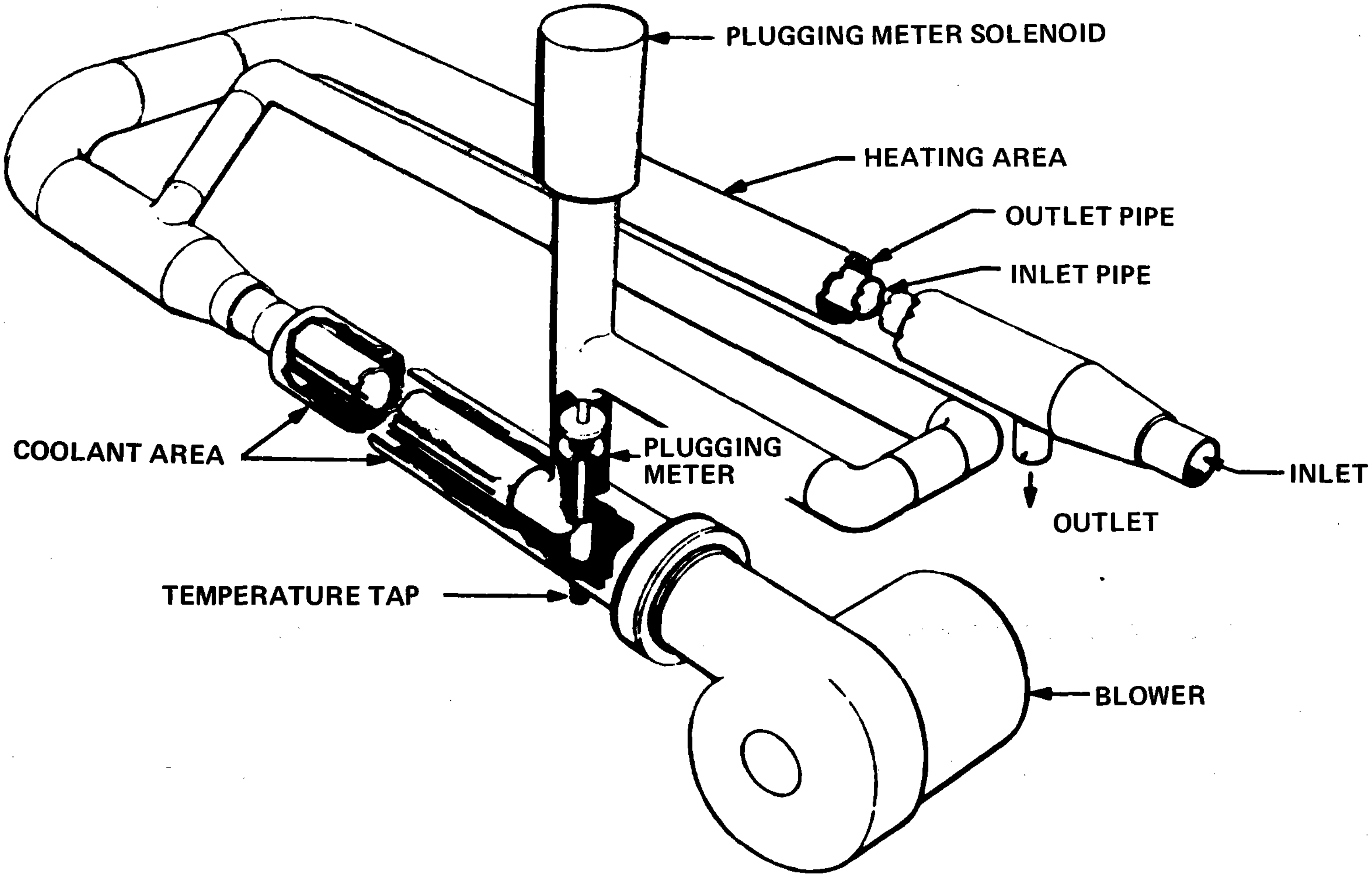
70-MA1-48-218

FERMI VAPOR TRAP



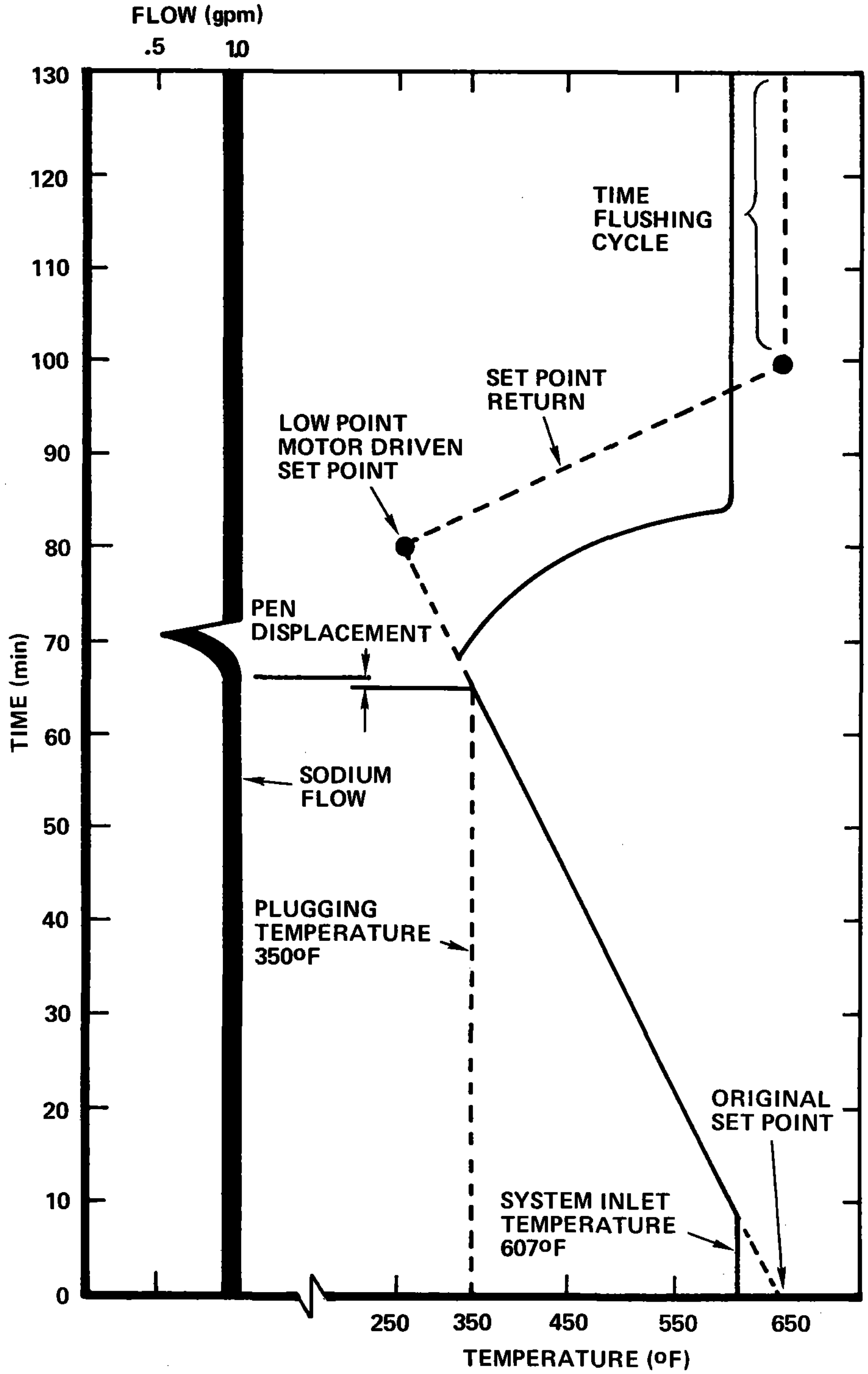
70-MA18-51-164

PLUGGING METER

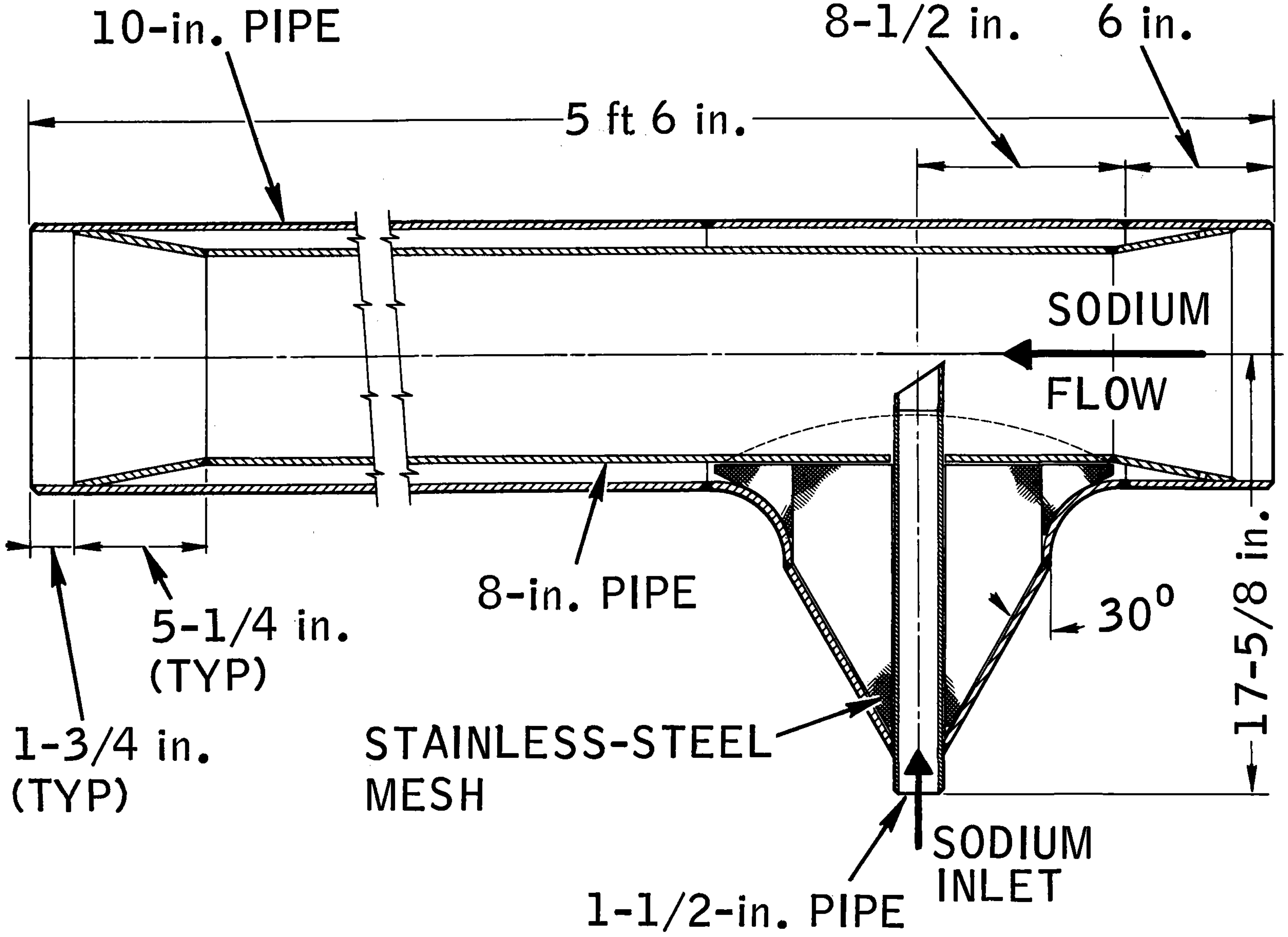


70-MA1-48-281

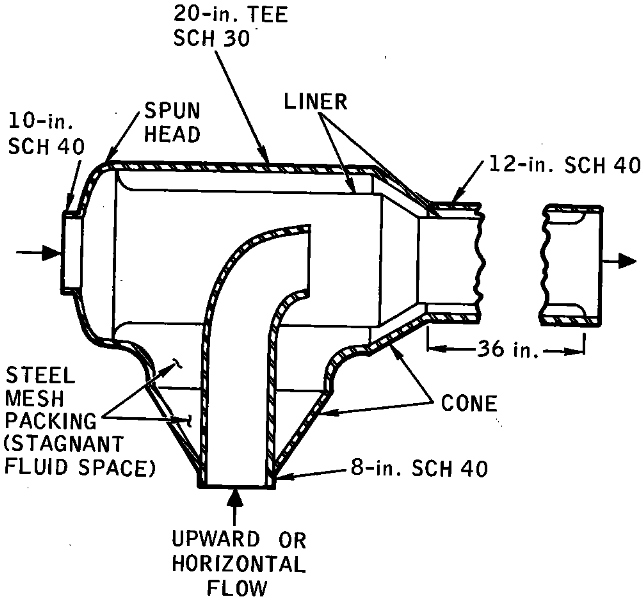
PREDICTED TWO PEN RECORDING OF PLUGGING DETERMINATION



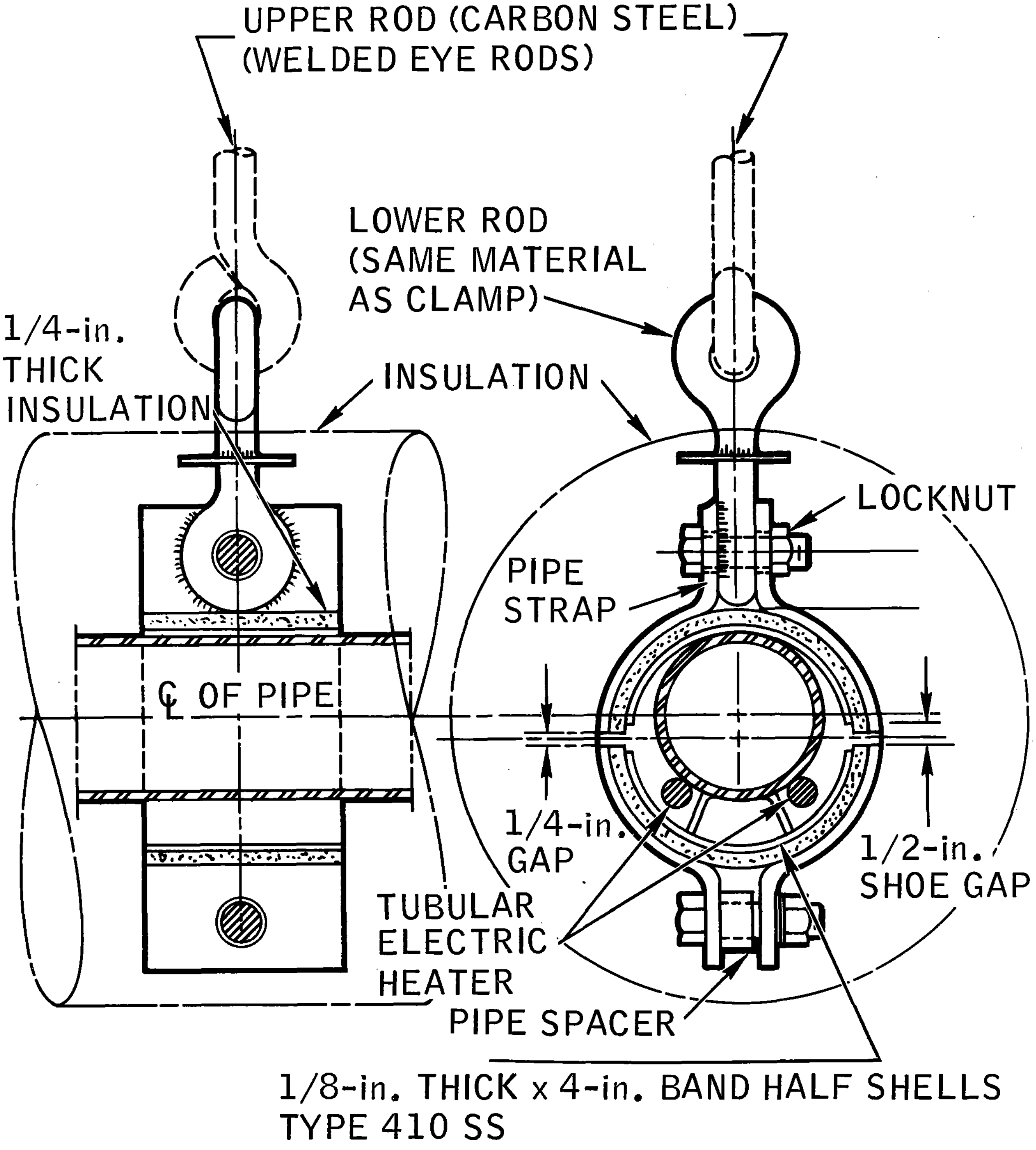
70-MA1-48-288


10-in. PIPE
5 ft 6 in.
8-1/2 in.
6 in.
SODIUM
FLOW
8-in. PIPE
30°
17-5/8 in.
5-1/4 in.
(TYP)
1-3/4 in.
(TYP)
STAINLESS-STEEL
MESH
SODIUM
INLET
1-1/2-in. PIPE

7-7694-214-1

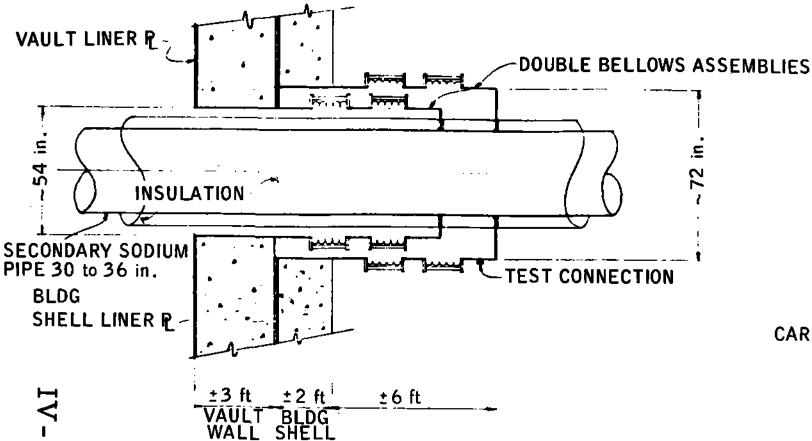

20-in. TEE
SCH 30
10-in.
SCH 40
SPUN
HEAD
LINER
12-in. SCH 40
36 in.
STEEL
MESH
PACKING
(STAGNANT
FLUID SPACE)
CONE
8-in. SCH 40
UPWARD OR
HORIZONTAL
FLOW

7-7694-215-2

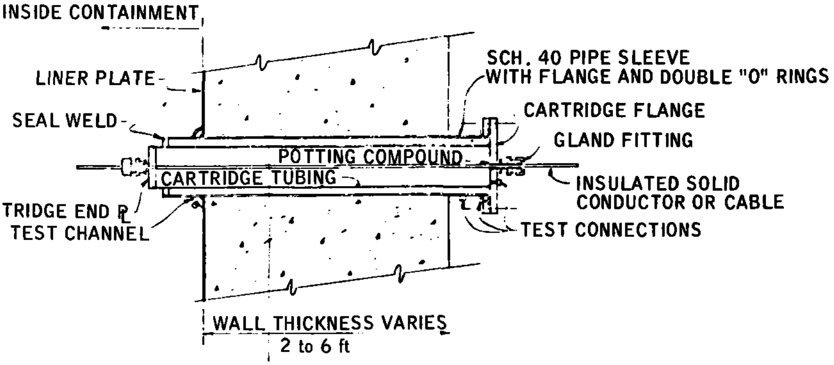

UPPER ROD (CARBON STEEL)
(WELDED EYE RODS)
LOWER ROD
(SAME MATERIAL
AS CLAMP)
1/4-in.
THICK
INSULATION
INSULATION
LOCKNUT
PIPE
STRAP
℄ OF PIPE
1/4-in.
GAP
1/2-in.
SHOE GAP
TUBULAR
ELECTRIC
HEATER
PIPE SPACER
1/8-in. THICK x 4-in. BAND HALF SHELLS
TYPE 410 SS

7-7694-214-2

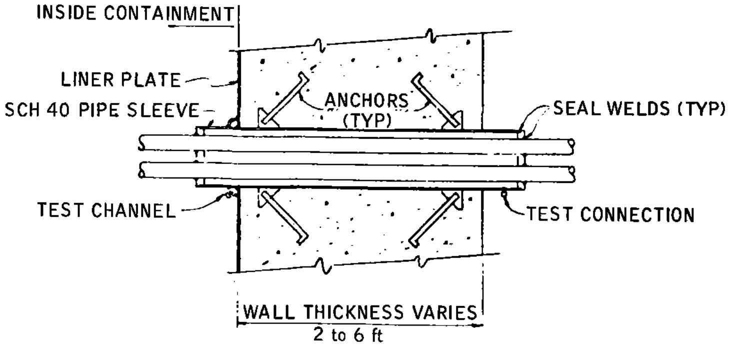
CONTAINMENT PENETRATIONS



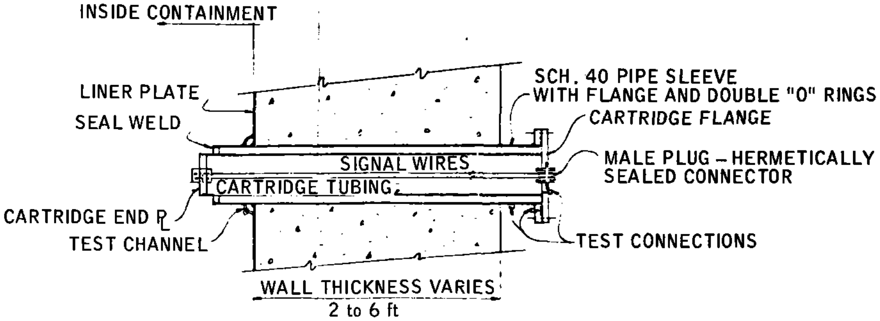
HOT PIPE PENETRATION
(TYPICAL SECONDARY SODIUM)



ELECTRICAL PENETRATION
SIGNAL CABLE ASSEMBLY
(VAULT PENETRATION SHOWN – BLDG SHELL SIMILAR)



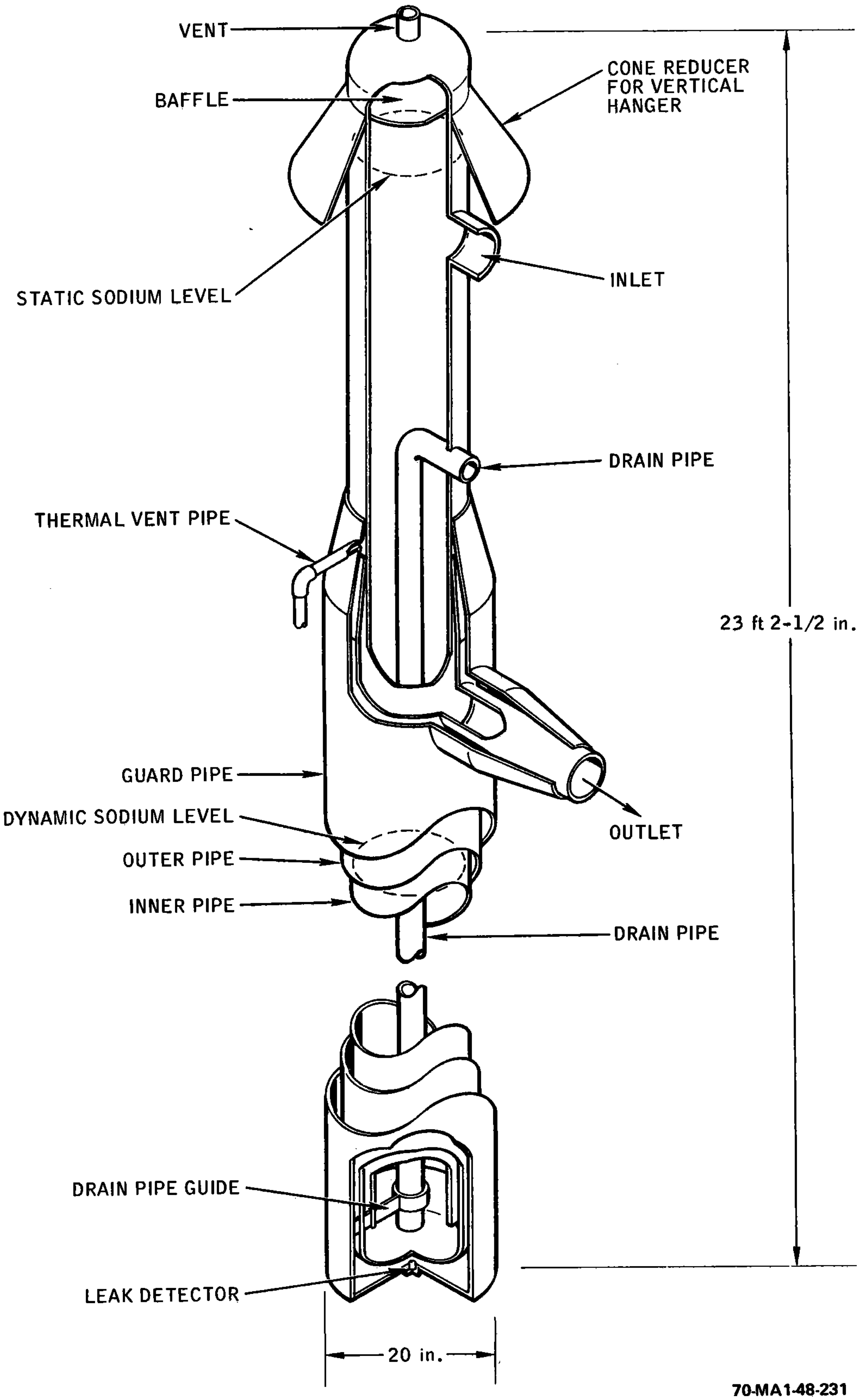
COLD PIPE PENETRATION



ELECTRICAL PENETRATION
SIGNAL CABLE ASSY
(VAULT PENETRATION SHOWN – BLDG SHELL SIMILAR)

70-F27-015-115

BALANCING LEG-HNPF



70-MA1-48-231

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SODIUM TECHNOLOGY COURSE, SESSION V

MATERIALS SELECTION

J. P. Page

A. INTRODUCTION

Good afternoon gentlemen, my talk today will deal with the selection of materials for sodium systems (Figure 1). Following some introductory remarks (Figure 2), I'll discuss the materials selection process. What it consists of, its steps, some ground rules and advice. I'll show you a "materials check list," which we will use as a foundation for the more technical discussions which follow. Then we'll run through a brief recap of sodium corrosion information, some observations and generalities on sodium corrosion and how it might or might not influence materials selection. You may be surprised to learn that sodium corrosion is not very often a determining factor in selecting materials. Then, after sodium corrosion, we'll spend a few minutes talking about the iron-chromium-nickel family of engineering alloys, especially the austenitic stainless steels which are probably the work-horse materials for sodium systems. Following that, we'll spend some time on mechanical properties, particularly high temperatures properties, how they are determined, how they are interpreted, and how they are used as a basis for design. Then I will discuss, very briefly, radiation effects on materials. You may think radiation effects to be out of place in a lecture on sodium technology, but I think that so many sodium systems applications involve nuclear reactors, particularly fast reactors, that it is, in fact, appropriate to dwell on the effects of radiation on materials in this course. I'll spend quite a little bit of time on sensitization as applied to the austenitic stainless steels. This is a very misunderstood phenomenon and if you don't get anything else out of this talk today, understanding sensitization a little better will mean that our time will have been well spent.

The next subject that I will touch on, very briefly, will be that of stress corrosion cracking. It, like sensitization, is a very important metallurgical phenomenon that is observed in austenitic stainless steels. The last technical section will be on four case histories. These will be very brief. Hopefully, I'll show how some of the technical topics that we will have discussed previously are actually applied in engineering practice in the selection of materials for nuclear sodium systems. We will consider materials selections for the vessel, the cladding, the control rod trip latch material and steam generator.

B. MATERIALS SELECTION PROCESS

Let's look at the materials selection process (Figure 3). The steps for materials selection are shown on this chart (Figure 4). It's intended to show that, as the design of a system or component progresses from a proposal through a study phase, conceptual design, preliminary design, final fabrication, and then finally operation — as the system progresses and matures — the concurrent process of materials selection also progresses and matures. It gets more detailed; and, as you see here, evolves from functional requirements through design requirements, through layout, and finally to detailed "build-to" drawings. At the same time as the design is progressing, the basis for materials selection is becoming more and more definitive: originally you work on the premise of experience, plus literature and theory, then you do some screening and technology tests followed by more specific development tests, and then finally you perform prototype or qualification tests which are actually testing the hardware to be used in the system. You can see that the "depth" of selection through this process is that you begin with the material class such as the austenitic stainless steel, high nickel alloy, or low alloy steel. As your design progresses you pick a material from that family or class, maybe with a backup and then finally you pick the material and recommend allowables. As you get into final design you have to specify great detail, usually, material composition as well as processes that are allowed. The next chart (Figure 5) shows the factors that should be taken into account during materials selection. Not just the requirements of the design, materials selection is a give-and-take proposition. The designer is given some functional requirements; unilaterally, or sometimes with the materials man, he comes up with a design concept, and out of this concept you get materials desirements (I chose this word quite carefully because I think that it's naive to think that there are materials requirements at this stage of the game). You have materials desirements and these are generally the properties that the designer would like, some idea of the lifetime and, very early in the process, an evaluation of all the credible environments. We'll talk about that in more detail later and I think you will understand why this is important. At the same time, the designer and materials man, very often with the program manager, project engineer, or manager of the job have got to agree on some basic ground rules of acceptable risk, acceptable research and development costs, acceptable component cost, and acceptable schedule. The selection of materials is very often constrained by one or more of these factors. Occasionally we can select a material that is very expensive but has a very low R&D cost; you might do this for a one-of-a-kind item. Conversely, if you are in production, you might be willing to invest the time and money into R&D in order to have a relatively low component cost. And, of course, very often the schedule is the determining factor: a material is selected that does not have a terribly long lead time. The point being in this particular chart that there is a great deal of give-and-take and a lot of subjective evaluation which occurs very early in the materials selection process. During the next few charts we'll discuss particular materials selection criteria; these can be used as a check list when you consider what material might be used for a given design application.

The next chart (Figure 6) deals with mechanical properties. I think it's obvious to most engineers that the short term tensile properties are important; these include the ultimate, yield, elongation, and reduction of area. You'll hear in a few minutes when we talk more about creep and stress rupture properties why they're often dominant mechanical properties for high temperature design. Fatigue, either low cycle fatigue at high temperatures or high cycle fatigue for more conventional structures may be important. Impact is usually a vital mechanical property. Depending on the application, any one of a number of other "special" mechanical properties may dictate your selection.

Turning from mechanical properties to physical properties (Figure 7) we see that such properties as thermal expansion, thermal conductivity, specific heat or melting temperatures may be of primary concern. You may want a low expansion material or a material with a high melting temperature. Electrical properties are obviously important in parts of the plant. Is it important that the part be magnetic or non-magnetic? Emittance can be important to heat transfer, especially in vacuum or space systems. Another important factor to be considered is the density for nuclear shielding at least, and then let's keep in mind the nuclear properties — cross sections and reactions products. Cross sections probably are not as important in a fast breeder reactor as they were in thermal reactors, but are significant and should not be forgotten in selecting a material, particularly if that material is likely to become radioactive. I'm thinking here about such elements as cobalt and tantalum which get pretty "hot" after exposure to fast neutrons.

This chart (Figure 8) deals with some properties which are generally more subjective than the ones we have talked about until now. Mechanical and physical properties can be measured; now we're getting into the "-ability" type of considerations and a few are listed here: weldability, brazeability, formability, machineability, and then metallurgical effects such as dimensional stability, phase changes, neutron effects, and thermal effects. Does the material become brittle just by sitting around in a high temperature for a long period of time and/or do neutrons affect properties? These criteria must always be taken into account in materials selection. Each property is not always important; a part that does not have to be welded does not really require weldability; however, weldability should be kept in mind in case breaks and repair is to be effected by welding it or welding an attachment onto that part. Thought in some depth and some detail should be given to whether or not any of these requirements really do apply to your part or your system.

The next chart (Figure 9) deals with compatibility properties which can be all-important. Reactions with solids, what I mean here, are solid-solid type diffusion reactions. These can be very important at high temperatures; the compatibility of a refractory metal, for instance, with an oxidation-resistant precious metal cladding may determine the lifetime of a high temperature radioisotope capsule. Generally speaking, however, in the temperature range that we're considering for most of our sodium systems, solid-solid reaction problems are the exception rather than the rule. The rule is much more generally — reactions with liquids. Obviously, we have to consider reactions with sodium, and should be thinking not only about pure sodium but impure sodium and what happens as the purity changes. I'll have a few charts on this and the serious student of sodium technology should investigate sodium corrosion in much more depth since time will not permit fuller coverage on this subject here. What is the effect of water? The earth has a lot of water on it, and therefore, consideration should be given to the selected material's reaction with pure water, tap water, and water that may be acidic or basic in nature. If the material can't tolerate water, you'll have to figure out how to keep it dry. Reactions with gases, oxidation reactions with air, reactions with steam should also be evaluated. Under unusual circumstances you can nitride, carburize, or decarburize your material. Occasionally (this may be surprising to some of you), you have to worry about the effects of vacuum. This was the case in some high temperature space reactors; you may have a high sublimation rate of materials at a high temperature in space vacuum, or you might have to worry about the loss of lubrication associated with vacuum.

The last of these materials selection criteria charts (Figure 10) deals with what I'll call "practical" properties. In many cases, certain regulatory or legal requirements, codes, or insurance requirements have a lot to do with your selection. Quite obviously, you must consider the availability of the material; i.e., is it available from competitive sources in the specifications acceptable to you as the user and to the supplier? Is there experience with that specification? Is there experience with the material? Has there been a fair amount of prior research and development? Is there a current program on that material that applies to your application, and quite probably most important of all, what application experience; what is the history of success of using that material in an application similar to the one that you are interested in? Let's not forget cost, including material cost, fabrication cost, and the cost of quality and reliability assurance. When we talk about cost, we should really be thinking about the total systems cost or at least the installed cost. Sometimes a low cost material ends up costing a lot more than one which was more expensive to begin with. This may be due to a higher reject rate, or problems presented in welding, or to any one of a number of adverse factors in fabrication. Many of us have been surprised, after buying a relatively inexpensive material, to learn that a higher priced material would have cost less and caused less trouble in the long run.

C. SODIUM CORROSION

Now I'd like to spend some time talking about sodium corrosion (Figure 11). A summary chart of the sodium corrosion of materials (Figure 12) shows the refractory metals to have, potentially, the best corrosion resistance to pure sodium; however, these will probably contain sodium with carbon and oxygen contamination. The system may contact not only sodium but also air, or nitrogen, or impure inert gas. Refractory metals are comparatively expensive and they are subject to oxidation and embrittlement, either by air or impure sodium. Furthermore, they are relatively "unproven," especially in a reactor environment. It is very possible that space systems, a few years from today, may have high temperature reactors that use these alloys of these metals as system materials, but at the present time they're a little out of reach. Not too far behind the refractory metals are iron and iron-rich alloys such as the stainless steels and Croloys; we'll be talking more about these later. Right behind the iron-rich alloys are the nickel-rich alloys, these are generally also very satisfactory for a very large percentage of the sodium system applications that we might be interested in. Ordinarily, we don't seriously consider using copper and its alloys, precious metals, or low melting elements; I'm thinking here of lead, cadmium, bismuth, and similar materials. We don't ordinarily use aluminum-rich alloys in sodium systems. However, for short periods of time, and for special purposes, we might consider using these alloys, but with great caution. Titanium and zirconium can be used, but they are a little too reactive for most of our requirements and are probably not researched enough at the present time to qualify as strong candidate materials for system applications. And, I have listed some of the "pests:" these are the elements that will migrate around the system and just give trouble in general.

The next chart (Figure 13) shows one basis for corrosion by sodium. This chart says that as sodium is heated, a metal which we'll call "M" is dissolved. Its solubility increases with increasing temperature. As the sodium is cooled the dissolved metal precipitates out of solution; it's just that simple!

The next chart (Figure 14) shows how this works in a loop; this particular case applies to corrosion of nickel. You see that in the hot leg of the loop the nickel dissolves at the surface or, if it's an iron-chrome-nickel alloy, the nickel diffuses through the iron and the chromium to the surface and then dissolves in the hot leg. It is carried around to the cold leg where it exceeds the solubility limit and precipitates. It either adheres to the wall or is cold trapped (if there is a cold trap in the loop), or it may return to the hot leg as particulate matter. I think that this is possibly one reason why the predicted corrosion rate of materials based on solubility limits will be very different from the observed corrosion rate: a small amount of particulate material is always returned to the hot leg, thereby satisfying solubility requirements.

That was one type of temperature gradient or solubility gradient mass transfer. Another type shown in the next figure (Figure 15) is the transfer of a "complex" and this explains, at least to a first-order approximation, why oxygen is the main cause of corrosion in iron systems. It's not the iron that's really dissolving; it's a complex of sodium oxide and iron oxide. The oxygen in this case, acts as a catalyst. The oxygen reacts with the sodium and iron to form a complex which dissolves in the hot leg (just as the nickel did in the previous example), runs around to the cold leg where it decomposes, releasing iron. Then the oxygen can conglomerate with the sodium, run back to the hot leg and react again to form the complex and continue the process of mass transfer. There is doubt as to whether or not this is really what happens, but it's a fairly good model.

The next chart (Figure 16) shows how "initial" corrosion of iron chrome alloys varies as a function of nickel content. It shows that as nickel goes up, the corrosion rate, at least the initial corrosion rate also increases, and this may be significant at temperatures above 1200°F, but probably not at lower temperatures as you will see later in charts. Why do I use the term "initial" corrosion? I think that's shown in the next chart (Figure 17), which gives the effect of time on sodium corrosion of iron-chrome-nickel alloys. The point being: as time passes the corrosion rates of high-nickel alloys and low-nickel alloys begin to converge. The reason for this is shown in this chart (Figure 18). Here the surface of the iron-chrome-nickel alloy, in this case stainless steel, is highly enriched in iron after exposure to sodium. Both the chromium and nickel have been leached from the surface, and I think you can see that, as a result of this, the rate-determining step starts to become the solution rate of iron in sodium, because the nickel and chromium have been depleted to the point that the diffusion distance becomes too great for them to influence the corrosion rate. Note the scale we're talking about: one-fourth of a mil. This ends up being the "ferrite layer;" it's ferrite because the chromium, nickel, and carbon have been removed from the surface. Later on we will discuss ferrite stabilizers in conjunction with metallurgy of the iron-chrome-nickel alloys.

The next chart (Figure 19) shows the relationship of several environmental effects on corrosion of stainless steels. This chart is really worth some study. One thing you can see almost immediately is that after ~15 ft/sec the velocity effect of sodium begins to saturate. Now, if you look at the oxygen contents and temperatures you see that the effect of oxygen content is very pronounced. Corrosion rate in the 25 ppm sodium at 1200°F is higher than the corrosion rate at 1350°F and 10 ppm oxygen.

The next chart (Figure 20) attempts to explain what is called the "heat flux effect" in the trade these days; this effect is simply that when you have a surface (cladding, for instance, in the fast breeder reactor) that transfers a terrifically high heat flux, the sodium immediately adjacent to the surface transferring the heat, is raised to a temperature somewhat higher than the bulk sodium in the rest of the loop. This temperature difference may be as much as 25 to 50°F; this is significant compared to the degree-or-two difference between the cladding and the sodium in a standard corrosion loop test. As a result of the higher temperature at the surface of the solid there is immediately adjacent to that surface, a small volume of unsaturated sodium; the actual corrosion temperature then is the temperature at the surface of the metal. There is a fair amount of research being done right now on the "heat flux effect" as it relates to fast breeder reactor systems.

The next chart (Figure 21) tries to put some of the data into perspective for you. We plotted the results of independent investigations that were quite well done and systematic (at least as far as we have been able to determine) and they are surprisingly consistent, particularly when you get into the details of the data and see that some interpretation is required in order to report corrosion rate in "mils per year." In any event, notice that at temperatures up to ~1200 or 1300°F you're only talking about a corrosion rate of a mil per year in 10 to 15 ppm-oxygen sodium. This purity is not terribly difficult to achieve by cold trapping. Raising the oxygen, as we pointed out earlier, has a dramatically deleterious effect on corrosion rate. Notice also that the curves apply to low alloy steels as well as the stainless steels. Again, I think this comes back to the suggestion that, after a short time, the nickel and chromium are leached out so you end up corroding the remaining iron surface.

Now, just so you won't think everything is peaches and cream, the next chart (Figure 22) shows that different austenitic alloys, Types 316 and 304 stainless steels and Incoloy 800, under comparable corrosion conditions are subject to different types of attack by sodium. The differences are not too significant in an engineering sense with the exception of fuel cladding. I think you can see, however, that some interpretation is required for reporting these observations in terms of "mils per year" corrosion. Further, you can see how weight loss measurements, converted to simple surface recession, can be highly misleading. The point I'm trying to make is that analysis of raw data coupled with discussions with the experimenter are needed for "fine-tuning" of materials information, expecially corrosion data.

An entirely different type of corrosion is carbon transfer or activity gradient mass transfer as illustrated in the next chart (Figure 23). This type of corrosion results from the fact that an element such as carbon can have a different composition, or more precisely, activity, in the metals in a sodium system. The sodium can act as a carrier, or a "shunt," and permit the carbon to transfer from one metal to another; during this process one metal becomes carburized and the other metal becomes decarburized. One explanation for this is shown in the next chart (Figure 24). The "stability" of several carbides is plotted; the lowest being the most stable. Carbon will be removed from iron carbide by chromium carbide and, in turn the chromium carbide is less stable than niobium, zirconium, or titanium carbides in that order. Therefore, the steel that has a surplus of titanium in it will tend to decarburize carbon steel which has only iron carbide in it. Thus, carbide stability can be the source of the activity driving force. This transfer of carbon may or may not be significant in the engineering application. Let me show you how we attacked the problem in one of our systems.

This chart (Figure 25) shows the results of some calculations based on experimental work, some diffusion coefficients and some assumptions on kinetics, as applied to the decarburization of a 2-1/4 chrome - 1% Mo steel exposed to sodium on one side. The carbon content gradually decreases from about 10 points to about 2 points (a point being a hundredth of a percent) over the period of the 250,000 hr of the life of the part. We estimated that at 0.02% carbon, the steel would have ~80% of its original strength. This number was factored into the design stress calculations. Since the carbon lost by this steel had to go some place, we calculated the concurrent carburization of the Type 304 stainless steel heat exchanger. This calculation, of course, had to take into account the relative surface areas and required some simplifying assumptions. This graph (Figure 26) shows that the carbon content of the stainless steel goes up from its original content of about 0.08% to a carbon content of maybe 0.20% (or 20 points). This level of carbon would probably not be very pleasant to work with in a fabricating material or to have to weld. However, the fact that it is carburized in situ is really not so bad.

The next graph (Figure 27) shows the effect of carbon content on the properties of the 304. You will see that at 20 points, or 0.2% carbon, there is only a slight loss in ductility coupled with a slight increase in ultimate strength. These are entirely acceptable to the design of the intermediate heat exchanger.

I would like to begin closing this section on sodium corrosion by showing you a picture (Figure 28) of a pump impeller from the sodium reactor experiment, or SRE. This particular impeller performed for over 30,000 hr in warm sodium, by warm I mean 300 to 500°F and it also performed for 6000 to 8000 hr in hot sodium, by that I'm talking about 700 to 1000°F sodium. The original machining marks that were there, that is, the grinding marks placed there for balancing of that impeller during fabrication are still apparent on the surface. You can see a little bit of surface hardening as shown by the smaller hardness impressions near the surface, but really nothing significant happened in all that period of time. Sodium is a very nice material to work with in terms of compatibility with engineering alloys.

Now let me summarize the sodium corrosion section of my talk with this next chart (Figure 29), in which I've tried to recap the two mechanisms of sodium corrosion. The first is carbon transfer, having the effect of changing mechanical properties but not necessarily changing dimensions significantly. What do you do about that? You select your materials quite carefully, and you adjust the design allowables; under certain circumstances you may use a hot trap (which is a "getter" that absorbs carbon). But I don't believe this is generally a desirable approach because you are only hastening the decarburization of the part that is giving up the carbon. The second corrosion mechanism that we have talked about is temperature-gradient or solubility-gradient mass transfer which is typified by nickel, iron, and chromium. This type of mass transfer does result in loss of section. This loss of section is not significant in a structural part which is one-tenth to one-inch thick, but it may be significant to cladding, which is maybe 10 to 20 mils thick. This loss of section or materials loss goes someplace; it will usually deposit in the cold leg. The implications then, of course, are that, if you're worried about losing section, you'll apply a corrosion allowance. Certainly you will have to consider the deposition of the material which is lost from the hot leg. In some cases this can be radioactive. Allowing for deposition means you don't have fine channels; you don't want to plug portions of the cold leg of your system. And as I pointed out, the effect of oxygen suggests that clean sodium and cold trap be used. This completes my recap of the sodium corrosion, at least as this metallurgist looks at it.

D. IRON-CHROMIUM-NICKEL ALLOYS

The next section of my talk will deal with the iron-chromium-nickel family of alloys (Figure 30). Let's begin by looking at a ternary phase diagram (Figure 31). At this point I'll begin with just the triangle that has iron, chrome, and nickel, at the corners. It also has a scale and if you look at the grid points and marks you will notice that, at any point in the triangle, the sum of the weight percent iron, the weight percent chromium, and the weight percent nickel has to equal 100, simply by the way it's constructed. With a diagram of this type we can plot material by composition, and the overlay (Figure 32) now superimposes some of the more common engineering alloys on this ternary graph. You see that the carbon steel is at the iron corner, low-alloy steel follows along the iron-chromium binary line because nickel is a more expensive alloy agent than chromium and it isn't needed for many applications. The Type 400 series stainless steels pick up where the low alloy steels leave off at about the 10% chromium line, and then as we go inboard, picking up nickel, we find the austenitic or Type 300 series stainless steels. Then if we walk along the diagram, toward the nickel corner, we find the high-nickel alloys, Incoloy 800 which is really a very high nickel stainless with ~35% nickel, and then your higher strength alloys, Inconel 718, Hastelloy X, and one of the old stand-bys — Inconel 600. In this discussion all these alloys are considered to be high in nickel.

The second overlay (Figure 33) shows the metallurgical phases that are normally considered to be present in these steels, and you'll see that along the iron-nickel side of the triangle we have the ferrite phase and, in the nickel region we have an austenite region and, between the two are the regions of two-phase stability, austenite plus ferrite. The effect of additional alloying elements on the stability of these phases is shown in the next chart (Figure 34).

Here you will see that nickel, carbon, manganese, and nitrogen all tend to promote the stability of austenite, whereas chromium, molybdenum, silicon, niobium, and possibly titanium, promote the stability of ferrite. Generally, you don't want ferrite in your austenitic stainless steels because that has a tendency to transform to sigma phase, which is a brittle phase. There is some argument about whether or not the sigma phase truly embrittles steel at service temperature. It may or it may not, but there is no reason to believe that it's doing much good, so ordinarily you do not want a surplus of these ferrite-promoting elements. Unfortunately, and whether we like it or not, it is true that a small percentage of delta ferrite in weld metal is very helpful in reducing microfissuring and cracking of welds, therefore, the metallurgist is faced with a dilemna in trying to balance between the undesirability of sigma phase on the one hand against the desirability of having some delta ferrite for improved weldability. I think it should be mentioned that I don't think we've looked sufficiently at the effect of sigma phase formation on the properties of weldments. This is a field of research in which I expect to see additional emphasis over the next few years. Let's come back now to the engineering materials we might consider for sodium systems.

The next chart (Figure 35) lists some advantages and disadvantages for our old friend, carbon steel. You can get carbon steel in various qualities. The advantages of the carbon steel family is, obviously, very low cost, easy availability, respectable weldability, and the fact that it doesn't crack from chloride stress corrosion. It has disadvantages in a nuclear system in that radiation raises its nil ductility temperature, i. e., the temperature below which a crack will tend to propagate with essentially no energy. Let's say that again: a material is extremely brittle below its NDT or nil ductility temperature. The NDT is observed in body-centered-cubic materials such as ferritic steels, molybdenum, and tungsten. It is not commonly observed in face-centered materials such as the austenitic stainless steels and nickel-base alloys. Carbon steel will rust, which may not be important, and it is subject to caustic stress corrosion cracking. This requires higher concentrations (we think) than comparable chloride stress corrosion cracking as it relates to stainless. And then, above ~800°F carbon steel will graphitize; by that I mean that the iron carbide will decompose and transform to graphite. Also, above 800°F, carbon steel will decarburize in the sodium system if there is any place for the carbon to go, and there will be if you have stainless in the system. Finally, above 800°F carbon steel has a very high oxidation rate and therefore is not suitable for long-term service in air. Generally we don't use carbon steel very much in sodium systems except possibly in dump tanks and parts of the system that are quite cool and generally isolated from the system during the majority of the system's life.

The next chart (Figure 36) shows some of the advantages and disadvantages of the low-alloy steels which are commonly known as the Croloys or chrome-molybdenum alloys. The advantages are a low material cost, their respectable strength to at least 1000°F, and, as the chromium goes up, the oxidation resistance becomes adequate. They don't graphitize because the chromium stabilizes the iron carbide phase, and also they are not susceptible to chloride stress corrosion cracking. These materials rust, and are difficult to weld; the difficulty in welding increases as the chromium content increases. They will have a reasonably high as-fabricated or as-welded nil-ductility temperature, and may or may not decarburize in the sodium system, depending on the temperature and what else is in the system. Earlier I showed you an example of a system in which decarburization was predicted. Now the Europeans have taken some of these steels and added niobium to them in order to make the carbides very stable and to resist decarburization. However, in this country these stabilized low-alloy steels have not been accepted by the American Society of Mechanical Engineers, or ASME. We have heard that these steels are quite difficult to weld and the people we know that have used them are not planning to use them for future reactor systems. The unmodified, unstabilized low-alloy steels are used very commonly in the U.S. for high temperature chemical processing and the like. These are good materials, and you will see that we intend to use them in the AI/GPU Fast Breeder Reactor.

The next family of materials are shown on this chart (Figure 37): the Type 400 series stainless steels. These are favored for their rust resistance and moderate cost. Cutlery and tools are made of these steels. However, they are not commonly used for high temperature application where ductility is needed. They are unfavorable because at ~800 to 900°F temperatures they become embrittled and form sigma phase, are quite difficult to weld, and possess a very high as-fabricated nil-ductility temperature. So, generally speaking, these steels are not acceptable for sodium technology applications.

The next chart (Figure 38) lists some advantages and disadvantages of the workhorse alloys of sodium systems; these being the austenitic, or Type 300 stainless steels. Their cost is reasonable. That's relative, of course, but their cost is moderate compared to refractory metals and nickel-base alloys; still very expensive compared to carbon steel. They have excellent high temperature strength and are quite readily welded; they don't require preheat treatment or post-heat treatment as do the low alloy steels. They don't have a nil-ductility temperature, as such, but do become embrittled by neutrons and occasionally heat treatment; however, I don't know of any instance in which they actually lost total ductility. They are rust resistant. There is much research disclosed on their properties, and what's good about them and what isn't, along with a great deal of experience in their application in sodium systems. Their disadvantages are: stress corrosion, sensitization, and sigma phase formation.

The high-nickel alloys are described in the next chart (Figure 39). These alloys are not generally subject to chloride stress corrosion cracking. They are quite weldable, although in thick sections and under restraint they are not considered to be as weldable as Types 304, 316, and 321 stainless steel. Also, they don't ordinarily have a nil-ductility temperature, and have a wide range of strengths, depending on alloy content and heat treatment. Some, like Inconel 600, lose strength rapidly with temperatures above 900°F, others such as Inconel 718 are among the strongest materials we know at temperatures of 1000 to 1200°F, or higher. The evident disadvantages in high nickel alloys are their high cost, as well as long lead times and low availabilities (which generally go hand-in-hand), particularly with the nickel shortage prevalent at the present time. They are weakened by lead and by sulfur; and extreme care is required in handling them in order to avoid contamination at welded surfaces. As we noted earlier, they're just not quite as good as the austenitic stainless steels in sodium corrosion resistance, or at least in their initial sodium corrosion resistance, but I wouldn't summarily dismiss nickel alloys on the basis of their lack of sodium corrosion resistance. These alloys should be carefully evaluated before any decision is made regarding their inadequacies.

The last chart of this series (Figure 40) shows other materials that might be used for special purposes. These include: brazing alloys, materials (canned or bare) for neutron absorption and materials which resist galling or self-welding. A special material might be needed for instruments, or seals; and ordinarily elastomers or similar materials are not in contact with liquid sodium but could be contacting sodium vapor or there might be some "dragout" or condensation in the neighborhood of the seal. You have to think about such things when you consider those materials. Consider cover gases also and their compatibility with sodium. Nitrogen for instance, has been considered as a cover gas but presents a problem in that the sodium is such a good getter that the stainless in the vapor phase can be nitrided. Don't forget your auxiliary system coolants; are you going to use NaK, kerosene, gas, or water? Each has its own problems and materials criteria.

Let's go back for a moment to the austenitic stainless steels. On this chart (Figure 41) I've listed the stainless steels that are most common to use in the sodium reactor business. They're pretty much all based on Type 302 which is the basic 18-8 (Cr-Ni) with about 15 points of carbon. If you reduce the nickel a little, you will reduce the cost and increase the rate of work hardening; this is Type 301. If you add some sulfur or selenium you would improve the machinability of this steel; this is Type 303 or 303 Se. As opposed to Type 301 where you reduced the nickel for increased work hardening, if you raise nickel, you reduce the rate of work hardening; this gives you the deep drawing stainless steel, Type 305. Take Type 302 and simply reduce the carbon a little bit (to 8 points maximum) and make a small adjustment in the chromium and nickel contents; You have Type 304 compared to Type 302 — this material welds more easily and has a decreased "sensitization potential" which we'll talk about later. For Type 304L you reduce the carbon even lower (in going from Type 302 to 304 you went from 15 points to 8 points); for Type 304L you limit your carbon content to 3 points, but at the same time you pay a penalty in weakening the steel slightly. If you want to use a Type 304 for high temperature application, you specify the carbon to range between the 10 points and 4 points; now you've got Type 304H.

If you add some titanium to a Type 304 you've got Type 321; this is a stabilized stainless steel which eradicates some sensitization problems. Now, if instead of titanium, you add niobium (or columbium to some of us old-timers) and tantalum, you will have essentially the same effect of decreasing sensitization, because these materials react with the carbon more readily than chromium at high temperatures. Add molybdenum to Type 304 to make Type 316; the molybdenum doesn't really do much stabilizing but it does strengthen the steel and provides some resistance to pitting corrosion. If you take Type 316 and reduce its carbon, to make Type 316L, you resist sensitization at the same time that you maintain some of the original strength. Type 316L, however, is also not commonly used for high temperature application; in fact, its use is not permitted by the ASME Boiler Code. Then we find Types 308, 309, and 310 with much higher alloy contents. Type 308 is a very common weld filler metal. These materials are subject to sigma phase formation because of their high percentage of ferrite-forming elements. This completes my "overview of engineering alloys."

E. MECHANICAL PROPERTIES

The next subject I would like to discuss is mechanical properties of interest in high temperature sodium systems (Figure 42). This next chart (Figure 43) leads into the subject of creep and stress-rupture and, in fact, a lot of high temperature effects. The reason I'm talking high temperatures at this time is that when we use sodium we are usually talking about a high temperature system. That's why we're using the sodium, and it's almost always a dominant design criterion that the materials we use have adequate high temperature mechanical properties. At about half the absolute melting point of most metals, the metal changes many of its low-temperature mannerisms and habits. Diffusion becomes very important and grain boundary sliding or creep becomes significant. Below half the melting point (~1000°F) as you see in this chart (give or take 100 or 150°F), the failure mode would usually be transgranular in nature, that is, the materials fail without much regard to grain boundaries. Above a temperature of ~1000°F, under sustained load, the grain boundary apparently becomes weaker than the body of the grain and you find the grain boundaries slipping, grains moving past each other, and this failure now generally occurs at the boundaries, in an intergranular manner. In fact, if you look at the microstructure of a creep specimen, you will very often find the grains are literally being pulled apart and the steel may look like a piece of Swiss cheese.

The next chart (Figure 44) shows a typical creep curve. Most of you have probably seen this, but let's run through it quickly. When a metal is pulled under load, it first takes up a certain amount of elastic strain. Then there is a period of time in which the strain rate is decelerating, after which there's a period of time called second stage creep in which the metal strains at a fairly uniform rate, and then as the material begins to "neck," it runs into the third stage creep. You can either report the second stage creep rate, which is the slope of the creep curve during second stage creep, or you can report an average stage creep rate that represents the total strain over a period of time that the metal was on test, or both. Of the two, the minimum creep rate is probably a better engineering number but you should never extend the time into the third stage creep region. At Atomics International, we have a rig, as shown by the next chart (Figure 45) which permits testing twelve specimens at the same time in sodium.

The sodium turns out to be an excellent protective atmosphere and heat transfer medium, and by individually pressurizing each of these little pieces of clad tubing, creep and creep-rupture data can be accumulated quite readily. The creep rupture data are obtained by monitoring the pressure gauge at the top of the specimen which is statically sealed. When the specimen ruptures, the pressure drops off to zero. Creep data are obtained by purposely relieving the pressure after a preset period of time, and then using the assumption (which I'm quite sure is valid) that no appreciable strain occurs after release of pressure. So you see we can get creep, creep-rupture, or even ductility data by measuring the change in the diameter after test. Let's look at some of the information that we have generated from use of this test setup and compare it to conventional uniaxial data.

The next chart (Figure 46) shows a comparison of tube-burst information for Types 304 and 316 stainless steel in sodium. You will notice that the Type 304 is stronger than the Type 316 at low temperatures, then it crosses over and becomes weaker at high temperatures; this is a real effect! Let's look at the next chart (Figure 47) which compares the creep curves resulting from biaxial and uniaxial loading of Type 304 in sodium at 1200°F. Note that under biaxial conditions a very low ductility exists compared to uniaxial conditions where there is considerably higher strain at failure, but note also that the rupture lives are really quite similar. This is completely different from the comparable curve shown in the next chart (Figure 48) for Type 316 stainless steel.

Here you see Type 316 with comparable ductilities under uniaxial and biaxial conditions, but having quite different rupture lives. Also, if you compare this with the previous figure, you see that the Type 316 is intermediate to Type 304 in its ductility at failure. These charts are really not intended to confuse you, but are intended to show that two materials which are thought of as being very much the same, Types 304 and 316, have quite different responses under mechanical loading at high temperatures. Let me go on with this comparison. The next chart (Figure 49) shows the effect of stress mode on rupture life of Type 316.

We've plotted the data for different levels of biaxiality (is the part in simple tension, under hoop stress, or hoop stress combined with tension?). In this case if you plot the maximum principal stress, all the points fit on a straight line.

Now let's consider Type 304 as shown in the next chart (Figure 50). This shows that the data only correlate if you use the Von Mises' theory. The point here is, gentlemen, that using the Von Mises' criteria for Type 304 normalizes the stress effect whereas in Type 316 we had to use the maximum principal stress in order to normalize the data.

The last in this series of mechanical property charts (Figure 51) shows a fairly subtle effect of environment on the creep mechanism of Type 304 under uniaxial creep. You see that the times to failure for the sodium and helium tests are not markedly different, but that the extension at failure is considerably higher in helium than it is in sodium. We can't yet explain this, but we think it is a significant effect.

Up to now, I have been showing you data that relate primarily to cladding design. For the bulk of the system design, you will probably be using the Boiler Code, or its equivalent. Just let me refresh your memory as to what the Boiler Code criteria are and how they apply to materials design allowables. As shown in the next chart (Figure 52). The American Society of Mechanical Engineers has accepted the use of the lowest value of any one of a number of mechanical properties for design allowables depending on the temperature and available data. At any temperature, you will use the lowest value of one of the following:

1) a quarter of the minimum ultimate tensile strength at room temperature,
2) a quarter of the minimum tensile strength at the service temperature,
3) 62-1/2% of the yield strength of the service temperature,
4) 60% of the average strength to cause rupture in 100,000 hr,
5) 80% of the minimum stress to cause rupture in 100,000 hr, or
6) stress to cause 1% creep in 100,000 hr.

These numbers provide sufficient conservatism for most high temperature design. If he chooses, the designer may use even more conservative criteria and, in some cases, that is exactly what we do at Atomics International. We are extrapolating data to 250,000 hr in order to give slightly more safety margin to our design.

The Boiler Code allowables for a number of materials are shown in the next chart (Figure 53), and here you can see why Inconel-600 is popular at low temperatures where it has a very high allowable. But, it drops off very rapidly. Incoloy-800, Grade 1, is an attractive material especially for steam generators below 1100°F. We would probably use the Grade 2 allowable because the Grade 1 relies on a specific heat treatment and we very seldom like to give ourselves credit for heat treatment in long-term applications. You see that Types 321 and 347 are the strongest stainless steels up to ~1175°F and, then Type 316 becomes the strongest, along with Incoloy-800. Type 304 is the weakest of the stainlesses. Now let's look at the chrome-molybdenum alloys; you will notice that the 5 Cr - 1/2% Mo is weaker than the 2-1/4 Cr - 1% Mo. Way down at the bottom of the chart is the carbon steel which is not permitted to be used for temperatures above 800°F. At the present time, there is a great deal of concern in not only the conventional pure tensile creep but especially the effect of low cycle fatigue superimposed on creep. The next chart (Figure 54) is intended to indicate the current analytical effort being expended on the prediction of the lifetime of materials undergoing a combination of creep, fatigue, and thermal shock loading.

I am sure there will be a great deal of experimental work devoted to predicting a lifetime of materials under combined load effects. These combined loads might include, for instance, an impact load on top of, or after, creep and fatigue. There is much to be learned in this whole area; the next chart (Figure 55) shows the effect, for instance, of time on the room temperature impact properties of Types 304 and 316. Note that the effect on Type 316 is considerably more pronounced than on Type 304. For both materials, there is a tendency to lose impact strength, probably due in part to sigma phase formation. Remember, this is room temperature effect; this effect may not be pronounced at the service temperature. Also, note that the temperatures on these curves are generally higher than we are planning on using (in at least our early sodium systems).

F. IRRADIATION EFFECTS

I think that I have talked enough about normal mechanical properties and now I would like to move fairly rapidly through a short discussion on irradiation effects (Figure 56) and, although the subject of irradiation effects may not be entirely kosher in this course on Sodium Technology, I think that we are generally talking fast reactors when we talk sodium technology, therefore, I will take time for irradiation effects. The next chart (Figure 57) tries to show why it is so difficult to make much sense out of irradiation tests; you simply have too many variables to be able to uniquely describe the history of the specimen. The irradiation conditions include the fluence, that is, how many neutrons did the part see? Flux, what is the rate of the neutrons hitting the part? What was the temperature during irradiation? What was the energy spectrum of the neutrons; was the test performed in a fast reactor or a thermal reactor? And, could there have been a chemical environment effect? Since it costs too much to run a test in the reactor, the material is irradiated and tested afterwards. Many people think this is not a good idea, but it is probably better than not testing at all. So, after the test, there are additional test conditions which may or may not be comparable to the imposed irradiation conditions, and these post-irradiation conditions, of course, involve temperature, strain rate, and chemical environment. So, it becomes very difficult to normalize data and what I will be talking about from now on will be simply a general assessment of the current state of the knowledge.

The next chart (Figure 58) attempts to summarize today's thinking on irradiation effects on metallic materials. At low temperature (remember our magic number of half the melting point — you may see that again in a few minutes) there is a minor increase in ultimate strength, the yield strength goes up markedly, and there is a major decrease in ductility. You remember I mentioned the NDT earlier for body-centered cubic materials. There is an increase in this, the temperature at which a material becomes very brittle. There apparently can be some creep enhancement either at low or high temperatures. At high temperatures, there is a major decrease in ductility for different reasons (we think) than the low-temperature decrease in ductility. I will try to explain that later. There is apparently a decrease in stress rupture life which might be associated with the loss of ductility, that is, a material ruptures before it strains as far as it might, unirradiated. There may be a minor effect on creep rate, possibly, coupled with creep enhancement. There is certainly one very serious effect that is new on the scene within the last few years. This is called void formation (and swelling). It seems to be unique to fast reactors and high temperatures.

Now let's run through some examples of these effects. The first one, on the next chart (Figure 59) shows the effect of irradiation and irradiation plus annealing on the stress-strain curve of Type 347 stainless steel. You will notice, the unirradiated and the irradiated plus annealed (that is, annealed after irradiation) actually follow the same curve; whereas, the material that was tested as-irradiated is somewhat stronger and less ductile. Let's look at the next chart (Figure 60). Compare the properties of the unirradiated material with that of the material that is irradiated and annealed, particularly the property of elongation.

If you test the material at room temperature, you will find that the unirradiated material has a 63% elongation, and after irradiating and re-annealing you get 57%; that is just about complete recovery of properties. The same thing happens when you test at 600°F temperature where an original elongation of 35% may be compared to an elongation of 32%. Looking at the high temperature test, you see that the unirradiated material had an original ductility of 26%. After irradiation that ductility dropped off to 1/2% and after annealing, remained at 1/2%; therefore, the loss of ductility at high temperature is not recoverable. We will explain why we think this happens in a few minutes.

The next chart (Figure 61) shows that the increase in transition (NDT) temperature is a function of fluence and irradiation temperature. For this type of irradiation effect a high temperature exposure is better than a low temperature exposure becuase the effects are annealing out. The next chart (Figure 62) shows some preliminary data which indicate a creep enhancement at reasonably low temperatures in the reactor environment. And the next chart (Figure 63) shows semi-quantitatively the effect of irradiation on short-term high temperature ductility of steel. We tried to show both void damage effects and helium bubble damage effects. The next chart (Figure 64) attempts to show you that as a result of the n,alpha reactions in a thermal or fast reactor, there will be helium formation, helium being the alpha particle, a product of the nuclear reaction. This helium is essentially insoluble in the metallic lattice in the body of the grain.

The helium atoms want to coalesce and leave the metal lattice. As they bounce around they will eventually find their way to the grain boundaries where they coalesce into bubbles. Under conditions of strain by grain boundary motion (remember what I said earlier about half the melting point and the creep mechanism being one of grain boundary sliding?) these bubbles result in cracks which make the metal fail at a relatively low ductility. If this same piece of metal were tested at low temperature, you probably wouldn't notice the difference because your failure mechanism is different; the material will fail across the body of the grain rather than through the grain boundary. That's why this loss of ductility effect is really only noticeable at high temperature — and, it's an irrecoverable effect. The recoverable effect which I mentioned earlier is somewhat akin to work hardening.

Electron micrographs of helium bubbles were taken for the next figure (Figure 65). The arrows point to the helium bubbles immediately adjacent to carbide particles in the stainless steel. In the next figure (Figure 66), we see the results of experimental work during which we injected helium into Type 304 stainless steel by a cyclotron. You will notice that as the helium concentration is increased at 1000° F, there isn't much effect on the elongation and the test piece is very much like the control. However, as the test temperature is increased, there is a more dramatic effect. We have found this helium injection by a cyclotron to be quite a valuable tool in studying the helium bubble effect.

The next chart (Figure 67) shows that there is an effect of irradiation of the creep rupture life of solution treated material. There is a loss of life; we think that this is probably due in a large part to a loss of ductility. Some early work shown in the next chart (Figure 68) tends to support the theory that there is not much difference between in-reactor and ex-reactor creep rates but the actual nuclear exposure of these parts is classified. More recent information on irradiation and enhanced creep may supersede these data.

Using your imagination, the next chart (Figure 69) shows voids in stainless steel. These voids are actually accompanied by a decrease in bulk density, and a number of other observations are listed in the next chart (Figure 70). Unlike the helium bubbles, these voids are not gas filled, and there doesn't seem to be a requirement for stress for their formation or growth. For some reason their population decreases in grain boundaries. The voids disappear on annealing and that is one thing that makes them different from the helium bubbles. They have a normal (by normal, we mean statistically "normal" or Gaussian) size distribution.

Apparently a small amount of helium is required for nucleation. It requires a fast flux, swelling is apparently isotropic, and if you have a part in a flux gradient, then you are going to get a density gradient, and, as a result of this, you will get a density gradient which will cause bowing due to differential swelling. This bowing or differential swelling creates the design problem caused by void formation and it has caused a great deal of concern in the design of reactor cores. We have had considerable success in simulating fast neutron void damage by means of a proton irradiation in accelerators.

The next figure (Figure 71) shows the voids that we were able to produce in steel in a fairly short period of time by an accelerator. Just as we used helium injection to answer some of our questions on helium bubbles, we are using proton injection to study void formation; it looks like it will be an extremely powerful tool for that purpose. This has been a very brief and oversimplified talk on irradiation effects but I hope by now you have a better understanding for the fact that although there is a lot we don't know, we are not totally lacking in either knowledge or theories in this important field of materials science.

G. SENSITIZATION

Our next subject will be that of sensitization of the austenitic stainless steels (Figure 72). What is sensitization? Sensitization (Figure 73), at least to me, is the loss of corrosion resistance of a stainless steel that results from precipitation of chromium carbide at a grain boundary which is accompanied by the loss of chromium in the region immediately adjacent to the chromium carbide precipitate. Let me say it again. At reasonably low temperatures, chromium and carbon react to form chromium carbide. This reaction appears to occur preferentially at grain boundaries. When the reaction occurs, the chromium immediately adjacent to the grain boundary has reacted with the carbon to form chromium carbide in the grain boundary and, therefore, the part of the grain right next to the chromium carbide particle is depleted of chromium. It's just that simple. You have a small region of non-stainless steel around every grain.

Now let's look at what happens with the time at temperature as shown in the next chart (Figure 74). If we hold a piece of steel at temperature and test its corrosion rate occasionally, we'll find that the corrosion rate will increase with time. This is due to the loss of the chromium to the carbide. Then, surprisingly, the corrosion rate will decrease with additional time; the reason being that the chromium is rediffusing back into the region that was previously impoverished. Now let's use this overlay chart (Figure 75) showing that at a lower temperature, that is, T_2, it takes longer to form the chromium carbide and the corrosion rate increases to a higher degree, but eventually the chromium will rediffuse and you will get back to around the original state. If this same type of test is done for a lot of different temperatures, we will end up with the three dimensional curve such as is shown in the next chart (Figure 76). You see how the peak of corrosion rate follows along a "ridge" and gets higher as time increases and temperature decreases.

Let me show you this same type of data in yet another presentation (Figure 77). The top curve is a contour map of the three-dimensional chart I just showed you. The bottom curve, which has exactly the same form, shows the effect of carbon content on the onset of grain boundary attack as determined by a controlled test. Notice that there is an equivalence between carbon content and corrosion rate. And notice that you can reduce the carbon content, and buy yourself some time but sensitization is not eliminated even with as low as 0.019% carbon. As you see by the lower curve, the steel will still sensitive. I'm not sure that this fact is generally appreciated. Another fact that is not generally appreciated is the effect of stabilizing elements with regard to sensitization. Let's make up a pseudo phase diagram such as is shown in the next chart (Figure 78) which shows a line for the solubility limit of chromium carbide in stainless steel. We have a steel with some carbon as shown at composition A. It cools down and then you operate it, let's say, at temperature T. Well, the amount of carbon available to react with chromium and sensitize is shown by the bracket. And, quite obviously, the lower composition A is (in an absolute sense) the lesser problem that you will have with sensitization. That's why you use the extra low carbon varieties of stainless in some applications. Now, if you add titanium, niobium, or tantalum as shown in the overlay (Figure 79), you can see that you have a more stable carbide which raises the temperature of the solubility limit, so it tends to react, let's say at temperature T_1. This process will remove a lot of carbon from solution, thereby effectively reduce the carbon content left to sensitize. Once below T_1 of the temperature at which the chromium carbide becomes stable, I think the steel will sensitize. The carbon will react with the chromium in spite of the presence of the Ti, Nb, or Ta. In fact, if you use a stabilized stainless steel improperly, you can get into trouble from "knife-line attack" which is illustrated schematically in the next figure (Figure 80).

Here we have a weld made between a piece of unstabilized and a piece of stabilized stainless steel. The unstabilized stainless steel will become sensitized in the region a short distance from the weld where the steel was at a temperature between 900 and 1400°F for a reasonably long period of time; that is, long enough for carbide to precipitate but not long enough for the chromium to rediffuse. The stabilized stainless steel will sensitize in a region immediately adjacent to the weld which was heated to just below the melting point. At this high temperature, the niobium or titanium carbides dissolve, but on rapid cooling do not precipitate. On reheating, the carbon will combine with whatever it sees first and that's likely to be chromium and so will precipitate as chrome carbide or at least as a mixed carbide. Either way this steel is sensitized and because this type of corrosion occurs so close to the weld and in such a narrow region, it actually looks like a knife cut and has been called knife-line attack.

To begin summarizing a little, if you want to resist sensitization in austenitic stainless steels as indicated in the next figure (Figure 81), you can operate it above 1200°F. You can solution anneal and quench so as to take all the carbon and chromium carbide into solid solution, and then operate at a low enough temperature that it doesn't reprecipitate. That's below 800°F or so. And neither of these first two approaches are practical in a sodium system that runs, say, between 700 and 1100°F. If you reduce the carbon you can resist sensitization for a period of time but you lose strength, and as I pointed out, it will eventually sensitize to some degree. You can add titanium or columbium which may make the steel less weldable and subject to knife-line attack; at low temperature the steel will eventually sensitize because at any temperature there will always be an initial degree of supersaturation of carbide. Often your best bet is to use the best material and to take great care to protect it. The next chart (Figure 82) lists some positive aspects of sensitization.

In my opinion, sensitization has essentially no effect on strength; let me put it this way, if it does have an effect, that effect is accommodated by the test as it is performed. In other words, any effect to weaken the steel or strengthen it is reflected in the creep curve. It simply has to be because the creep curve is made while the steel is sensitizing. There is a fair amount of work to indicate that there probably is not much of an effect on ductility under normal engineering applications and this includes cryogenic work. There might be an effect of very high strain rate. Sensitization doesn't seem to have an effect on oxidation resistance or sodium compatibility and again, what we are basing this statement on is that the tests have to be performed on materials that are sensitized or in the process of sensitization.

H. STRESS CORROSION

Now, I would like to speak briefly on the subject of stress corrosion (Figure 83). My discussion on this extremely important topic is limited because we just don't know enough about stress corrosion to give you a very comprehensive picture. The next chart (Figure 84) shows stress corrosion cracking by one man's definition to be very rapid crack formation and propagation under certain specific environmental conditions. In the case of austenitic stainless steels, the presence of tensile stress is usually required. You have a halide, usually chloride. You apparently have to have the water phase present and, ordinarily it is above ambient temperature, that is, from 150°F up to the temperature of boiling water and pressurized water reactors, and steam generators, so it can be quite high. And while the stress corrosion cracking is not so rapid that it's explosive, you can have an explosive type of failure resulting from weakening due to stress corrosion cracking in any pressurized system; it is quite rapid.

Some test data, shown in the next chart (Figure 85), illustrate the effect of nickel content on the minimum time for small wires to break. You can see the minimum in the curve is at about 8 to 10% nickel where failure occurred in less than 1 hr. That, gentlemen, is exactly where the austenitic stainless steels are found on this graph. In other words: they have the composition most susceptible to stress corrosion cracking, at least in this particular test. It is thought that anything that lasts longer than 100 hr in this test is essentially immune to field failure. This is one reason why Incoloy-800 with about 35% nickel is viewed with great favor by people who are concerned with stress corrosion cracking.

It is not just chlorine, as can be seen in the next graph (Figure 86). It can be an effect of chlorine plus oxygen, either one of which may not be dangerous alone, but when combined, they can be very potent. And now, closing the discussion on the austenitic stainless steels, I am showing on this figure (Figure 87) some heat treatments that should be used for the various types of austenitic stainless steels. You can see that for both normal and high carbon, the preferred heat treatment is a high temperature solution anneal and rapid quench. Holding at low temperature will give partial stress relief. Stabilized and low carbon steels are better to work with when they're annealed at an intermediate temperature, such as 1650°F. This is above the chromium carbide precipitation temperature range but within the refractory carbide precipitation range. This permits a "tie-up" of the carbon with the titanium or niobium. You can "overage" normal stainless steel to the point that you actually diffuse the chromium back into the impoverished regions. This is not inconceivable for critical parts but you might be talking hundreds of hours of heat treatment which is not normally practical. You can heat treat the stabilized and low carbon steels in the sensitizing temperature range for a short period of time. This is really not good practice, though. I will summarize by saying that the austenitic stainless steels are fine materials and they deserve tender loving care with proper attention given to their environment and to the details in fabrication processing control.

I. CASE HISTORIES

The last technical section of my talk will deal with four case histories (Figure 88). I hope to illustrate how materials selection is done in current engineering practice.

The first case history is Vessel Material Selection (Figure 89) and in the next figure (Figure 90) we've drawn a picture of what the reactor vessel for a fast breeder reactor might look like, and the parts as they might be shipped to the site. This assumes that the vessel itself is too large to be shipped. It really doesn't make that much difference in the analysis because our selection will not be dictated by how or where the vessel is built. The way we approached this problem was to establish what the vessel might look like and what it's functional requirements were. Then we performed a detailed "environmental analysis" as outlined in the next chart (Figure 91). And we considered what that vessel might see in it's lifetime — from cradle to grave. We considered fabrication and shipping. We considered what might happen during installation, erection and storage. We considered operation and maintenance procedures. We considered various accidents and what might be done and we considered shutdown and retirement. Our questions were really based on what can happen or how can we protect the material. An example of our reasoning is shown in the next chart (Figure 92) which is a simplified version of a number of tables we made. In this case it shows what we were thinking about during fabrication. We made these, as I mentioned, for all phases of the plant's life. Looking at this chart, you can see that contamination during fabrication can come from a number of sources. Even temperature might be of concern if you are working with a material that is brittle at low temperatures. We tried to list all environmental conditions, what the effects of these conditions might be on materials and we tried very hard not to presuppose a material (although in all honesty we had been thinking about stainless). We tried to open the door to ferritic steels although we were most interested in nickel based alloys as alternates at that time. And we asked ourselves, what can you do about some of these effects? Some of the countermeasures were easy and some were not necessarily very easy to accomplish. We did some structural analysis and, as shown in the next figure (Figure 93), it turns out that when we used Inconel 600, the vessel got considerably thicker. This increased the problems of thermal stress in addition to raising cost and difficulty in fabrication. We reviewed, as shown in Figure 94, the materials of construction of previous liquid metal reactors and found that every reactor to date has been built from a 300 series stainless steel (with the exception of a reactor built at Oak Ridge as a two-hundred hour experiment for the Aircraft Nuclear Propulsion program). Summarizing our investigation on the next chart (Figure 95), we graded each of six materials on several criteria. As you can see, we didn't think that any of these materials could not be used. Our conclusion is shown in the next chart (Figure 96) which says that Type 304 stainless steel in spite of its problems with regard to sensitization and stress corrosion has a lower risk than the nickel base alloys.

The next case history is that of the Selection of Cladding Material for a fast breeder reactor (Figure 97). The requirements for cladding are listed in the next chart (Figure 98). The thin wall cladding tubing has to contain the fuel and fission product gases of the fast breeder reactor. This includes the liquid sodium environment, temperatures to 1200°F (possibly higher), one and one-half year service life, a high fast neutron flux, internal gas pressure and strain as the fuel swells and exerts stress on the cladding. These requirements can be recombined into fabricability in handling mechanical properties, thermal stability, irradiation stability, and sodium corrosion (Figure 99). The same things we have been talking about the last few hours, and comparing the materials largely on the basis of the data that I showed you earlier; for instance, cold worked Type 316 stainless steel is the strongest - cold worked Type 304 is the weakest (Figure 100). Remember that the curves crossed. On the basis of swelling information, we feel that the cold worked cladding will swell less than annealed material as shown in the next graph (Figure 101). Sodium corrosion effects are compared on the next chart (Figure 102). The summary chart (Figure 103) ranks the candidate materials and we end up selecting cold worked Type 316 stainless steel even though it has a tendency to decarburize. I think this remains to be proven in a large system. The next case history (Figure 104) deals with the selection of the material for the part of the control rod — the Trip Latch. The function of the part in question is shown in the next chart (Figure 105). It is a critical part that supports the neutron absorber section and releases it rapidly when a fast shutdown is required. The design requirements are a life of 10 years, of 500 "trips," radiation that isn't too high, environment of slowly flowing sodium, a reasonably high temperature of 1200°F, and, ordinarily, very low stresses except that during the trip operation there is an impact load that can be quite high. Taking these requirements and changing them into materials desirements, as we talked about earlier, resulted in the thinking as reflected in the next chart (Figure 106). We needed high strength, coupled with low self-welding, neutron damage, sodium corrosion or friction properties. The result of our thinking and literature review as shown in the next figure (Figure 107) is that we recommended a combination of tungsten, molybdenum, and nickel base alloys for the various contact points that are shown. We didn't have enough information to make a clear-cut decision and, as a result, we recommended a test program. The test concept is shown in the next figure (Figure 108) in which we have a configured specimen that will be pressed against a mating specimen for some period of time and then a "breakaway force" will be measured. The materials that we recommended for testing are shown in the next chart (Figure 109).

The last case history that I would like to discuss is that of the Selection of a Steam Generator Material (Figure 110). Our design requirements for a steam generator are shown in the next chart (Figure 111). The steam generator sees a modest temperature, very high steam pressure, long life (30 years), high purity sodium, we're not sure about the water purity, and we felt that the steam generator had to have a Boiler Code stamp. The steam generator is designed as shown in the next chart (Figure 112). Basically a long pipe, it's a modular steam generator with a relief nozzle, and a bend, or hockey stick at one end in order to relieve differential expansion between the tube bundle and the shell. It is quite a simple design and features a butt weld between the tube and the tube-sheet so as to avoid crevices and permit radiographic inspection of all welds. This will improve the reliability of the unit. The summary of our thinking is shown on the next chart (Figure 113) which resulted in our selection of 2-1/2% Cr · 1% Mo as shown in the next chart (Figure 114).

J. SUMMARY

In summary (Figure 115), about all I can say, is that materials selection (Figure 116) is simply a matter of defining requirements, knowing materials, and then matching these materials to the requirements. The last chart (Figure 117) presents a brief list of references you might find useful for the selection of materials for sodium systems. Thank you for your attention this afternoon.

SELECTION OF MATERIALS
FOR
SODIUM SYSTEMS

J.P. PAGE
PROJECT ENGINEER
MATERIALS APPLICATIONS

MATERIALS SELECTION OUTLINE

- INTRODUCTION
- MATERIALS SELECTION PROCESS
- SODIUM CORROSION
- IRON-CHROMIUM-NICKEL ALLOYS
- MECHANICAL PROPERTIES
- RADIATION EFFECTS
- SENSITIZATION
- STRESS CORROSION CRACKING
- CASE HISTORIES
  - VESSEL
  - CLADDING
  - CONTROL ROD TRIP LATCH
  - STEAM GENERATOR
- SUMMARY

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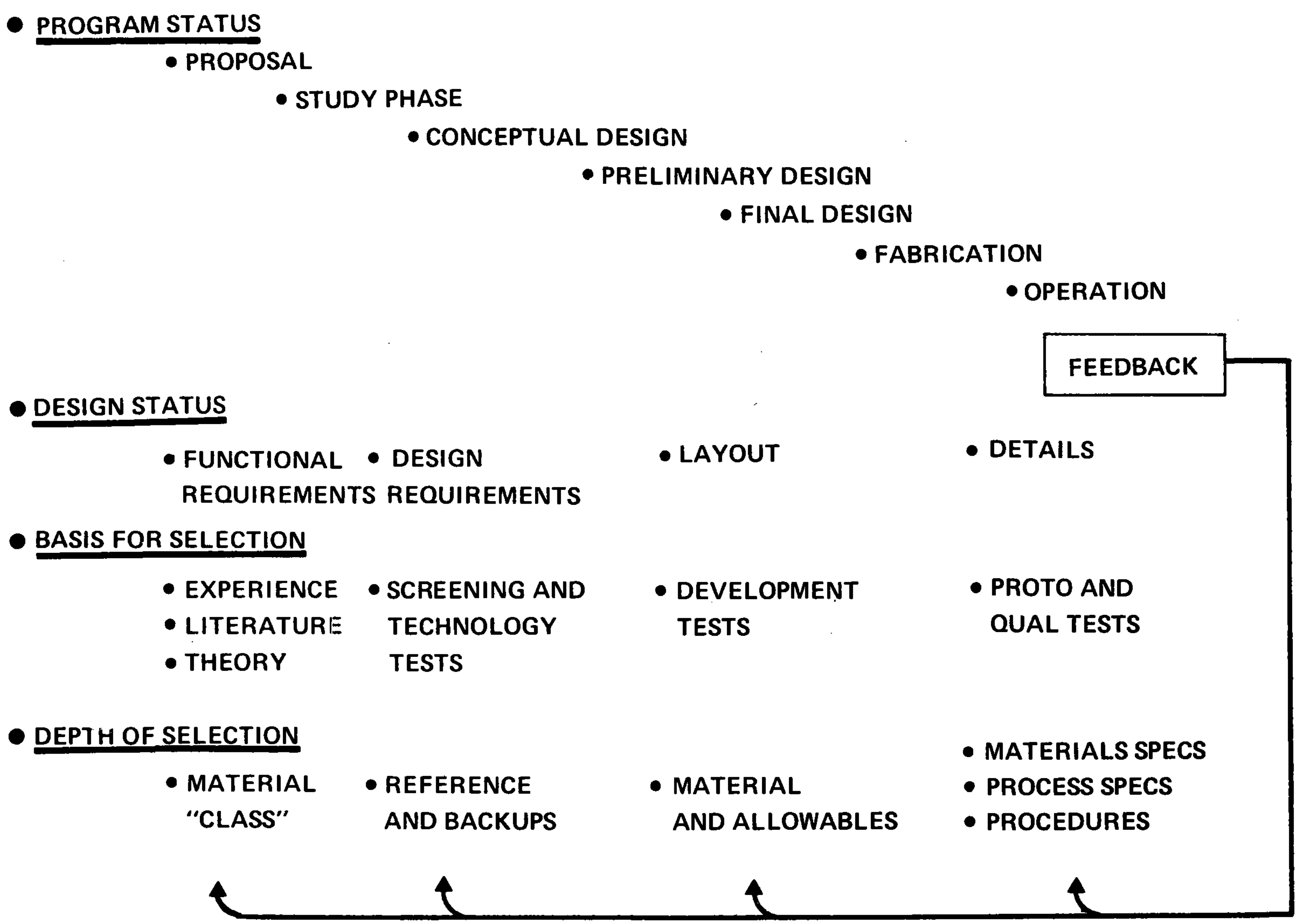
MATERIALS SELECTION PROCESS

STEPS OF MATERIALS SELECTION



- **PROGRAM STATUS**
  - PROPOSAL
  - STUDY PHASE
  - CONCEPTUAL DESIGN
  - PRELIMINARY DESIGN
  - FINAL DESIGN
  - FABRICATION
  - OPERATION

FEEDBACK

- **DESIGN STATUS**
  - FUNCTIONAL REQUIREMENTS
  - DESIGN REQUIREMENTS
  - LAYOUT
  - DETAILS
- **BASIS FOR SELECTION**
  - EXPERIENCE
  - LITERATURE
  - THEORY
  - SCREENING AND TECHNOLOGY TESTS
  - DEVELOPMENT TESTS
  - PROTO AND QUAL TESTS
- **DEPTH OF SELECTION**
  - MATERIAL "CLASS"
  - REFERENCE AND BACKUPS
  - MATERIAL AND ALLOWABLES
  - MATERIALS SPECS
  - PROCESS SPECS
  - PROCEDURES

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PROPER MATERIALS SELECTION INCLUDES CONSIDERATION OF:

- FUNCTIONAL REQUIREMENTS
- DESIGN CONCEPT
- MATERIALS DESIREMENTS
  - PROPERTIES
  - LIFETIME
  - ALL CREDIBLE ENVIRONMENTS
- ACCEPTABLE RISK
- ACCEPTABLE R&D COST
- ACCEPTABLE COMPONENT COST
- ACCEPTABLE SCHEDULE

9-N7-129-5

MATERIALS SELECTION CRITERIA

A.

- MECHANICAL PROPERTIES
- SHORT-TERM TENSILE
  - ULTIMATE
  - YIELD
  - ELONGATION
  - REDUCTION OF AREA
- CREEP AND STRESS-RUPTURE
- FATIGUE
- IMPACT
- HARDNESS
  - SOMETIMES OTHERS, SUCH AS
    - MODULUS OF RUPTURE
    - COMPRESSIVE PROPERTIES
    - SHEAR AND TORSION PROPERTIES
    - FRACTURE TOUGHNESS

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MATERIALS SELECTION CRITERIA

B.

- PHYSICAL PROPERTIES
- THERMAL
  - EXPANSION
  - CONDUCTIVITY
  - SPECIFIC HEAT
  - MELTING TEMPERATURE
- ELECTRICAL
  - RESISTIVITY
  - DIELECTRIC
- MAGNETIC
- EMITTANCE
- DENSITY
- NUCLEAR
  - CROSS SECTIONS
  - REACTION PRODUCTS

MATERIALS SELECTION CRITERIA

C. METALLURGICAL PROPERTIES

- WELDABILITY
- BRAZEABILITY
- FORMABILITY
- MACHINABILITY
- DIMENSIONAL STABILITY
  - THERMODYNAMIC (PHASE CHANGES)
  - NEUTRONS
- PROPERTY STABILITY
  - THERMODYNAMIC
  - NEUTRONS

MATERIALS SELECTION CRITERIA

D. COMPATIBILITY PROPERTIES

- REACTIONS WITH SOLIDS
- REACTIONS WITH LIQUIDS
  - SODIUM
    - PURE
    - IMPURE
  - WATER
    - PURE
    - IMPURE NEUTRAL
    - ACIDS
    - BASES
- REACTIONS WITH GASES
  - AIR
  - STEAM
- VACUUM EFFECTS

MATERIALS SELECTION CRITERIA

E. PRACTICAL PROPERTIES

- REGULATORY REQUIREMENTS
- INSURANCE REQUIREMENTS
- AVAILABILITY
    - LEAD TIME
    - COMPETITIVE SOURCES
    - ACCEPTABLE SPECIFICATION
- EXPERIENCE
    - PRIOR R&D
    - ON-GOING R&D
    - APPLICATION
- COST
    - MATERIAL
    - FABRICATION
    - QUALITY AND RELIABILITY ASSURANCE

SODIUM CORROSION

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SODIUM CORROSION OF MATERIALS

BEST – REFRACTORY METALS (Nb, Mo, Ta, W), BUT EXPENSIVE, OXIDIZE, EMBRITTLE, UNPROVEN

GOOD – IRON AND IRON-RICH ALLOYS

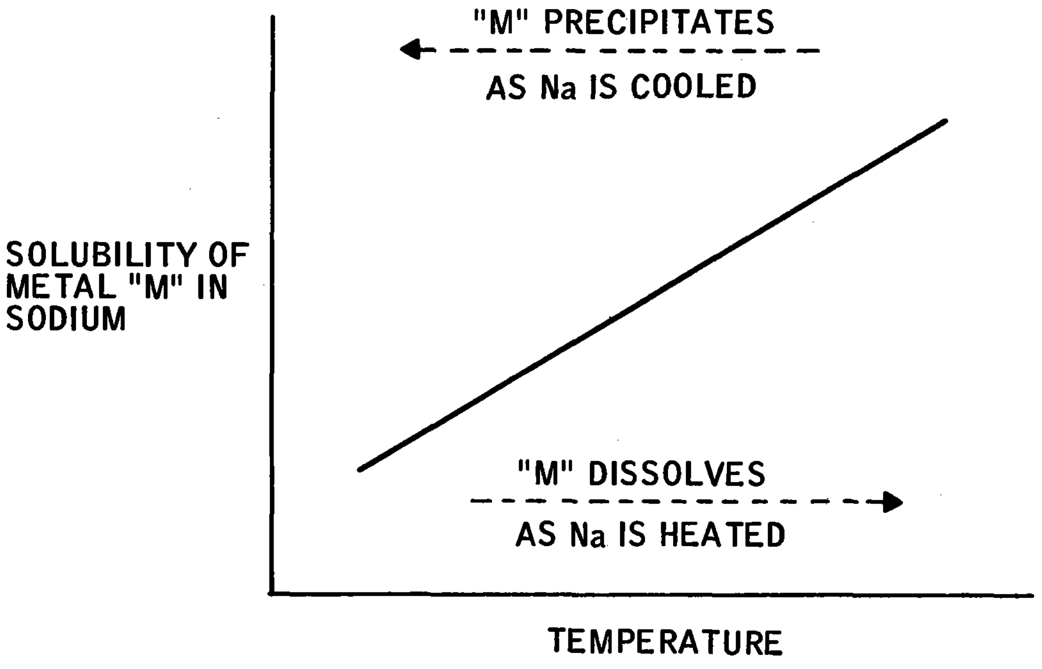
GENERALLY OKAY – NICKEL-RICH ALLOYS

GENERALLY POOR – COPPER AND ITS ALLOYS
PRECIOUS METALS
LOW-MELTING ELEMENTS
ALUMINUM AND ITS ALLOYS

DARK HORSES – TITANIUM, ZIRCONIUM

PESTS – CARBON, SILICON, SULFUR, PHOSPHORUS, MANGANESE, NITROGEN, OXYGEN

EFFECT OF TEMPERATURE ON SOLUBILITY



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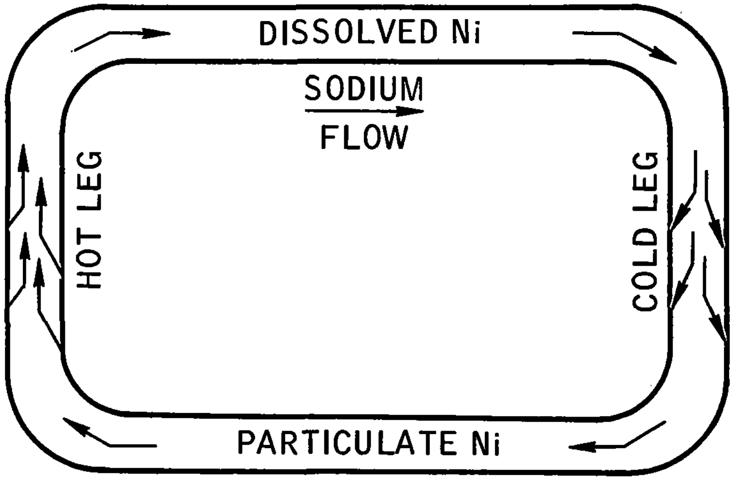
SOLUBILITY - GRADIENT MASS TRANSFER

CASE "A" - TRANSFER OF ELEMENT -(e.g.Ni)

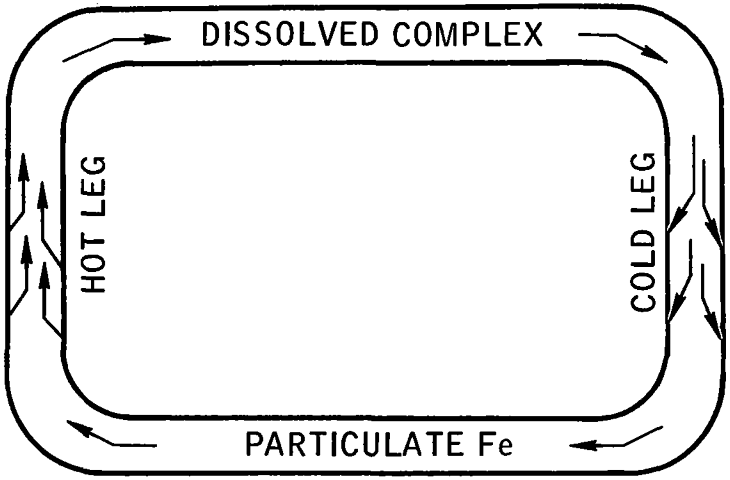


NICKEL DIFFUSES
TO SURFACE AND
DISSOLVES

NICKEL PRECIPITATES
AND ADHERES OR IS
TRAPPED OR RETURNS
TO HOT LEG

SOLUBILITY - GRADIENT MASS TRANSFER

CASE "B" - TRANSFER OF COMPLEX - e.g. $Na_2O \cdot FeO$



IRON REACTS
TO FORM COM-
PLEX WHICH
DISSOLVES

COMPLEX
DECOMPOSES,
YIELDING
FREE IRON

REACTION: $3\ Na_2O + Fe \underset{COLD}{\overset{HOT}{\rightleftharpoons}} 2\ \underbrace{Na_2O \cdot FeO + 2Na}_{COMPLEX}$

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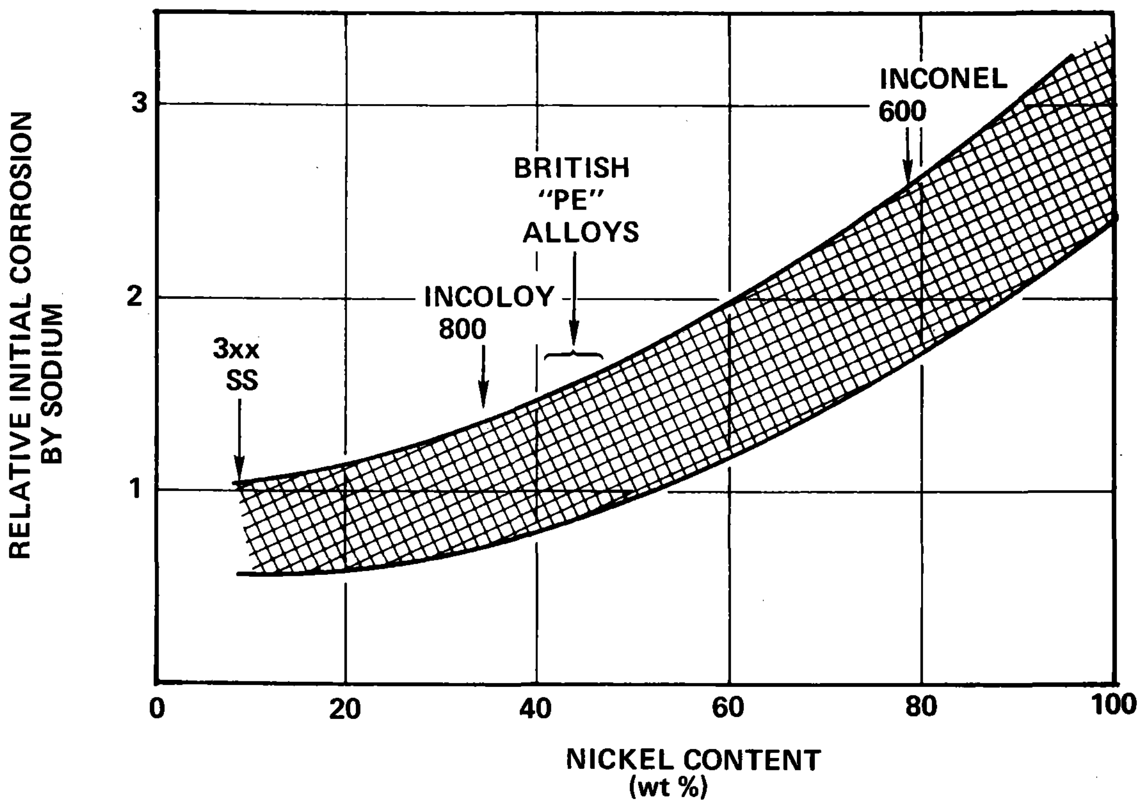
INITIAL CORROSION OF IRON-CHROME-NICKEL ALLOYS



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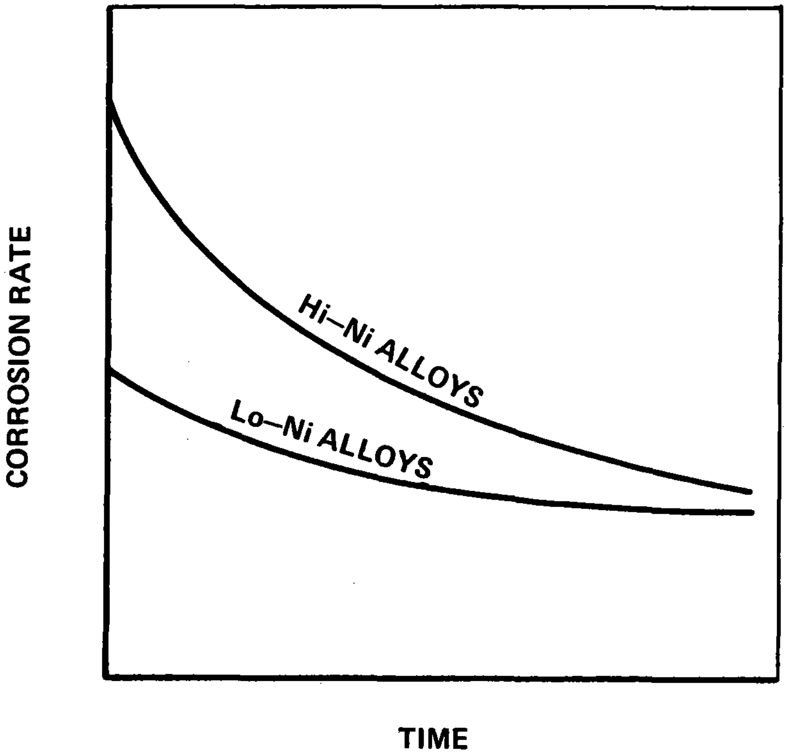
EFFECT OF TIME ON SODIUM CORROSION OF IRON-CHROME-NICKEL ALLOYS



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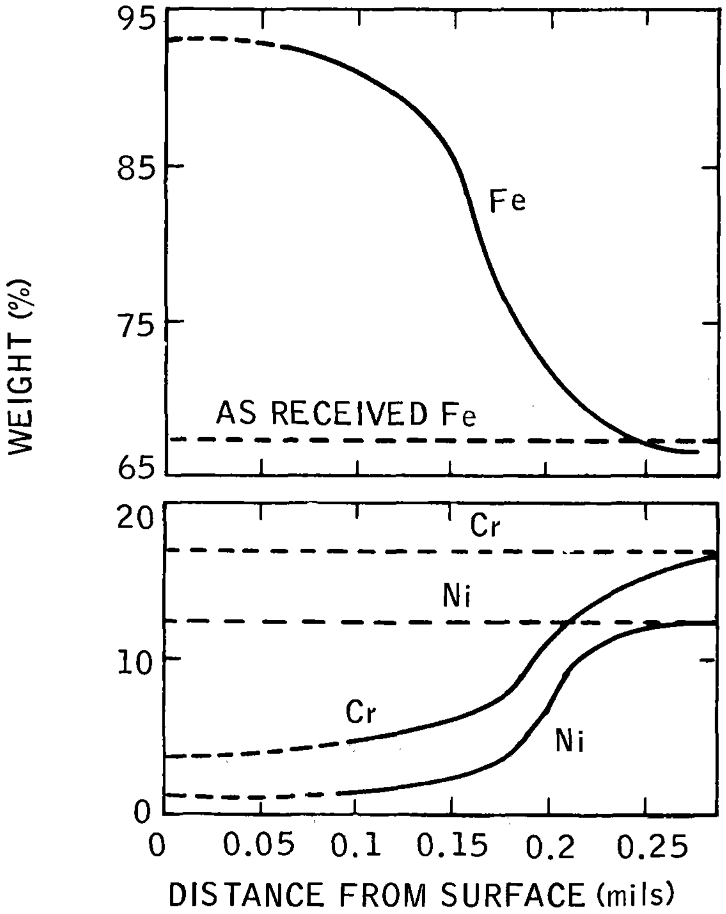
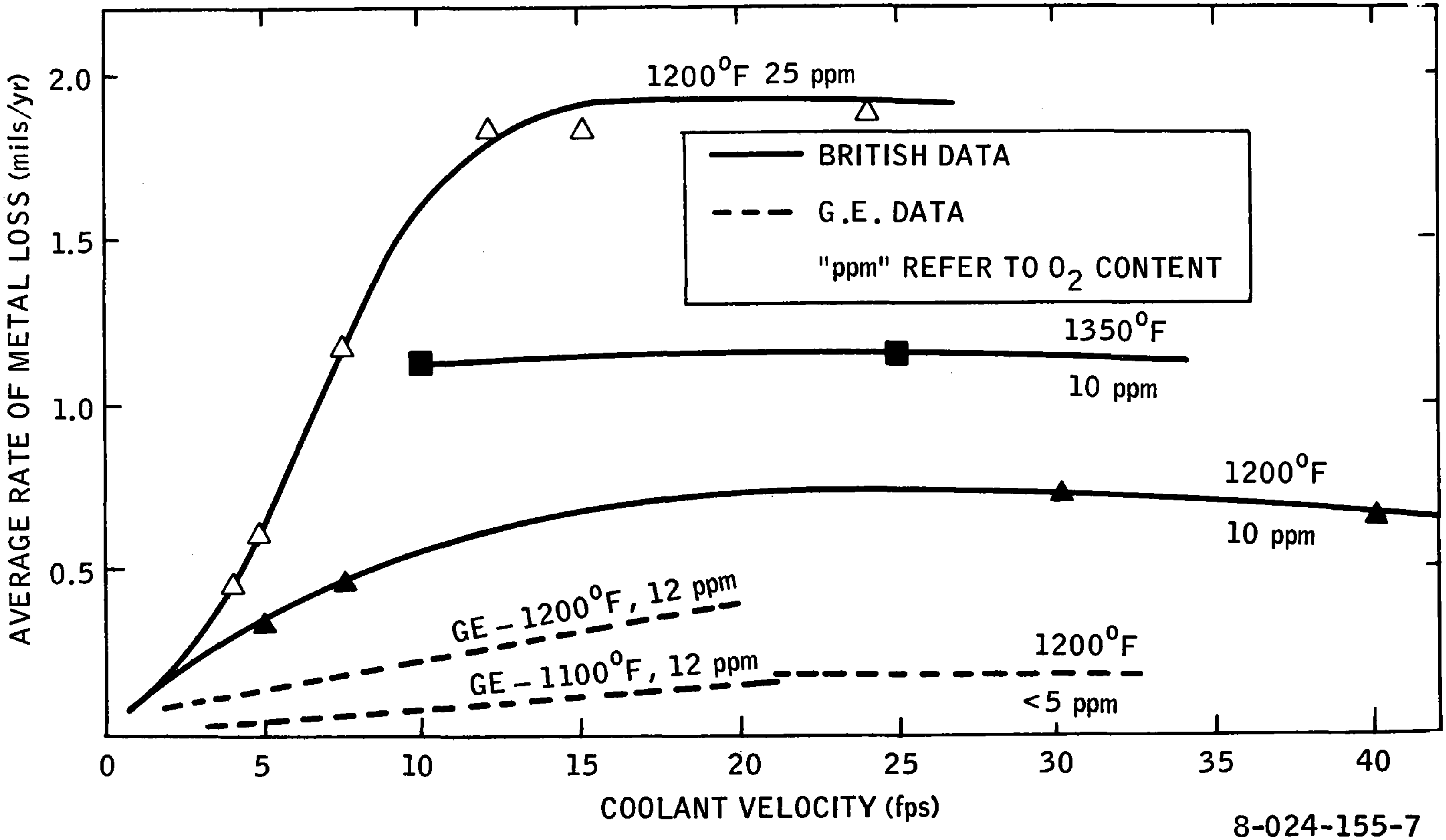
COMPOSITIONAL CHANGE IN SS ASSOCIATED WITH ELEMENTAL LEACHING IN Na



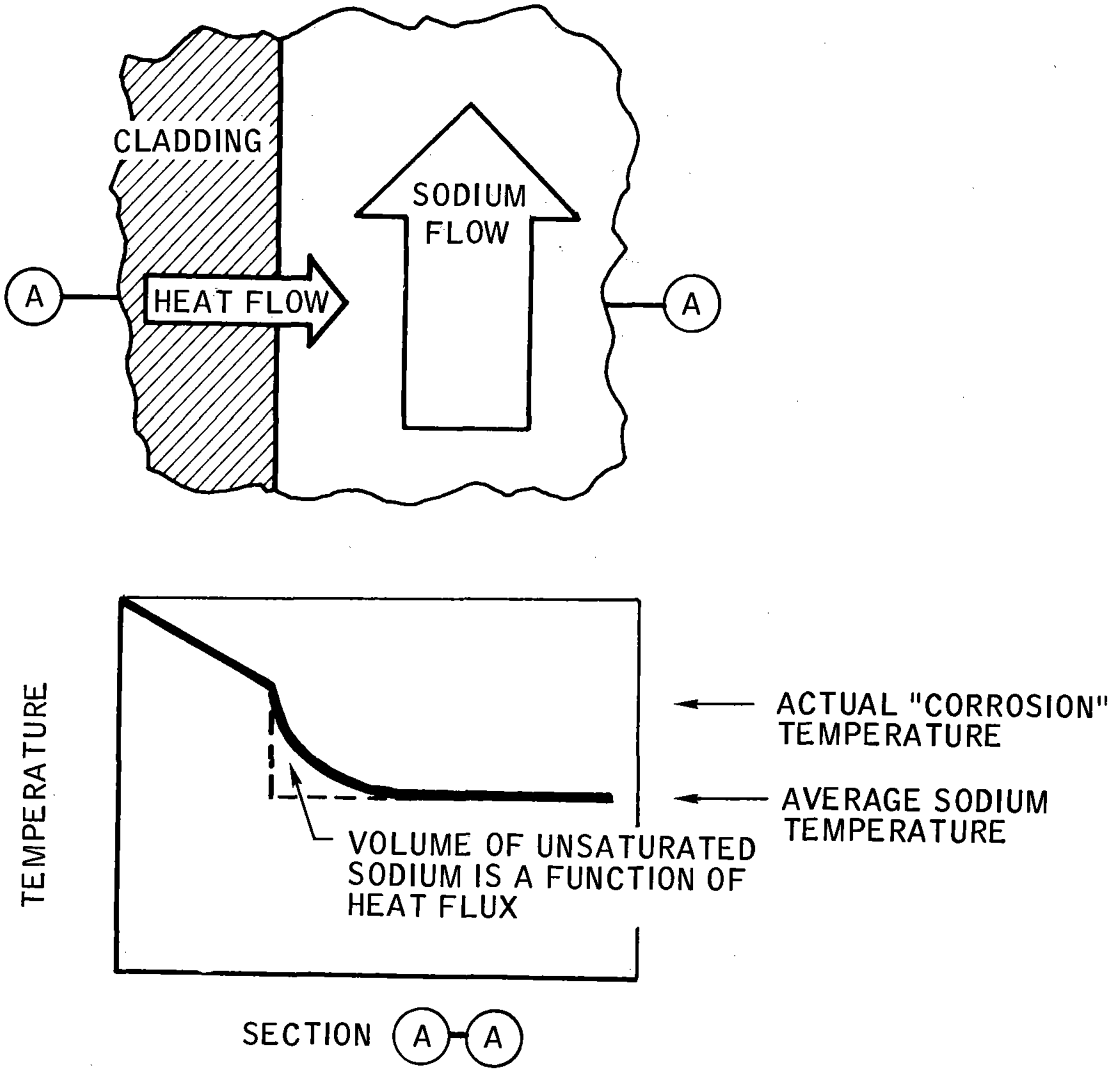
9-010-116-23

ENVIRONMENTAL EFFECTS ON CLADDING CORROSION



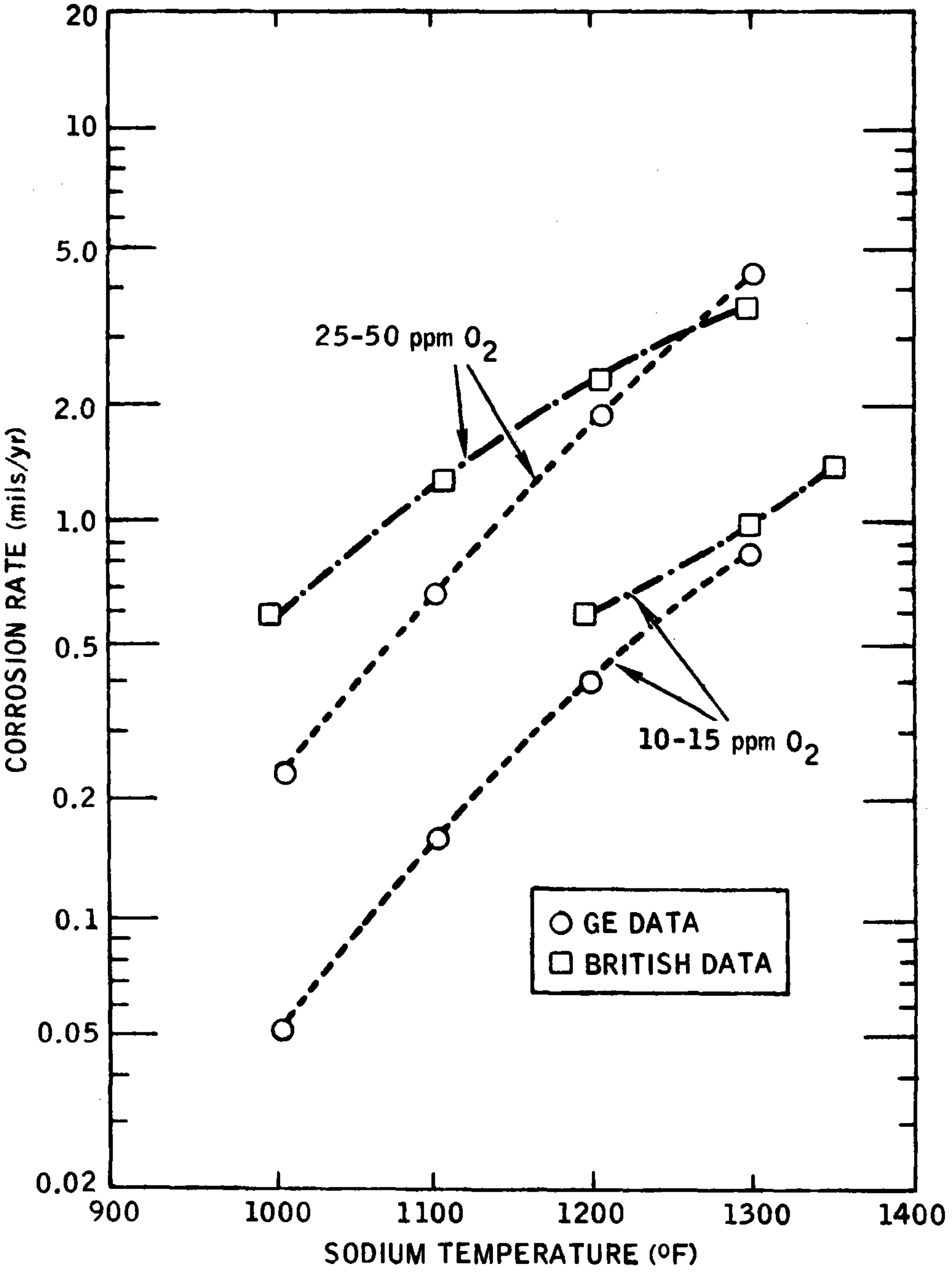
8-024-155-7

THE "HEAT FLUX EFFECT"



SODIUM CORROSION DATA

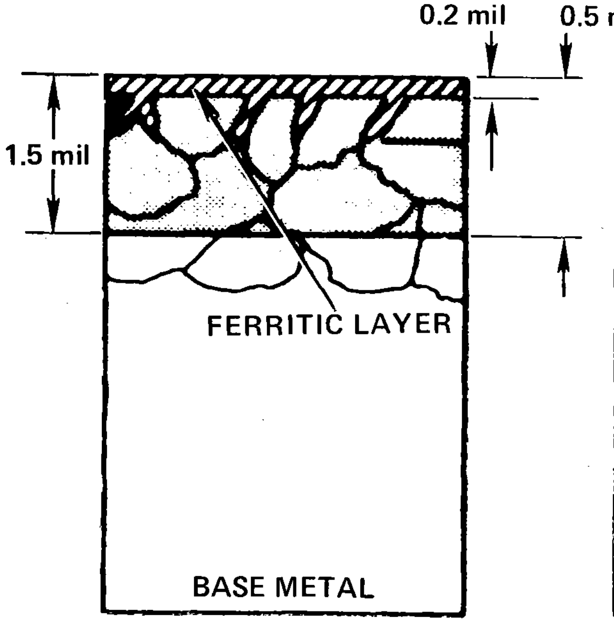
FOR 300 STAINLESS STEELS; 2¼ Cr - 1 Mo STEEL, AND 5 Cr - ½ Mo STEEL



8-024-155-47

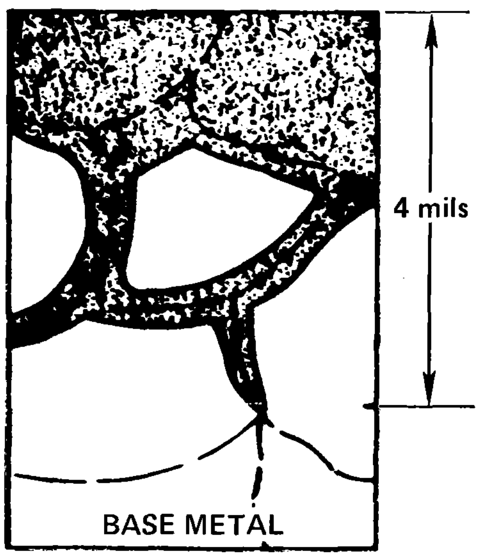
MICROSTRUCTURE AFTER EXPOSURE TO FLOWING SODIUM (<10ppmO_2) AT 1300°F FOR 2000 HOURS (GE-BRDO)

DISTURBED ZONE
NO PHASE CHANGE



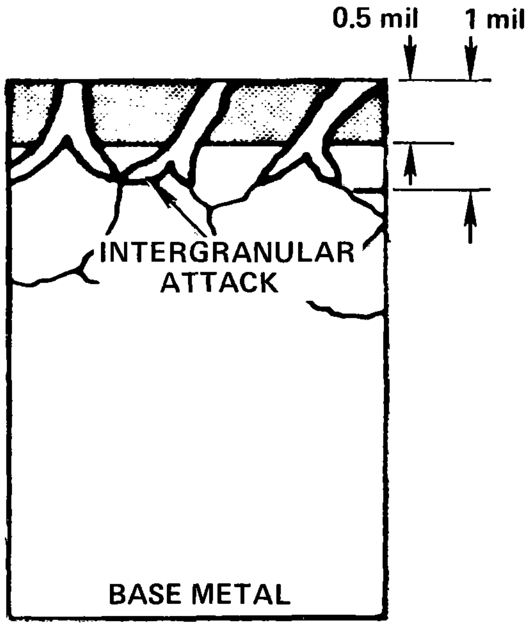
316 STAINLESS STEEL
Sharp gradient at surface. Accelerated Dissolution at Grain Bounderies resulting in phase change and Shallow Gradient into the Bulk.

DISTURBED ZONE
AND
PHASE CHANGE



304 STAINLESS STEEL
Shallow gradient. Deep Penetration Associated with Grain Bounderies resulting in Bulk Transformation.

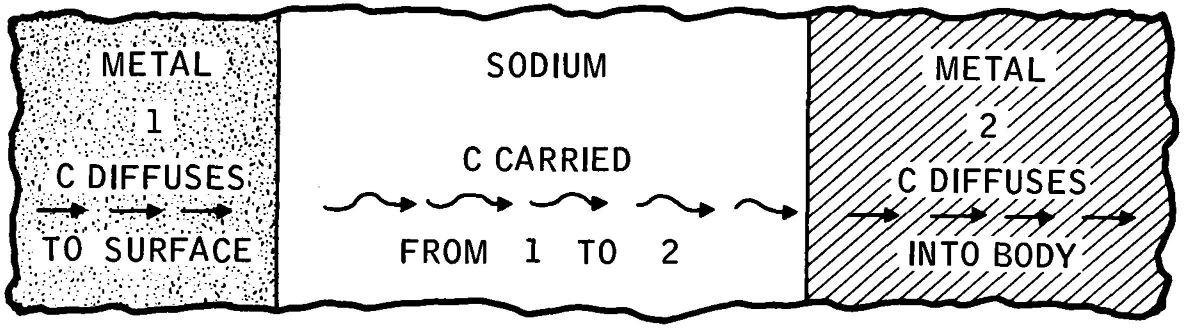
COMPOSITIONAL
DISTURBANCE
NO
PHASE CHANGE



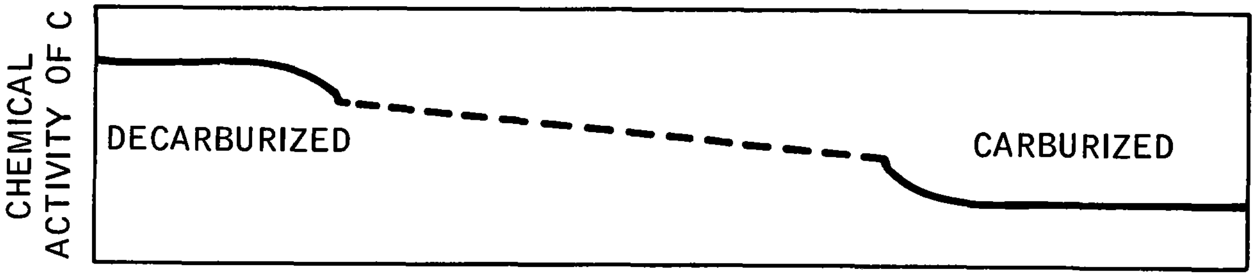
INCOLOY-800
Sharp gradient at surface. Accelerated Dissolution at Grain Bounderies resulting in Grain Boundary Voiding.

9-S9-103-3

ACTIVITY - GRADIENT MASS TRANSFER
(e.g. CARBON TRANSPORT)

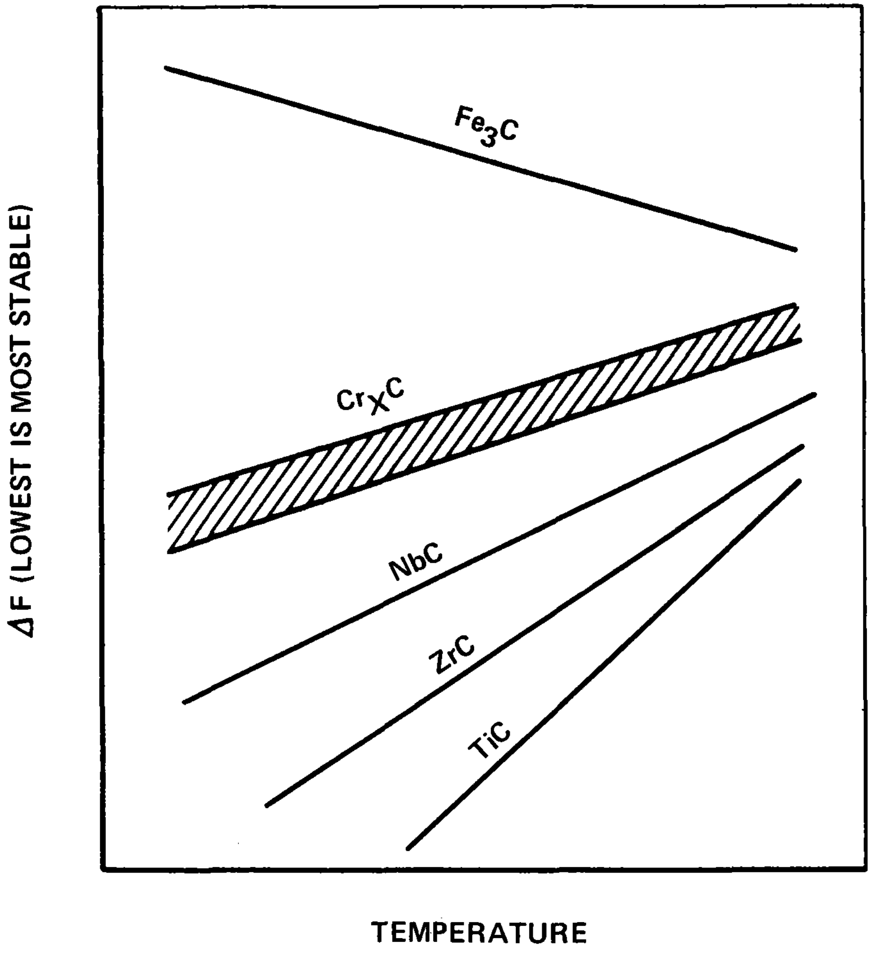


PHYSICAL REPRESENTATION



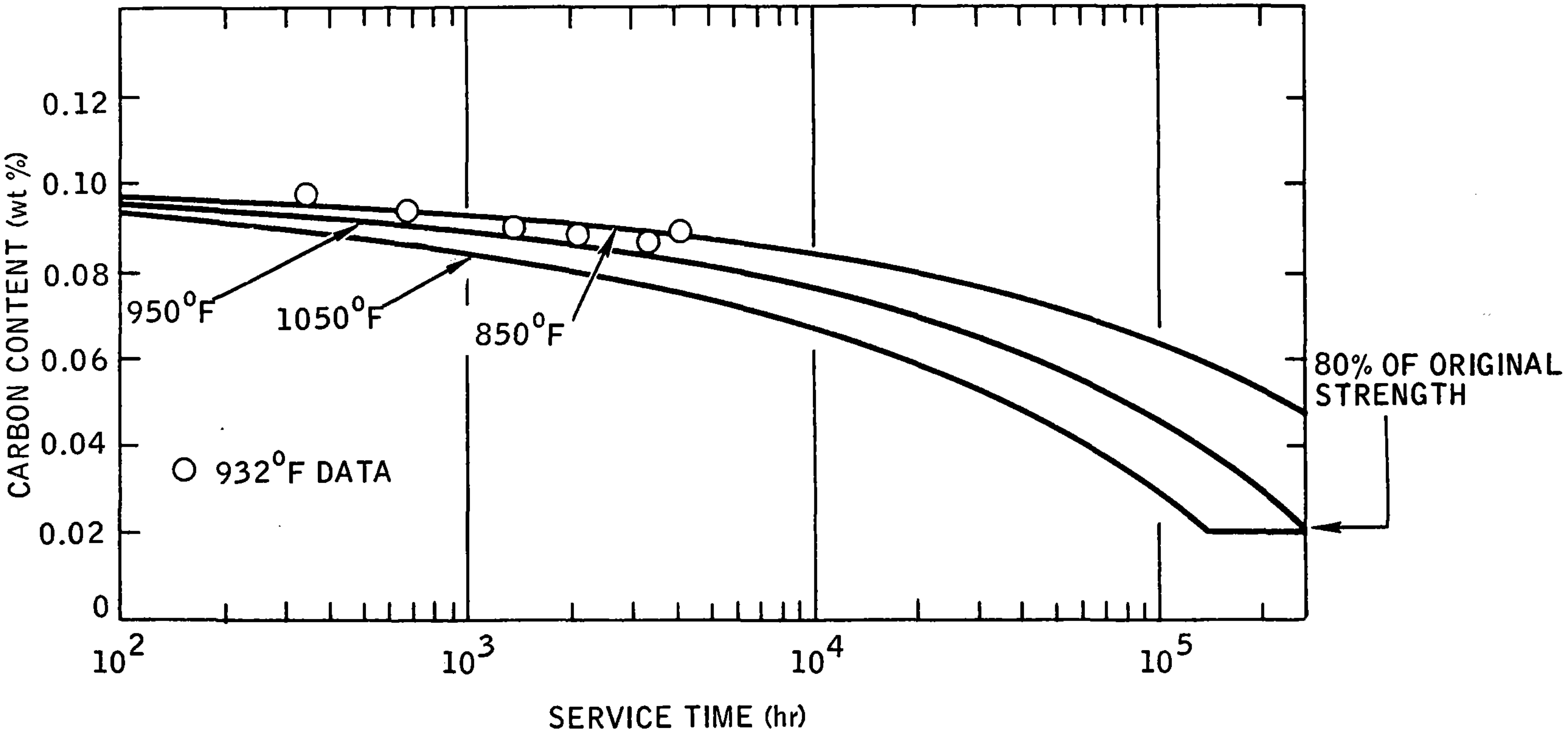
ACTIVITY PROFILE

ACTIVITY OF CARBON FOR SEVERAL METAL CARBIDES



9-010-116-20

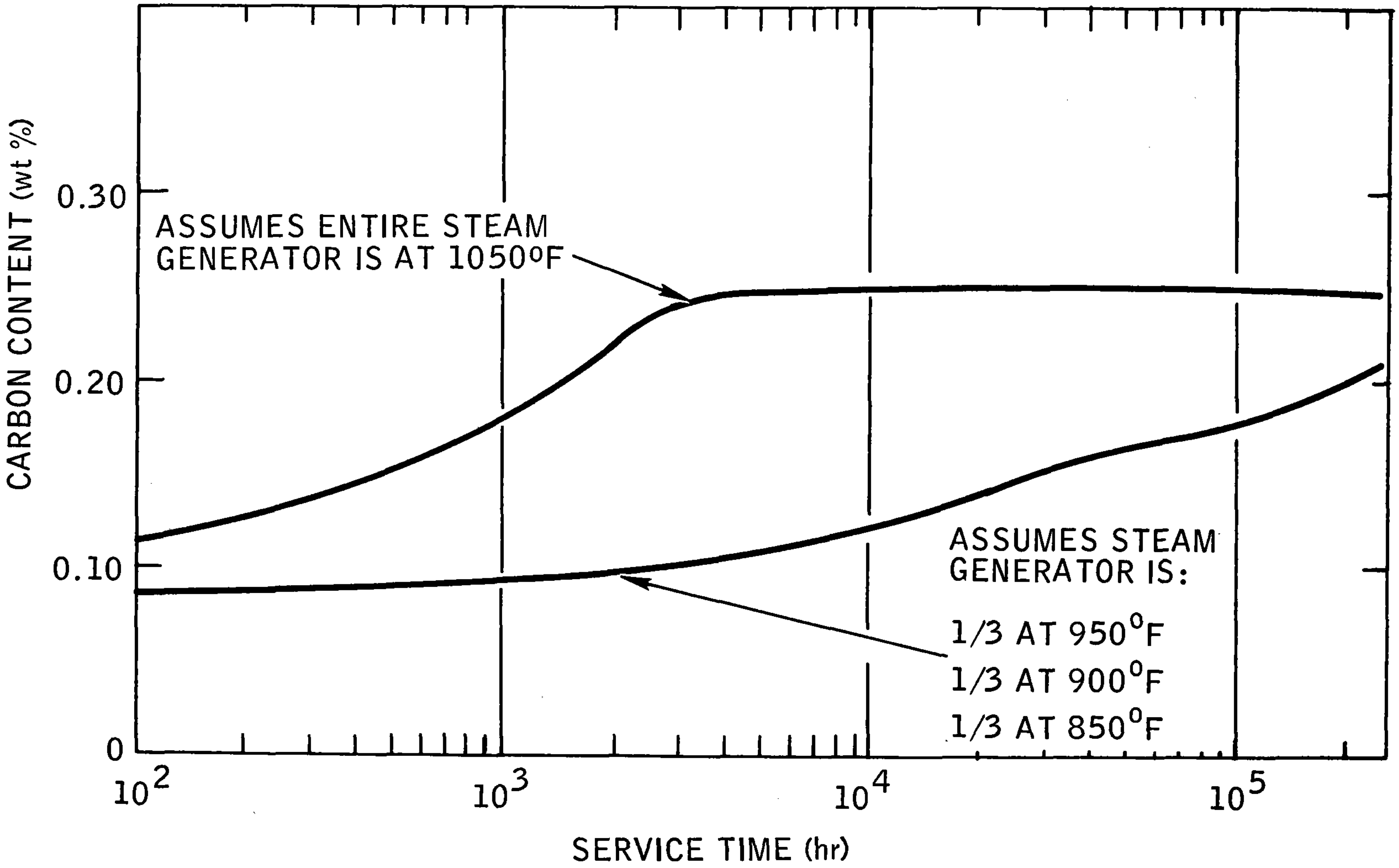
DECARBURIZATION OF 0.095-in. THICK 2¼Cr-1Mo STEEL BY SODIUM (ONE SIDE)



8-09-144-48

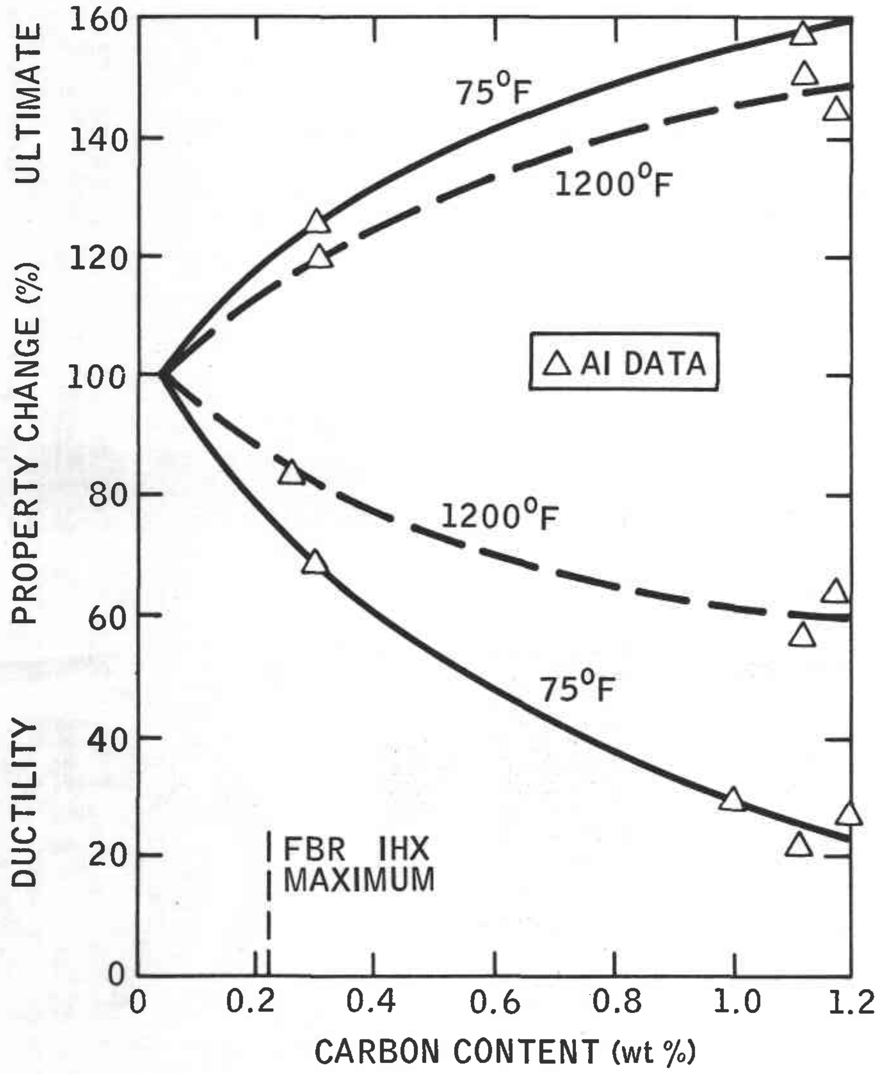
CARBURIZATION OF 304 STAINLESS STEEL FBR INTERMEDIATE HEAT EXCHANGER

(IN SECONDARY CIRCUIT WITH 2¼Cr-1Mo STEAM GENERATOR)



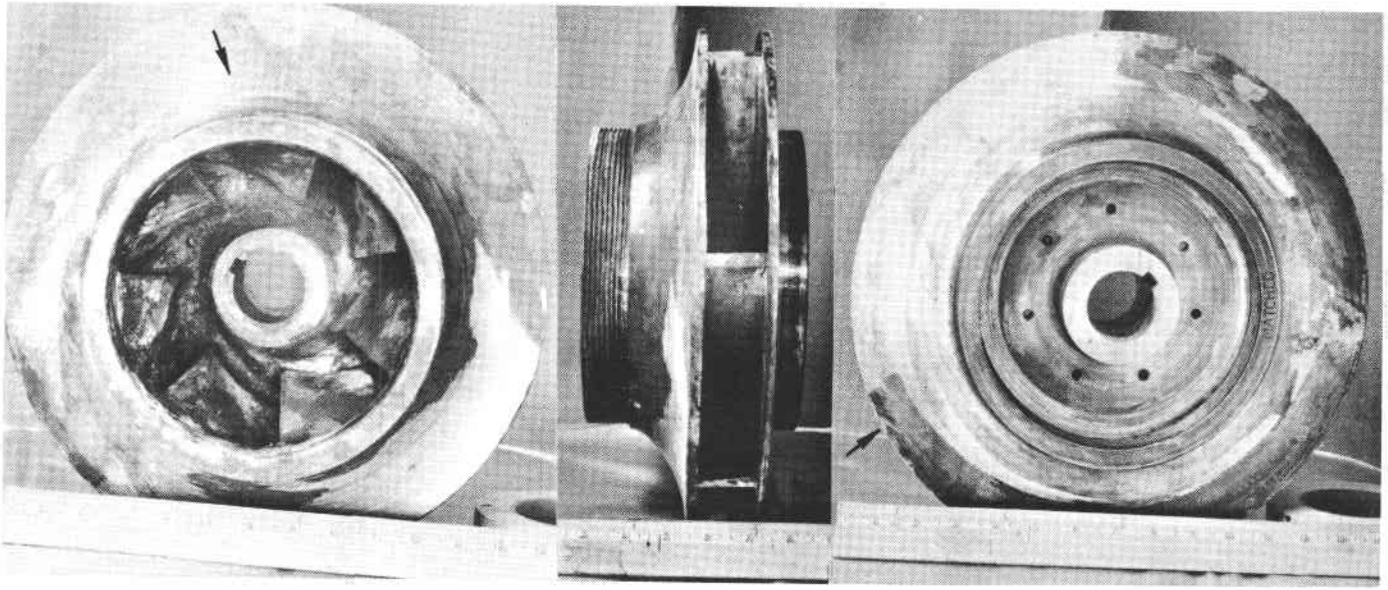
8-09-144-47

EFFECT OF CARBON CONTENT ON PROPERTIES OF 304 STAINLESS STEEL

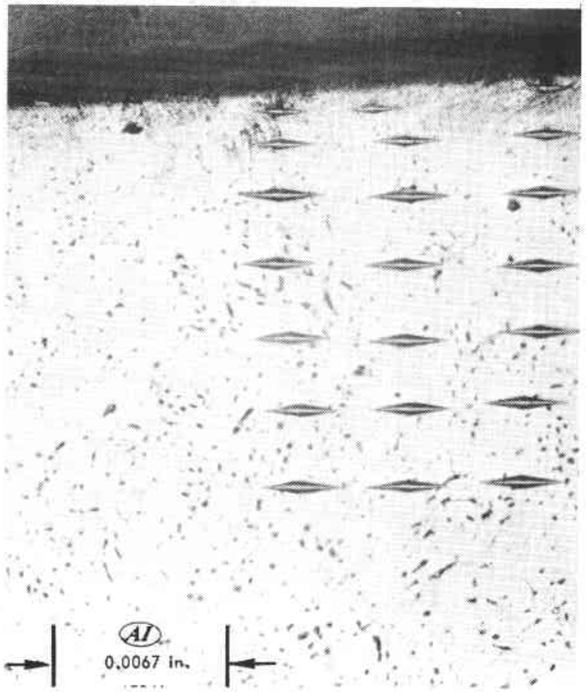


7-A15-184-9

SRE MAIN PRIMARY PUMP IMPELLER



AFTER CLEANING BY HOT OIL IMMERSION



MICROSTRUCTURE OF CAST TYPE 316 STAINLESS STEEL IMPELLER BLADE

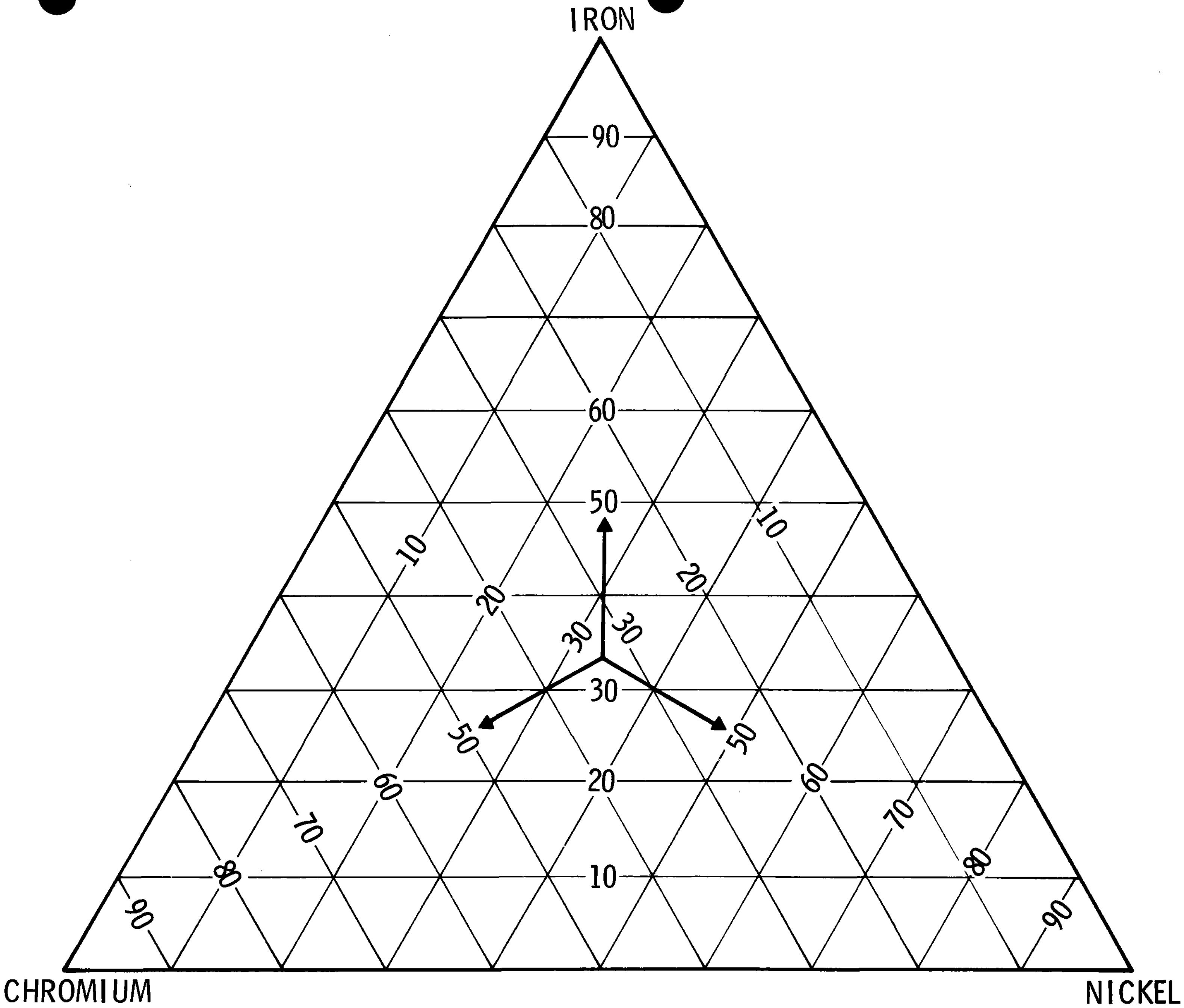
66-6095-81-5

SODIUM CORROSION SUMMARY

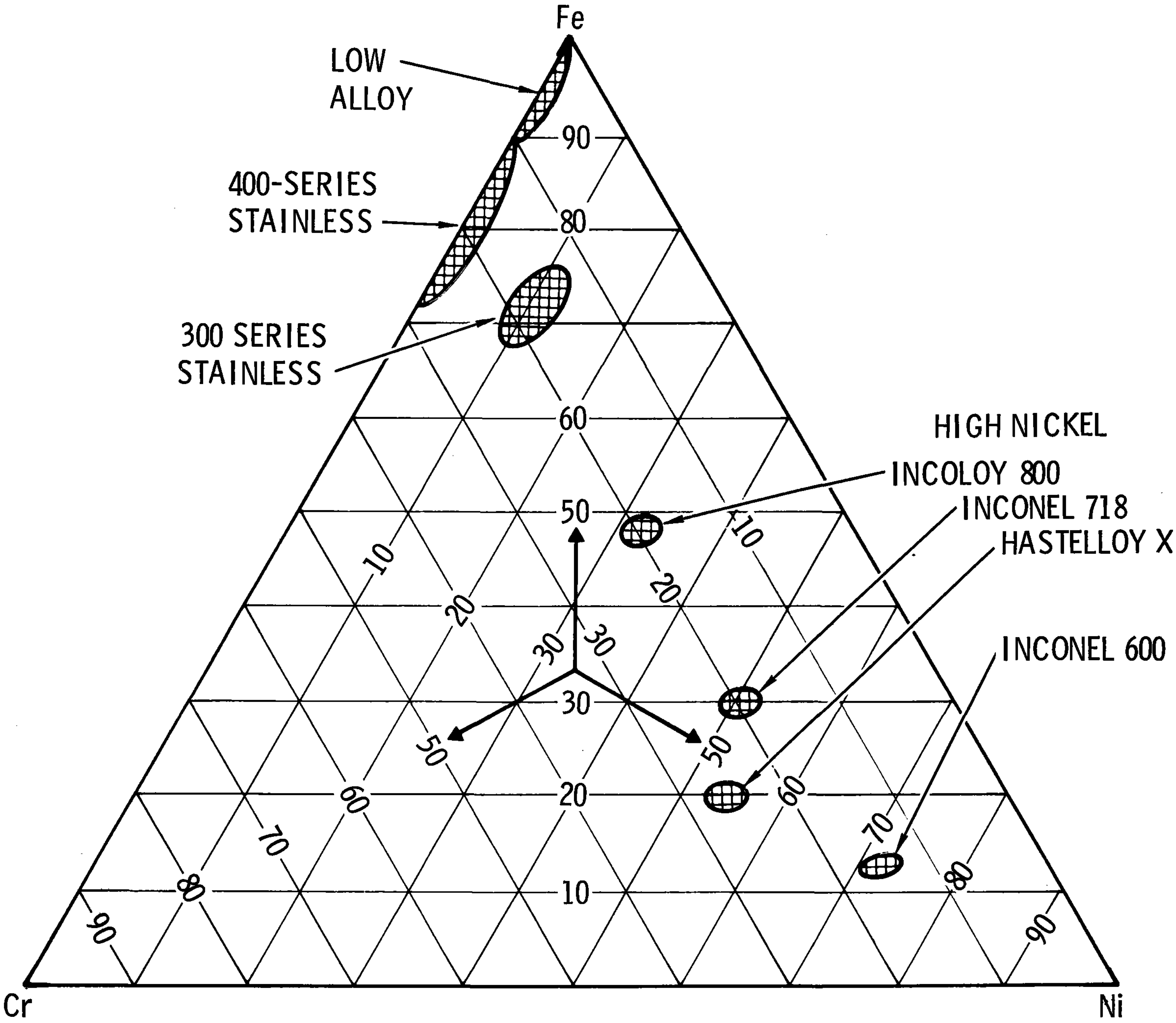
CORROSION MECHANISM	EFFECT	DESIGN IMPLICATION
ACTIVITY-GRADIENT MASS TRANSFER (CARBON TRANSFER)	ALTERS MECHANICAL PROPERTIES NO DIMENSIONAL CHANGE	CAREFUL MATERIALS SELECTION ADJUST DESIGN ALLOWABLES USE HOT TRAP
SOLUBILITY-GRADIENT MASS TRANSFER (NICKEL AND IRON TRANSFER)	LOSS OF SECTION DEPOSITION IN COLD LEG	APPLY CORROSION ALLOWANCE ALLOW FOR DEPOSITION USE CLEAN SODIUM USE COLD TRAP

7-A15-184-1

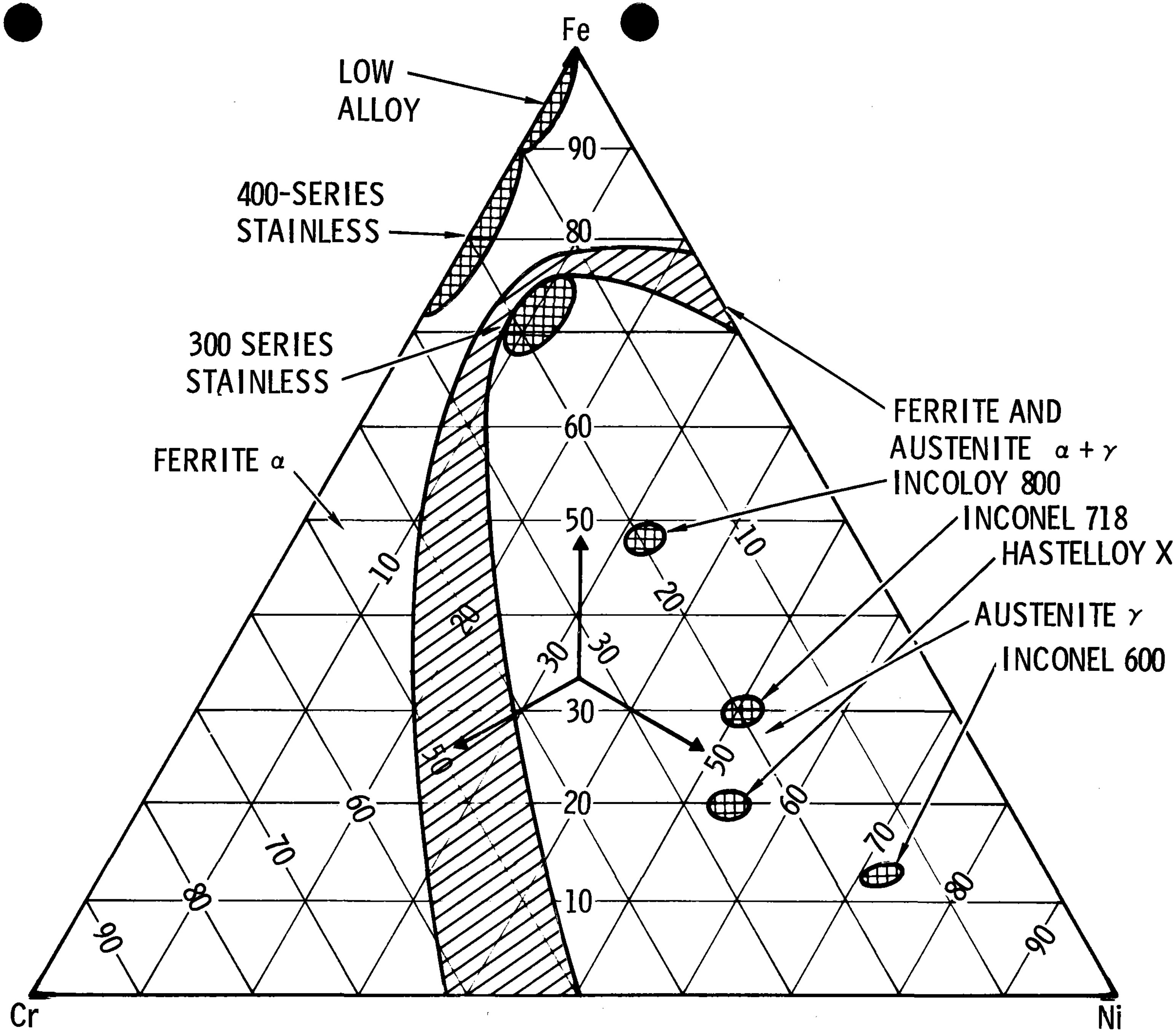
IRON-CHROMIUM-NICKEL ALLOYS


IRON
90
80
60
50
30
20
10
10
20
30
50
60
70
80
90
10
20
30
50
60
70
80
90
CHROMIUM
NICKEL

70-MA1-48-375



70-MA1-48-375A



70-MA1-48-375B

EFFECT OF ALLOYING ELEMENTS ON STEELS

- PROMOTE AUSTENITE
  - NICKEL
  - CARBON
  - MANGANESE
  - NITROGEN

- PROMOTE FERRITE
  - CHROMIUM
  - MOLYBDENUM
  - SILICON
  - NIOBIUM

70-MA1-48-355

CARBON STEEL

<u>ADVANTAGES</u>

- VERY LOW COST
- READY AVAILABILITY
- GOOD FABRICABILITY
- NO CHLORIDE SCC

<u>DISADVANTAGES</u>

- IRRADIATION RAISES "NDT"
- RUSTS
- CAUSTIC SCC
- ABOVE 800°F
  - GRAPHITIZES
  - WEAK
  - WILL DECARBURIZE
  - OXIDIZES

70-MA1-48-364

LOW-ALLOY STEEL

ADVANTAGES	DISADVANTAGES
• LOW COST	• RUSTS
• STRONG TO 1000°F	• HIGH WELD COST
• OXIDATION OK	• HIGH AS-FAB "NDT"
• WON'T GRAPHITIZE	• MAY DECARBURIZE
• NO CHLORIDE SCC	

70-MA1-48-365

"400" - SERIES STAINLESS

ADVANTAGES	DISADVANTAGES
• RUST RESISTANT	• 880^{0}F EMBRITTLEMENT
• LOW COST	• VERY DIFFICULT TO WELD
	• HIGH AS-FAB "NDT"

"300"-SERIES STAINLESS

ADVANTAGES

- MODERATE COST
- GOOD STRENGTH
    - EASILY WELDED
    - NO NDT
- RUST RESISTANT
- MUCH RESEARCH
- MUCH EXPERIENCE

DISADVANTAGES

- STRESS CORRODES
- SENSITIZES
- SIGMA PHASE

HIGH NICKEL ALLOYS

ADVANTAGES	DISADVANTAGES
• NO CHLORIDE STRESS CORROSION	• HIGH COST
• QUITE WELDABLE	• WEAKENED BY Pb AND S
• NO NDT	• NOT AS GOOD AS STEELS RE: SODIUM CORROSION
• WEAK TO VERY STRONG	

70-MA1-48-371

OTHER MATERIALS

- BRAZING
- NEUTRON ABSORPTION
- ANTI-GALL AND SELF-WELD
- INSTRUMENTS
- SEALS
- COVER GASES
- COOLANTS

SOME AUSTENITIC STAINLESS STEELS

302	18 Cr - 9 Ni – 0.15C
301	REDUCE Ni – INCREASE WORK – HARDENING
303	ADD S OR Se – IMPROVE MACHINABILITY
305	RAISE Ni – REDUCE WORK – HARDENING
304	REDUCE CARBON – DECREASE SENSITIZATION
304L	MORE SO – MORE SO – WEAKENED
304H	TIGHTEN LIMITS – MAINTAIN TEMPERATURE STRENGTH
321	ADD Ti – DECREASE SENSITIZATION
347	ADD Nb AND Ta – DECREASE SENSITIZATION
316	ADD Mo – STRENGTHEN AND PITTING RESISTANCE
316L	THEN REDUCE C – DECREASE SENSITIZATION
308	HIGH Ni AND Cr – IMPROVE OXIDATION
309	
310	

70-MA1-48-350

MECHANICAL PROPERTIES

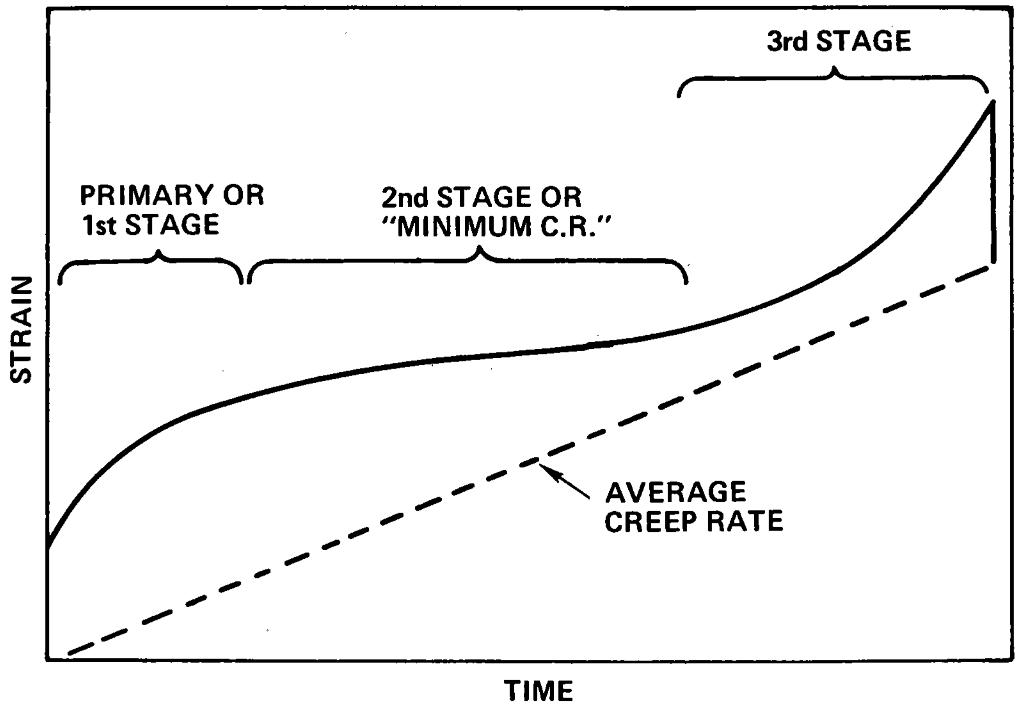
MOST METALS CHANGE
"CHARACTER"
AT ABOUT HALF OF THEIR
MELTING POINTS, ON AN ABSOLUTE
TEMPERATURE SCALE

$$\left[\frac{T_m}{2}\right]_{\substack{\text{3xx}\\ \text{STEEL}}} = \frac{2600 + 460}{2} - 460 \cong \underline{\underline{1000^{\circ}F}}$$

- DIFFUSION-CONTROLLED REACTIONS BECOME SIGNIFICANT
- GRAIN BOUNDARY SLIDING (CREEP) BECOMES SIGNIFICANT

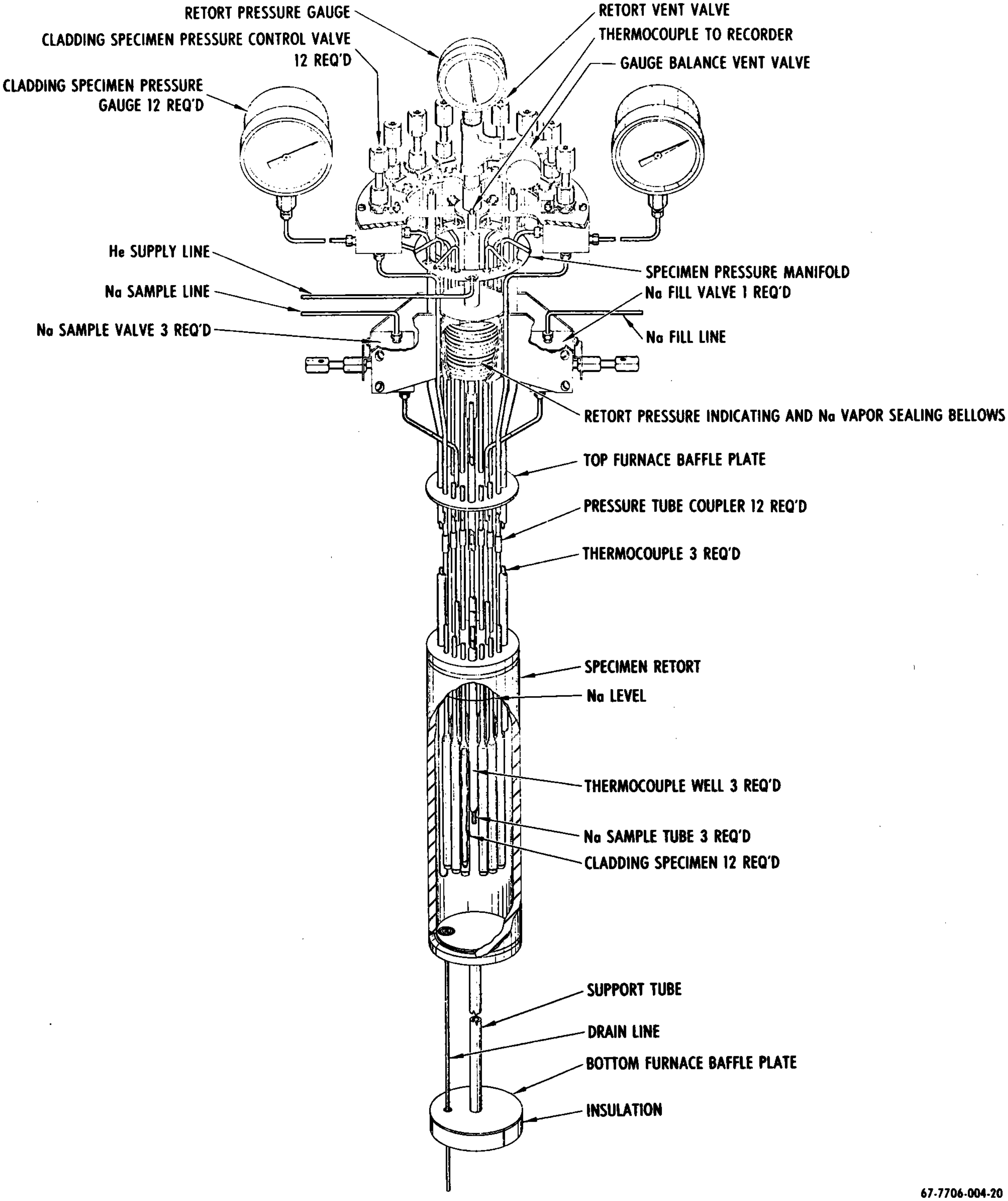
9-N7-129-12

TYPICAL CREEP CURVE



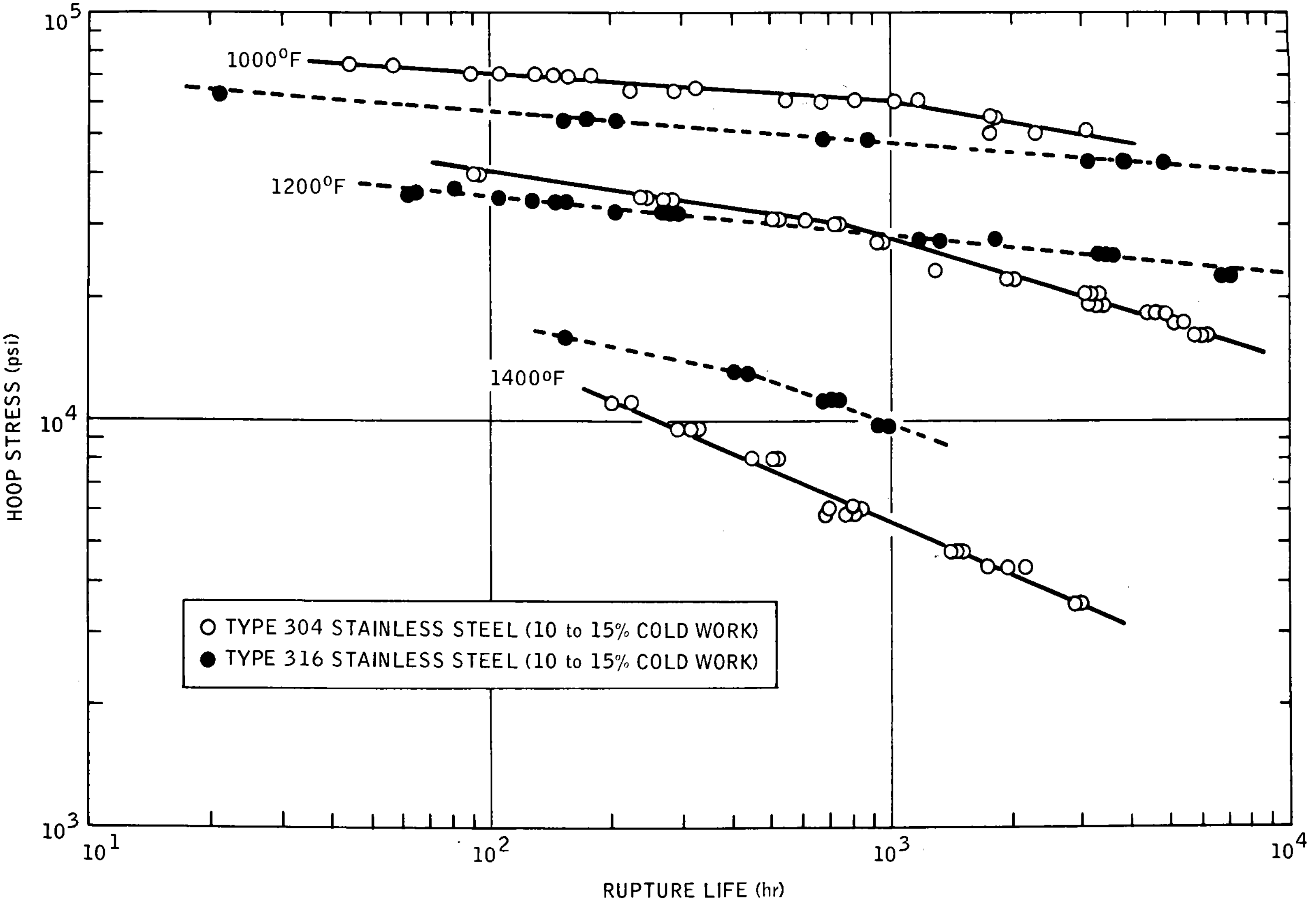
9-N7-129-13

12 PIN BIAXIAL CLADDING TEST RETORT FOR LMFBR



67-7706-004-20

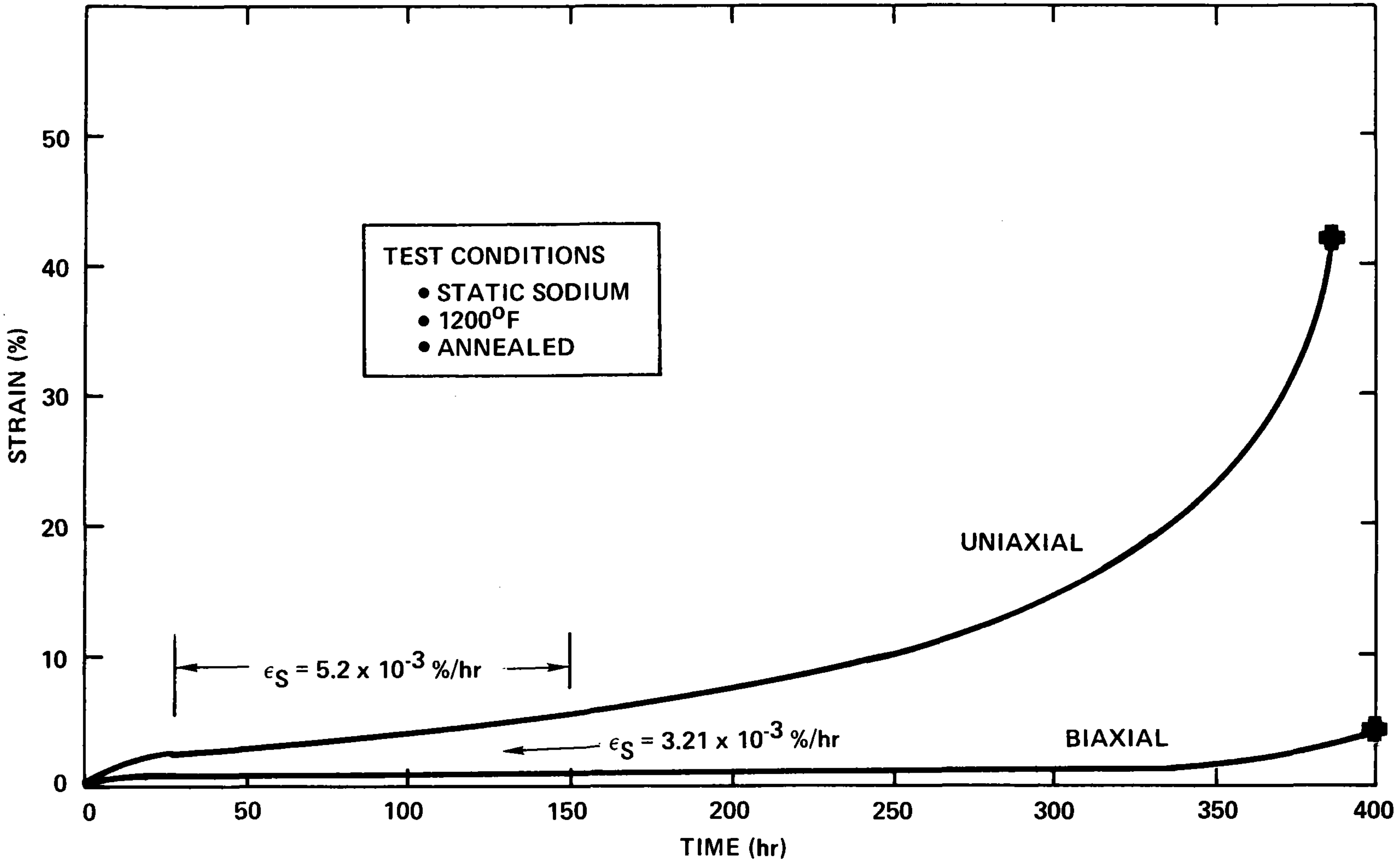
BIAXIAL STRESS-RUPTURE BEHAVIOR OF COLD WORKED TUBES OF 304 AND 316 SS IN STATIC SODIUM



8-025-157-2A

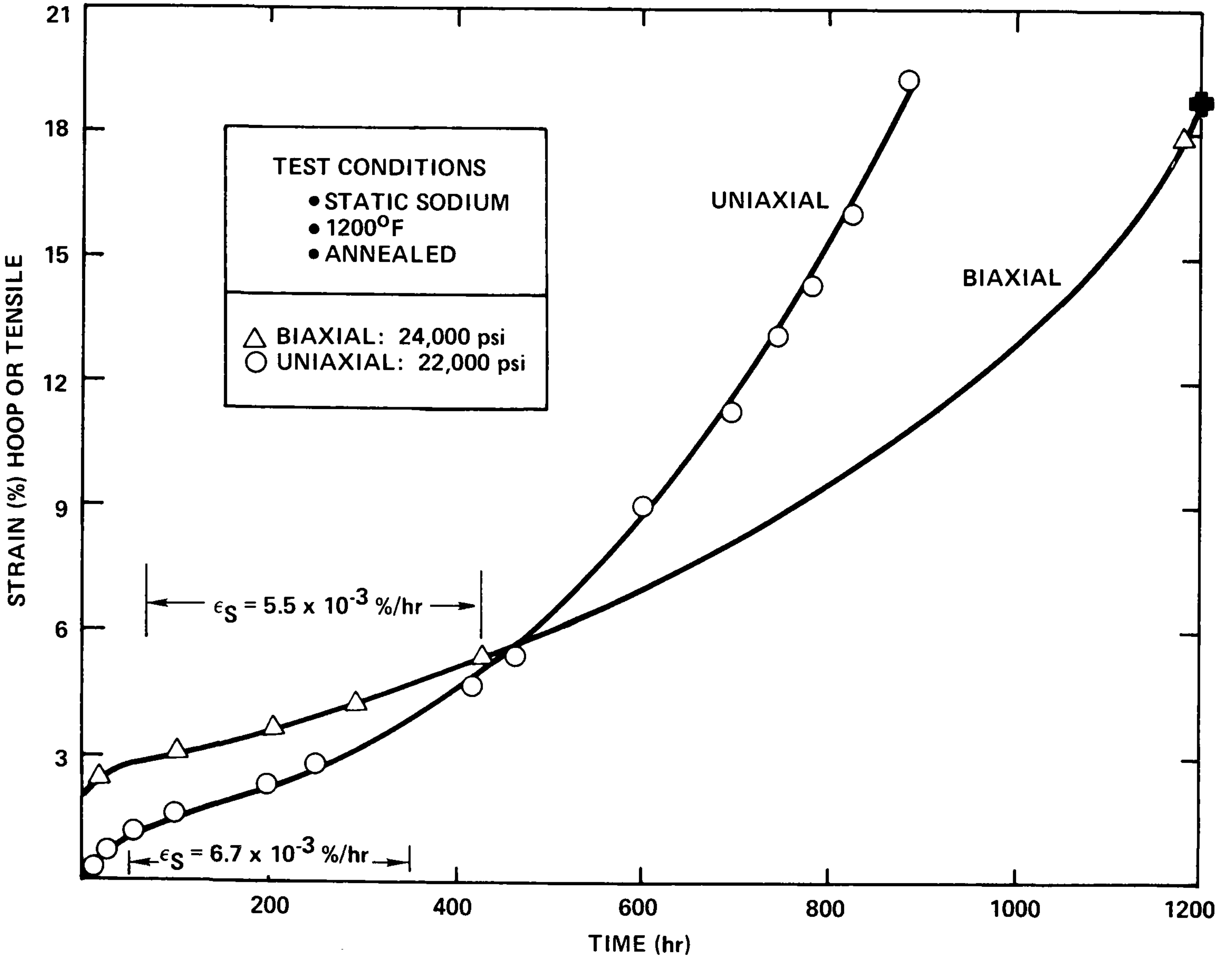
COMPARISON OF BIAXIAL AND UNIAXIAL CREEP OF ANNEALED TYPE 304 STAINLESS STEEL SHEET IN 1200°F SODIUM

(STRESS=25,000 psi)



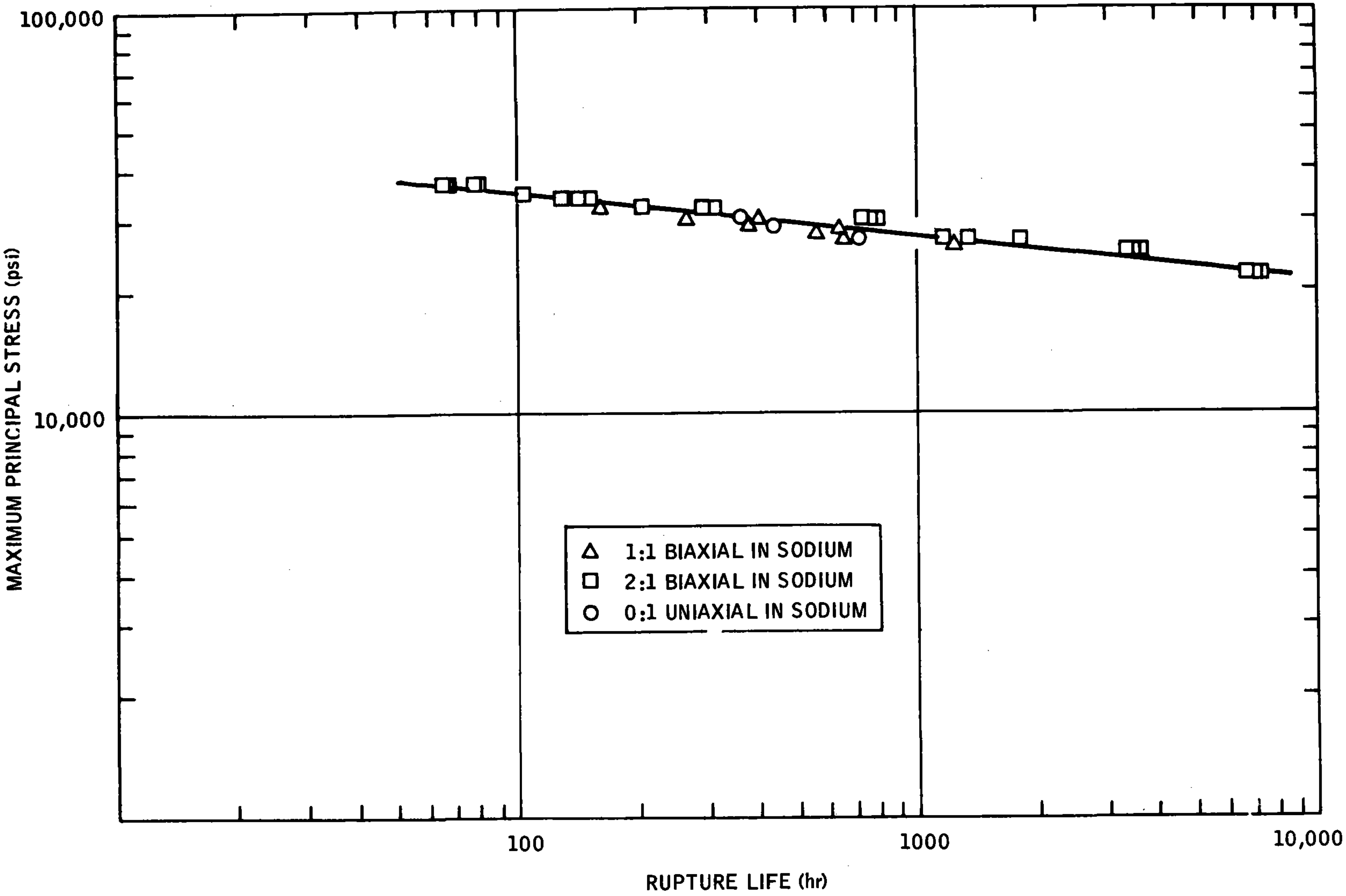
9-N7-091-7A

COMPARISON OF BIAXIAL AND UNIAXIAL CREEP OF TYPE 316 STAINLESS STEEL



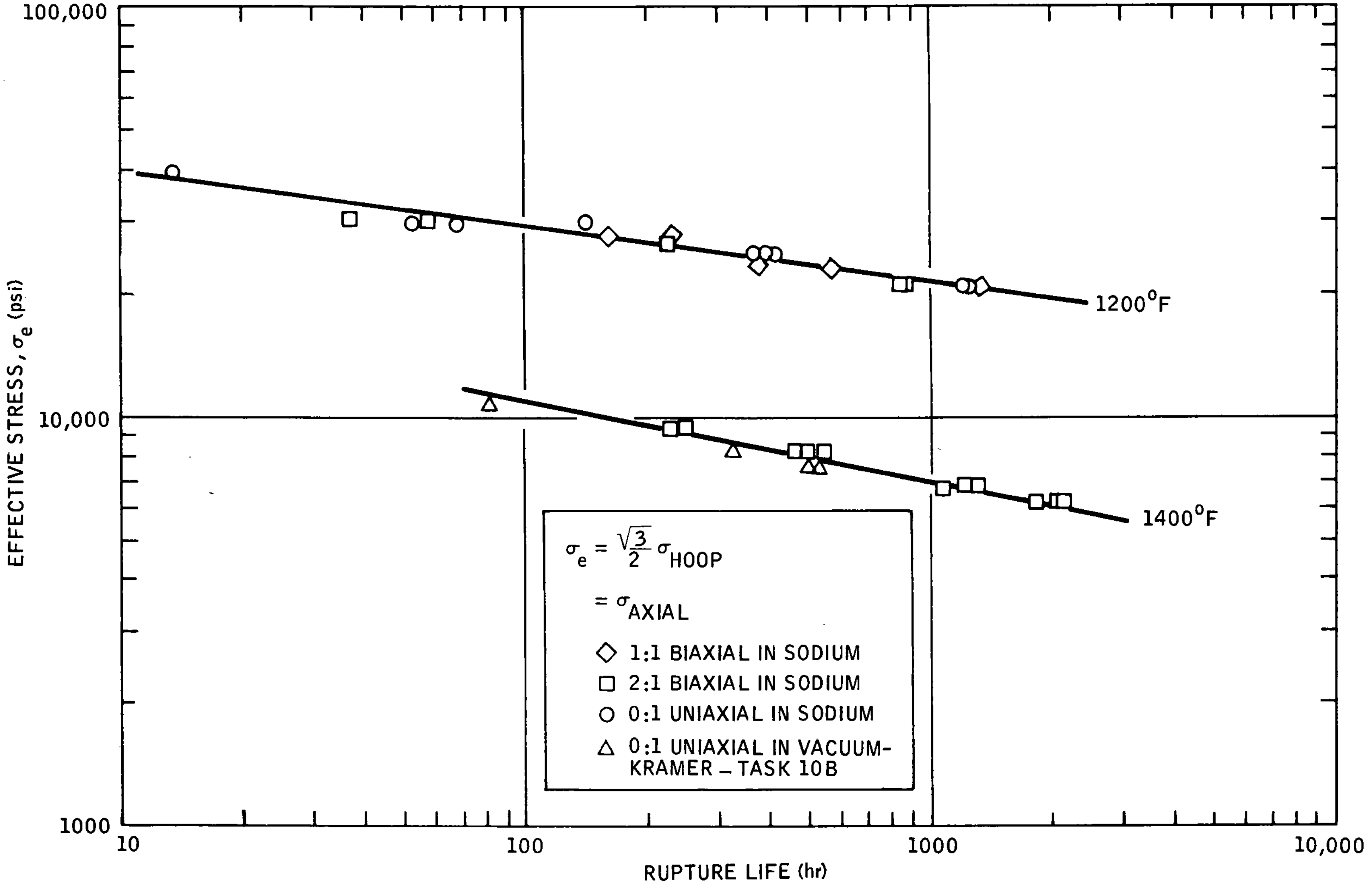
9-N7-091-9A

EFFECT OF STRESS MODE ON COLD WORKED (10-15%) TYPE 316 SS TUBING IN 1200°F SODIUM



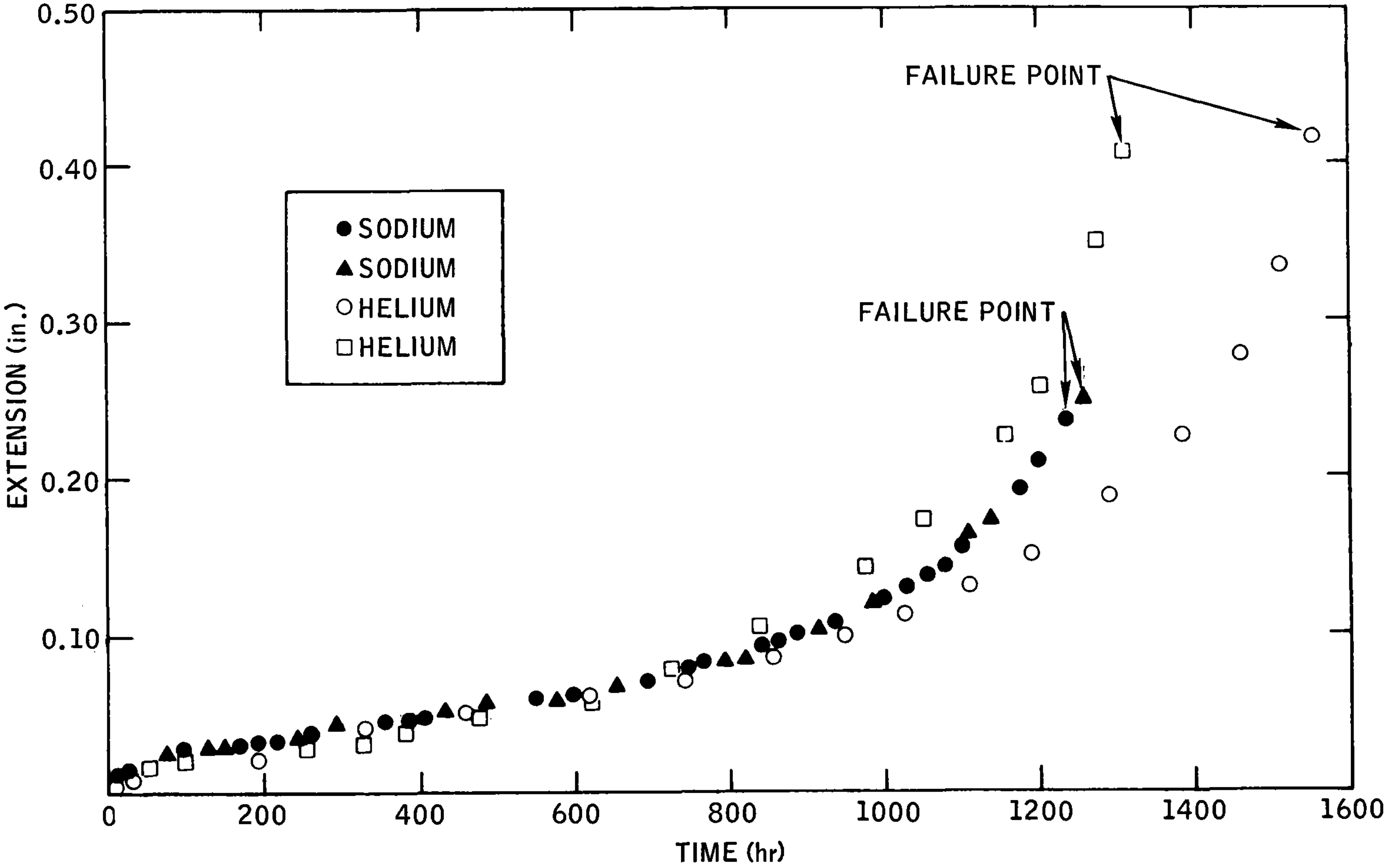
9-JY24-085-21

CORRELATION OF STRESS STATE WITH RUPTURE LIFE USING VON MISES' YIELD THEORY-ANNEALED 304 STAINLESS STEEL



9-JY24-085-23

UNIAXIAL CREEP OF ANNEALED TYPE 304 STAINLESS STEEL IN 1200°F SODIUM AND HELIUM ENVIRONMENTS–21,000 psi STRESS



9-AU12-091-15

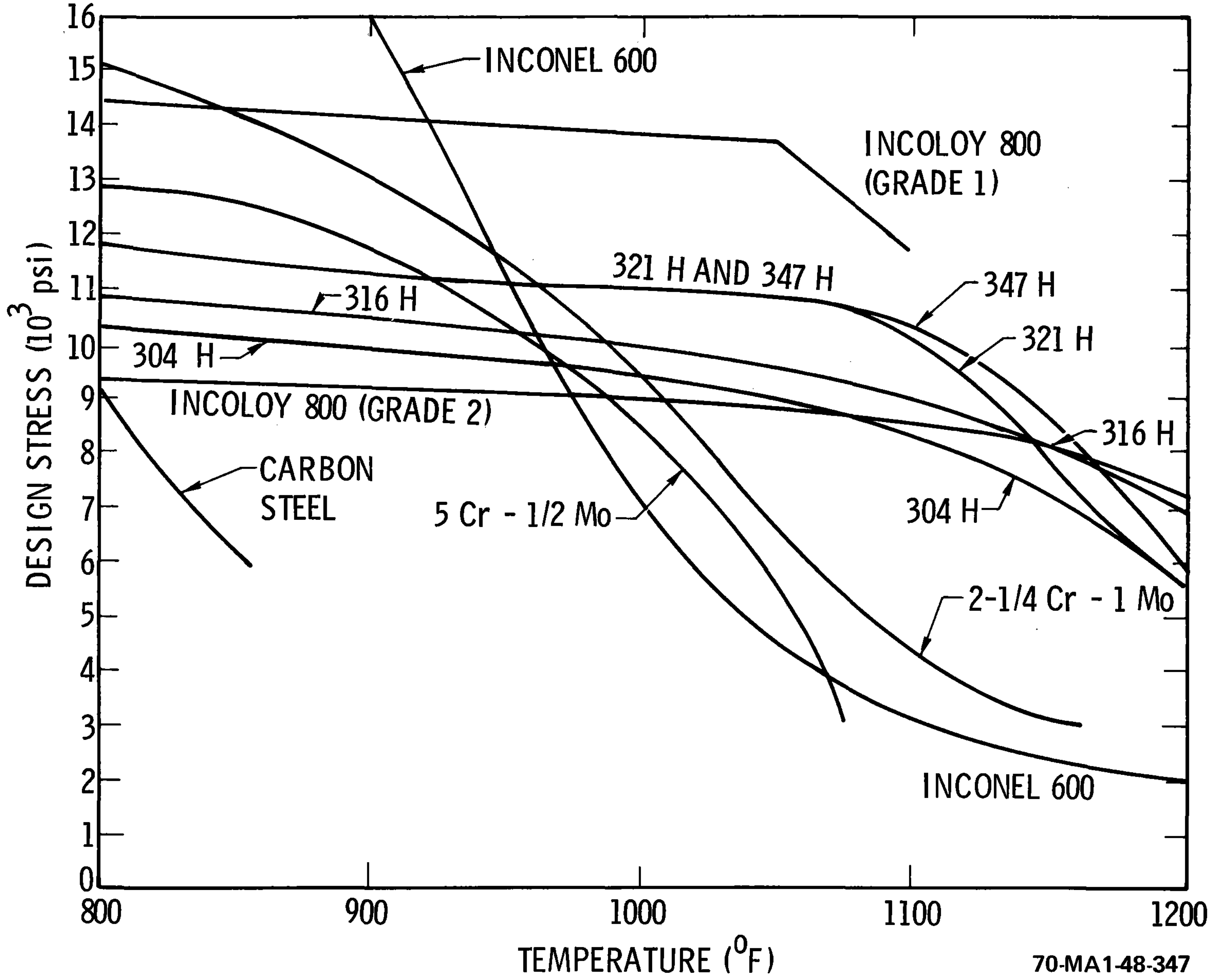
STRUCTURAL DESIGN CRITERIA

(ASME)

- LOWEST VALUE OF
    - 25% OF MINIMUM TENSILE STRENGTH AT ROOM TEMPERATURE
    - 25% OF MINIMUM TENSILE STRENGTH AT SERVICE TEMPERATURE
    - 62-1/2% OF MINIMUM 0.2% OFFSET YIELD STRENGTH AT SERVICE TEMPERATURE
    - 60% OF AVERAGE STRESS TO CAUSE RUPTURE IN 100,000 hr
    - 80% OF MINIMUM STRESS TO CAUSE RUPTURE IN 100,000 hr
    - STRESS TO CAUSE 1% CREEP IN 100,000 hr

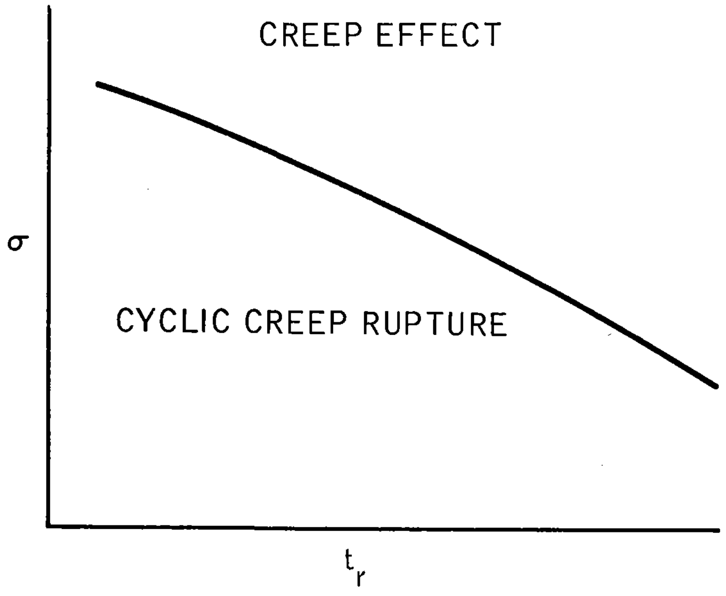
70-MA1-48-353

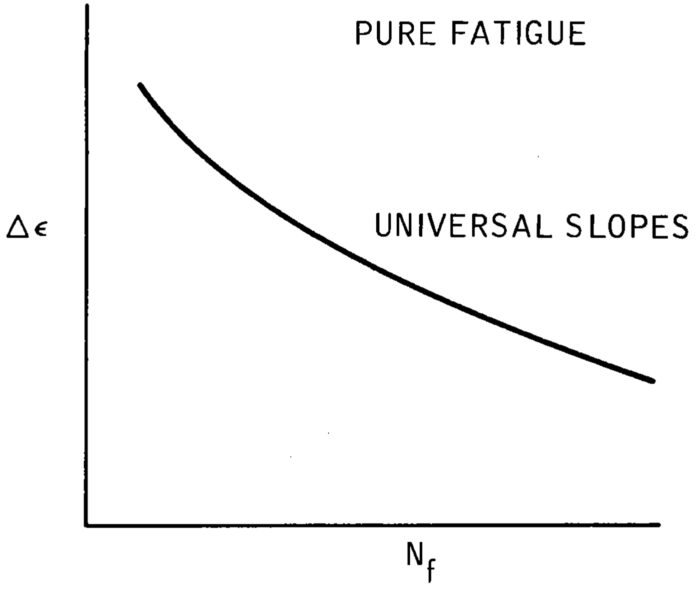
ASME BOILER CODE ALLOWABLES FOR CANDIDATE FBR MATERIALS



70-MA1-48-347

DAMAGE ANALYSIS BY COMBINED EFFECTS OF CREEP AND FATIGUE



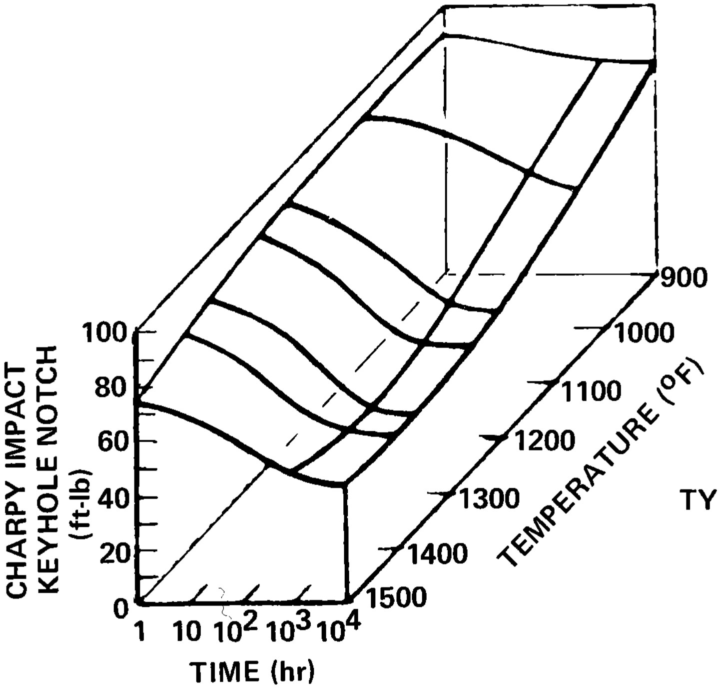


$$\sum(\text{CREEP DAMAGE}) + \sum(\text{FATIGUE DAMAGE}) = 1$$

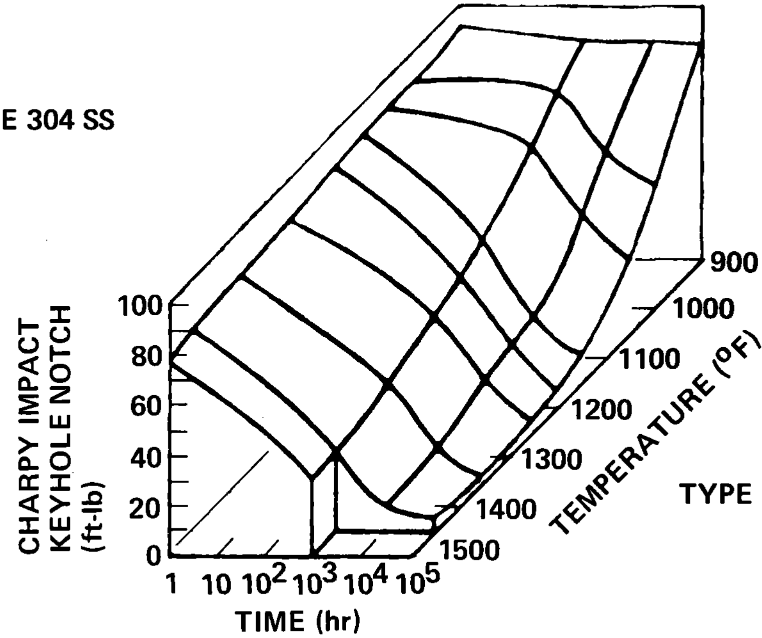
$$\sum \frac{t}{t_r} + \sum \frac{n}{N_f} = 1$$

70-MA1-48-368

EFFECT OF TEMPERATURE AND TIME OF EXPOSURE ON ROOM TEMPERATURE IMPACT PROPERTIES



TYPE 304 SS



TYPE 316 SS

70-MA1-48-367

RADIATION EFFECTS

9-N7-129-14

RADIATION EFFECTS VARIABLES

- RADIATION CONDITIONS
    - FLUENCE
    - FLUX
    - TEMPERATURE
    - NEUTRON ENERGY SPECTRUM
    - CHEMICAL ENVIRONMENT
- TEST CONDITIONS
    - TEMPERATURE
    - STRAIN RATE
    - CHEMICAL ENVIRONMENT

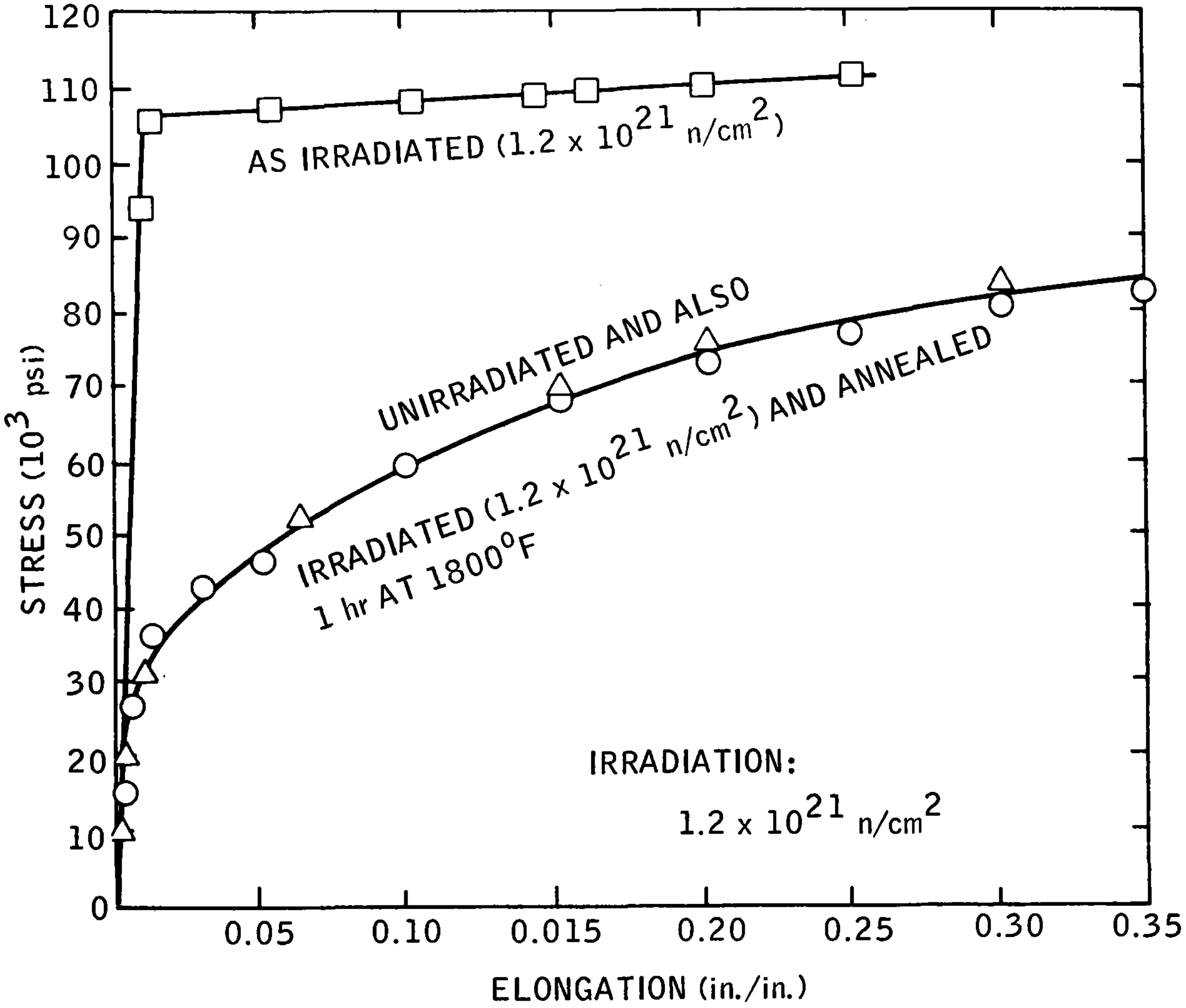
9-N7-129-15

RADIATION EFFECTS ON STRUCTURAL MATERIALS

- AT LOW TEMPERATURE (<1/2 T_m)
  - MINOR INCREASE IN ULTIMATE
  - MAJOR INCREASE IN YIELD
  - MAJOR DECREASE IN DUCTILITY
  - INCREASE OF DUCTILE-TO-BRITTLE TRANSITION TEMPERATURE OF BODY-CENTERED CUBIC METALS
  - POSSIBLE CREEP ENHANCEMENT
- AT HIGH TEMPERATURE (>1/2 T_m)
  - MAJOR DECREASE IN DUCTILITY
  - DECREASE IN STRESS RUPTURE LIFE
  - MINOR (?) EFFECT ON CREEP RATE
  - VOID FORMATION AND SWELLING DURING EXTENDED EXPOSURE TO FAST NEUTRONS

9-N7-129-16

ROOM TEMPERATURE STRESS-STRAIN CURVES FOR TYPE 347 S.S.



7-A15-184-13

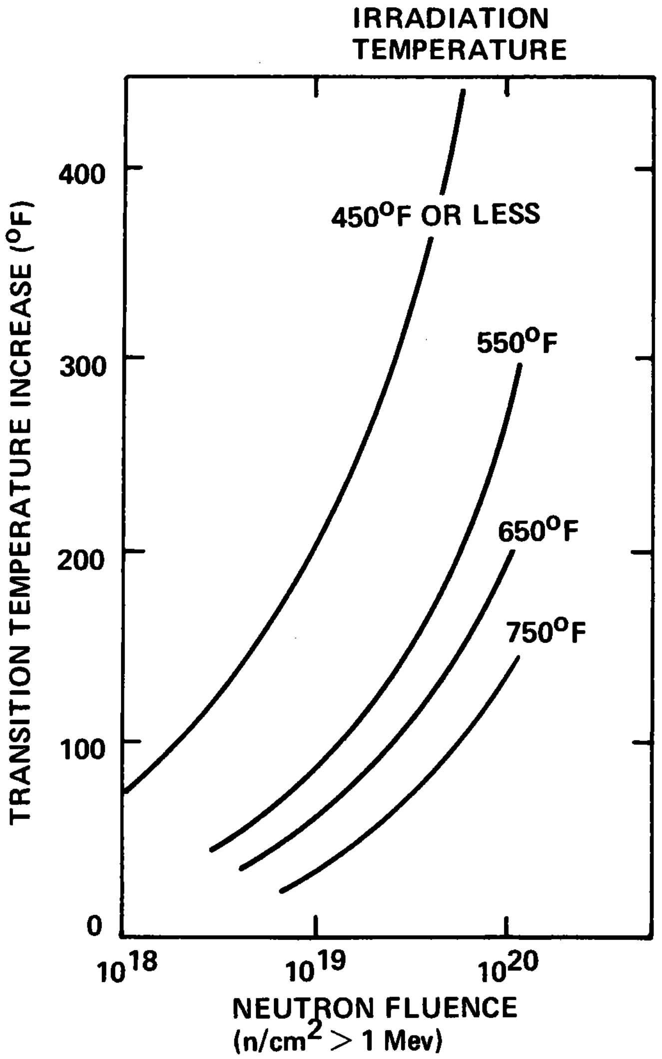
SUMMARY OF BMI 347 SS TENSILE TEST EXPERIMENTS

Ref: BMI 1767

TEST TEMPERATURE	PROPERTY	CONTROL (UNIRRADIATED)	AS-IRRADIATED (~10^{22} nvt, FAST, AT 140°F)	IRRADIATED AND ANNEALED (1 hr, VACUUM)
ROOM	F_{TY}	35 ksi	110 ksi	(1800°F) 33 ksi
	F_{TU}	90 ksi	112 ksi	87 ksi
	e	63%	33%	57%
600°F	F_{TY}	29 ksi	87 ksi	(1800°F) 26 ksi
	F_{TU}	65 ksi	88 ksi	62 ksi
	e	35%	14%	32%
1380°F	F_{TY}	22 ksi	35 ksi	(2400°F) 19 ksi
	F_{TU}	35 ksi	35 ksi	20 ksi
	e	26%	0.5%	0.5%

7-A15-184-25

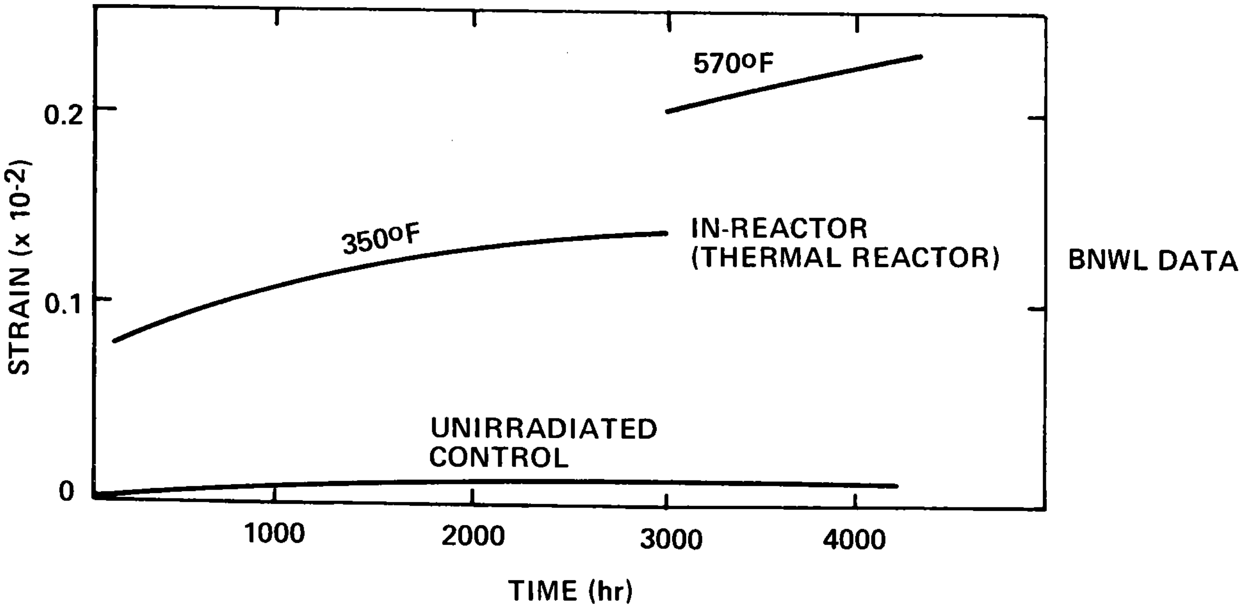
TRANSITION TEMPERATURE INCREASE FOR A302-B 6 in. PLATE STEEL



REF:
L.E. STEELE
ATOMIC ENERGY
REVIEW VII, 2

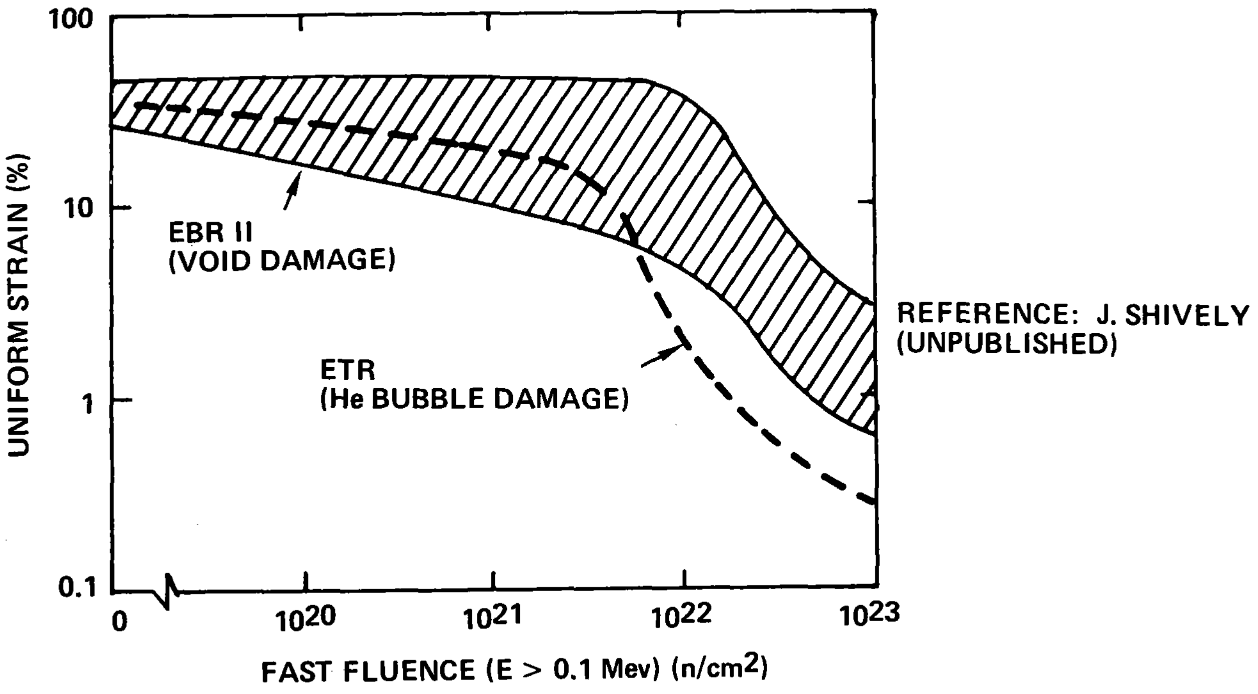
9-N7-129-17

IRRADIATION CREEP IN ANNEALED 304 SS AT TEMPERATURE AND 35,000 psi STRESS



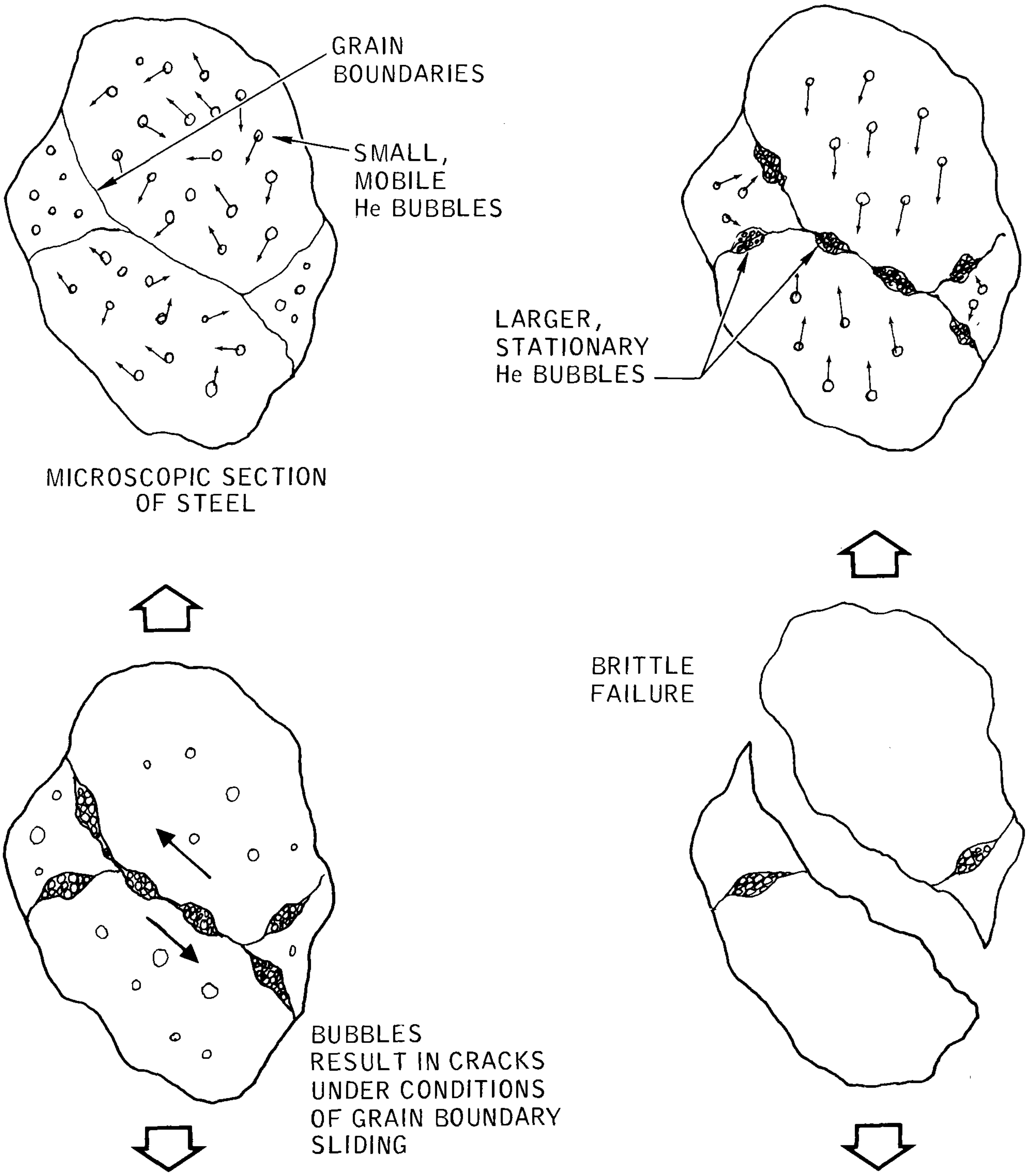
9-N7-129-18

EFFECT OF IRRADIATION ON SHORT-TERM DUCTILITY OF AUSTENTIC STEEL

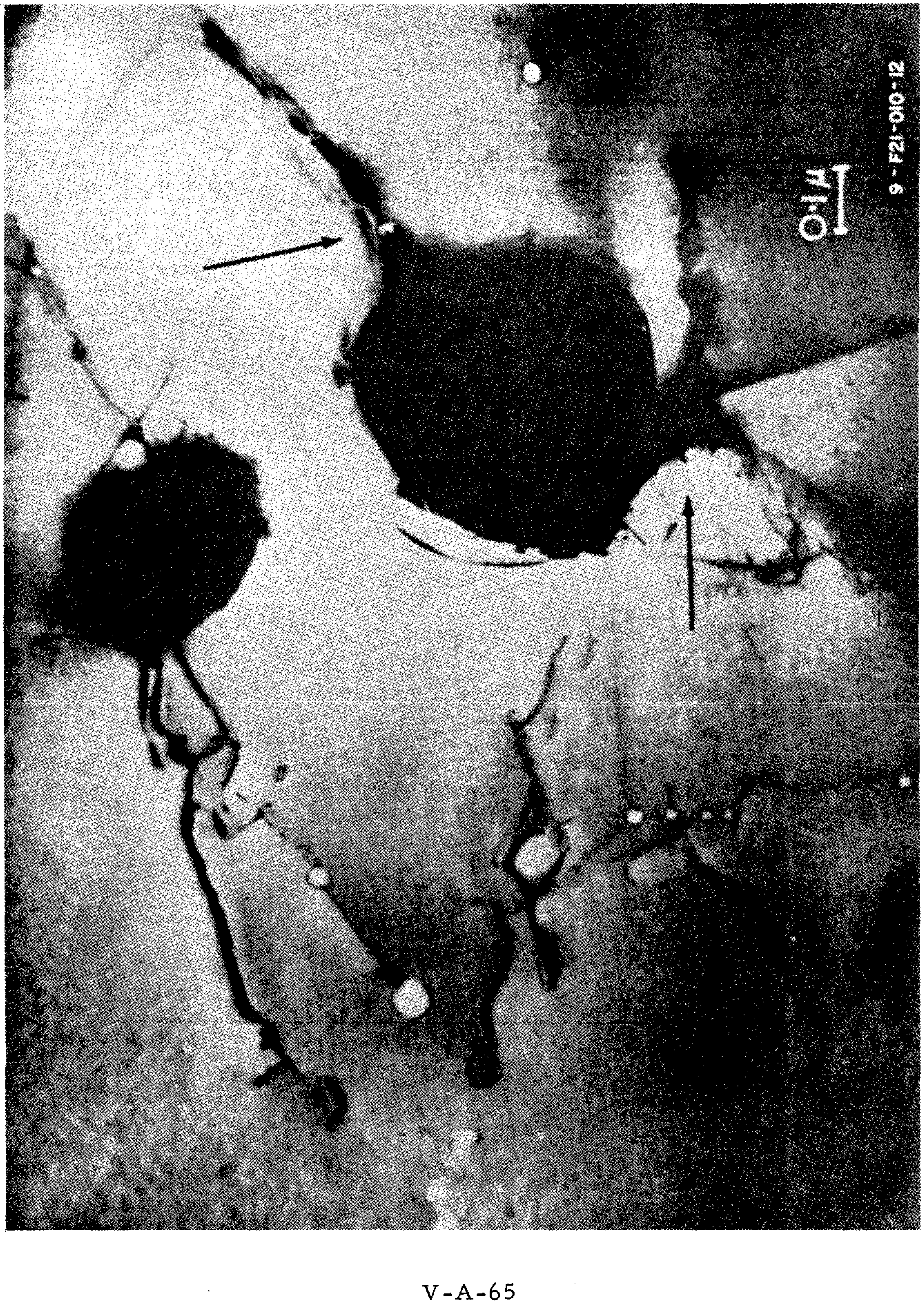


9-N7-129-20

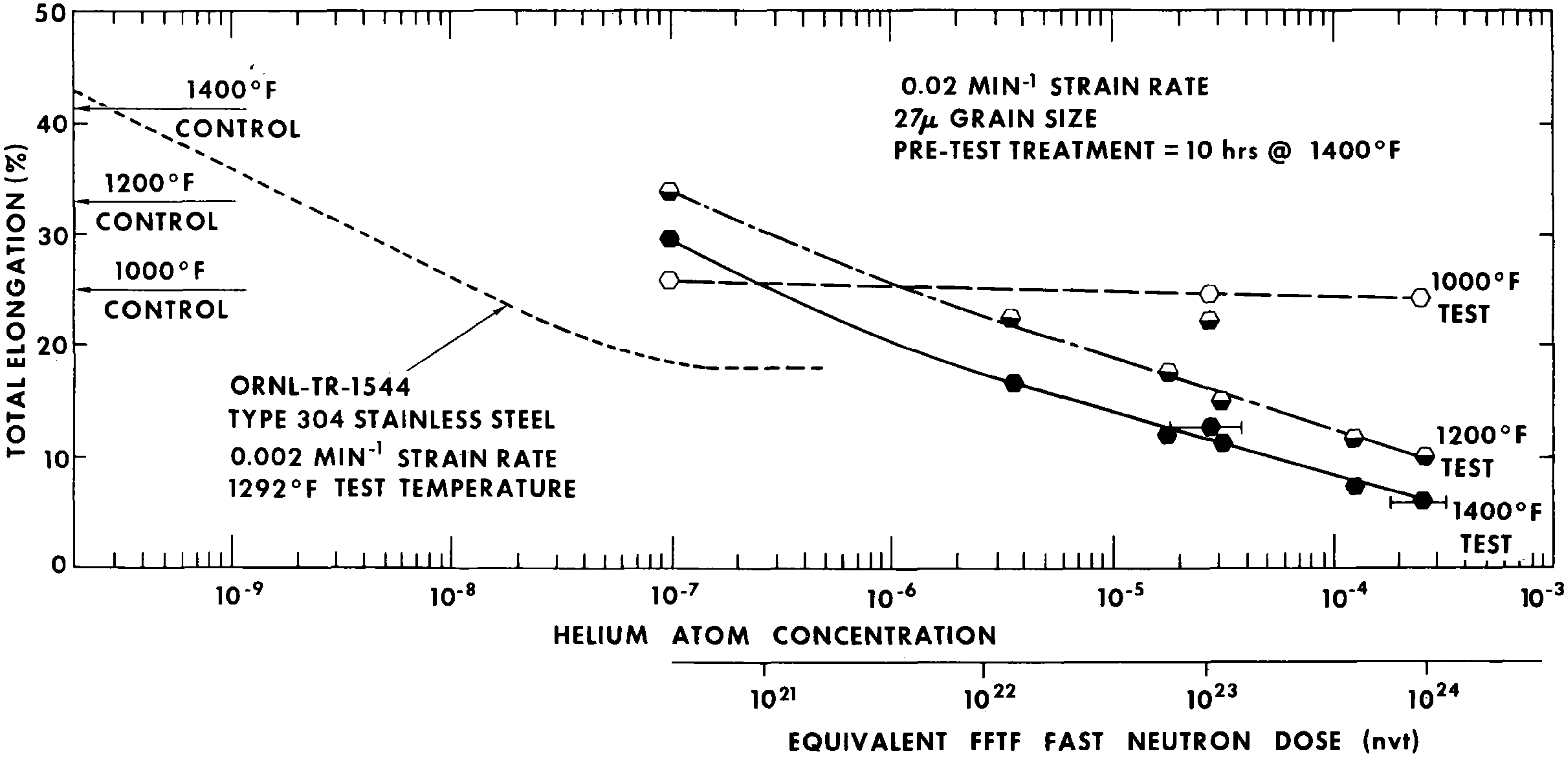
BRITTLE FAILURE DUE TO HELIUM BUBBLES



7-A15-184-26

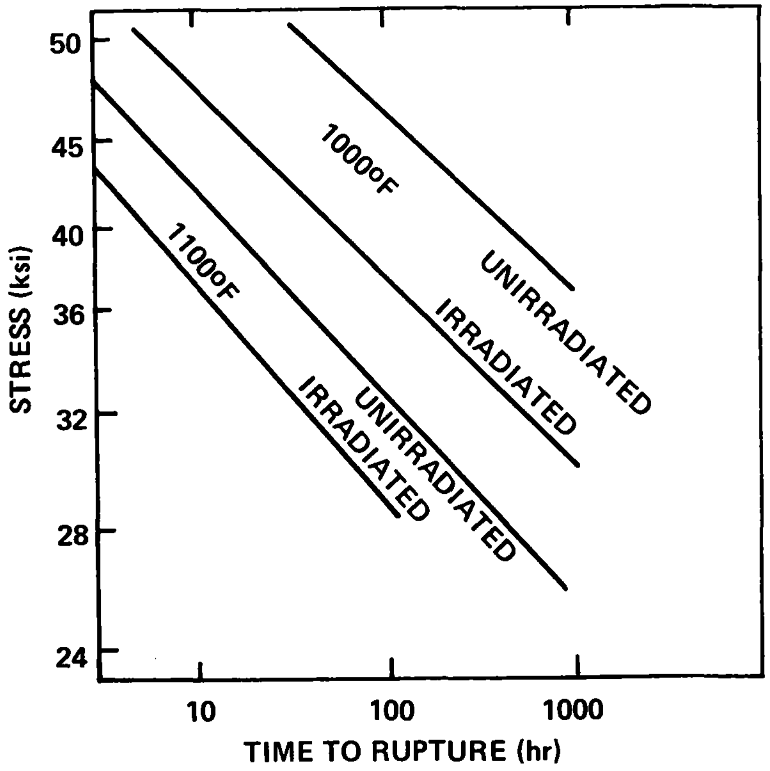

0.1μ
9 - F21-010-12

HELIUM EMBRITTLEMENT IN TYPE 304 STAINLESS STEEL



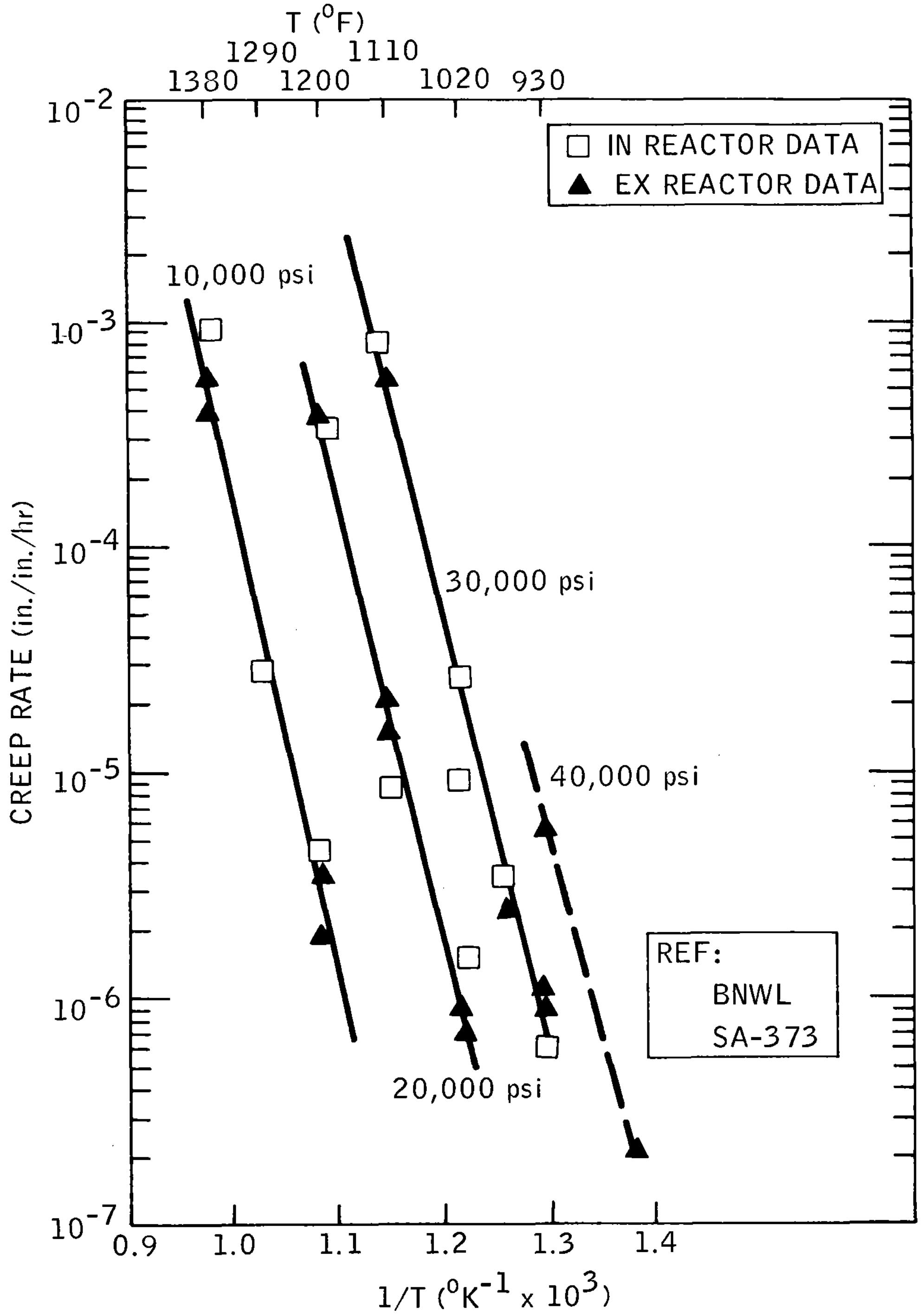
7-7706-147-1

POST IRRADIATION CREEP RUPTURE OF SOLUTION-TREATED 304

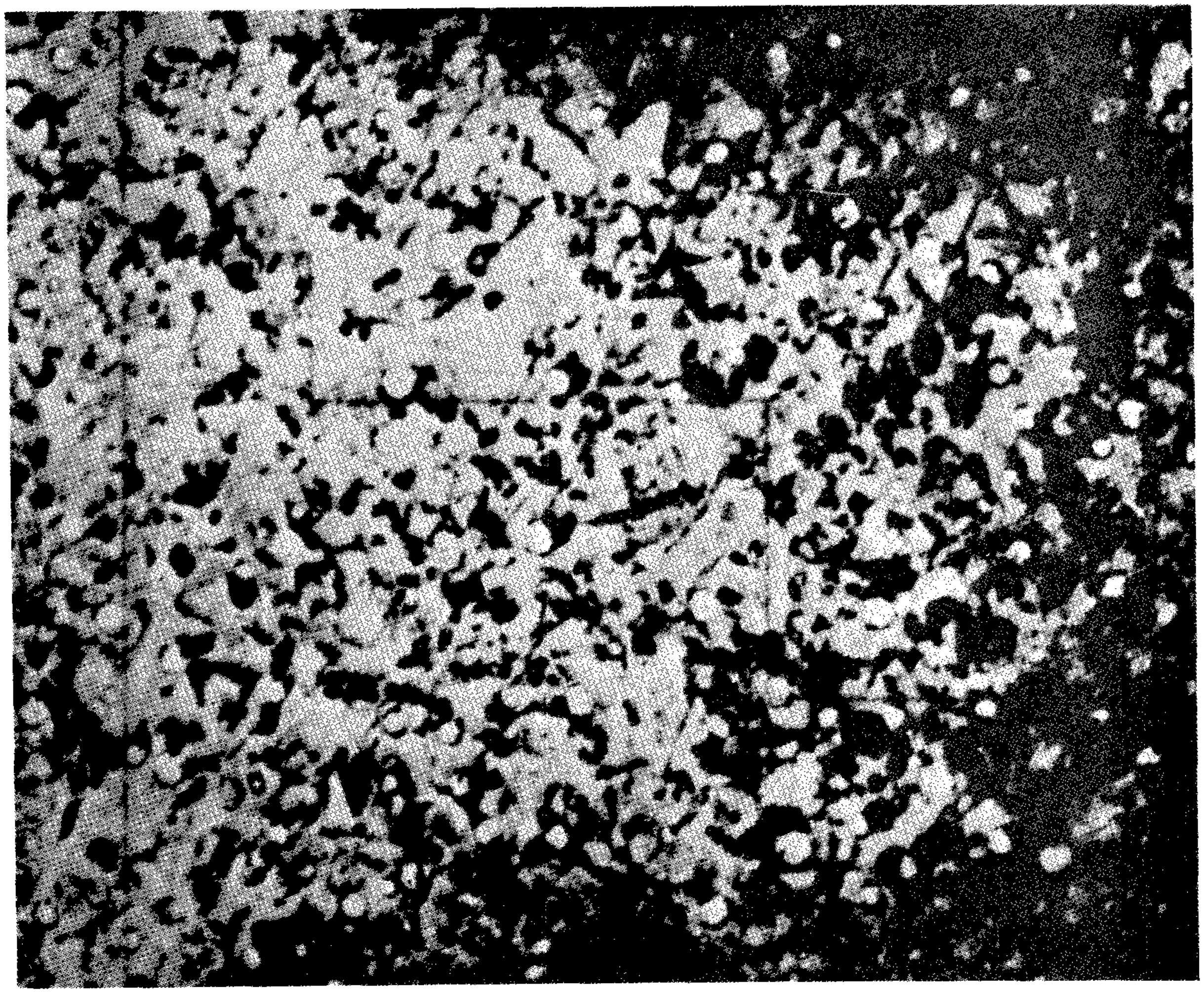


9-N7-129-19

ARRHENIUS PLOT OF IN-REACTOR AND EX-REACTOR CREEP RATES FOR ANNEALED 304 STAINLESS STEEL



7-A15-184-16



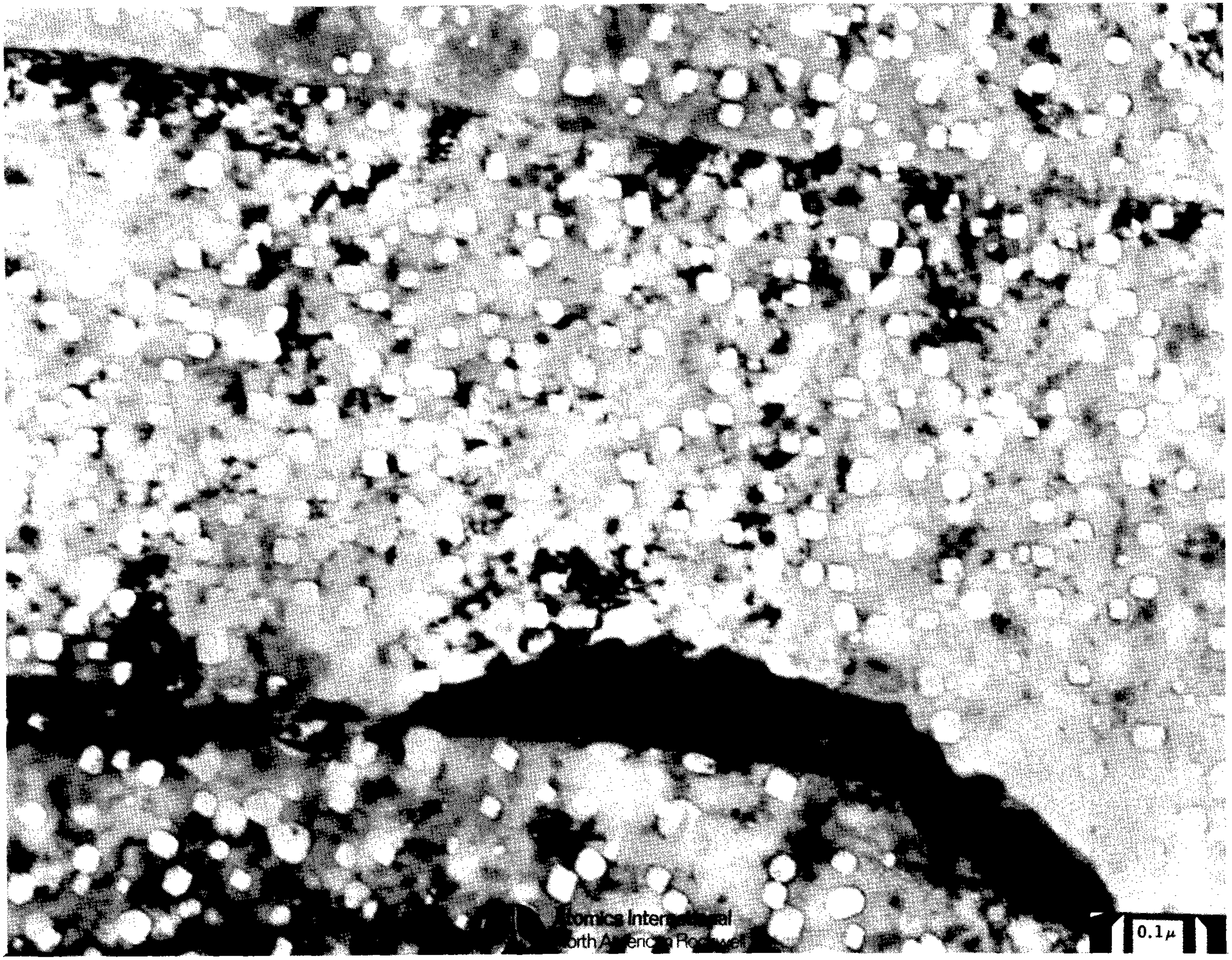
AERE - R 5269 Fig. 11 x160,000

Stainless steel fuel pin cladding irradiated at 450°C to 5.2×10^{22} n.cm^{-2}

70-MA1-48-264

VOID FORMATION IN STEELS

- OBSERVATIONS
  - NOT GAS FILLED
  - STRESS NOT REQUIRED
  - SIZE AND DISTRIBUTION DIMINISHES NEAR GRAIN
  - BOUNDARIES
  - DISAPPEAR UPON ANNEALING
  - NORMAL SIZE DISTRIBUTION
  - HELIUM REQUIRED FOR NUCLEATION
  - FAST NEUTRONS REQUIRED
  - CAUSES ISOTROPIC SWELLING
  - CAUSES BOWING (DIFFERENTIAL SWELLING)

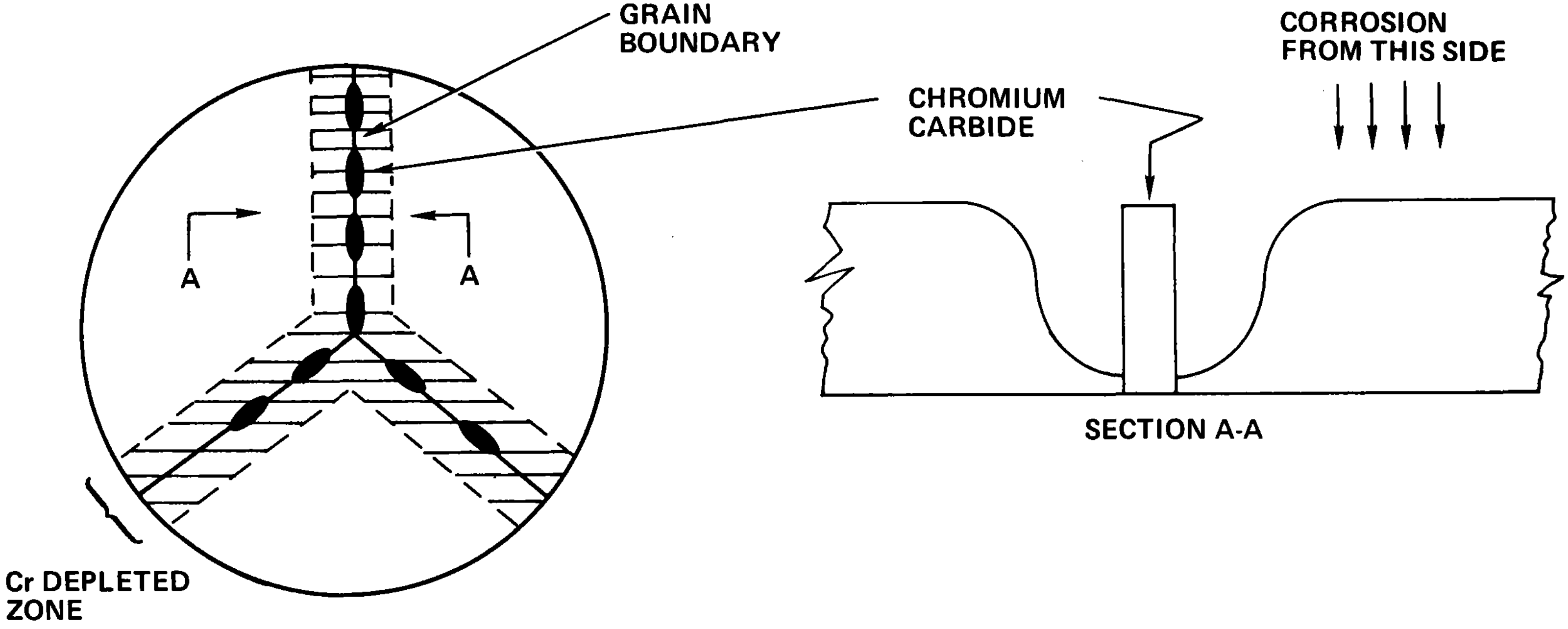


9-N3-116-173

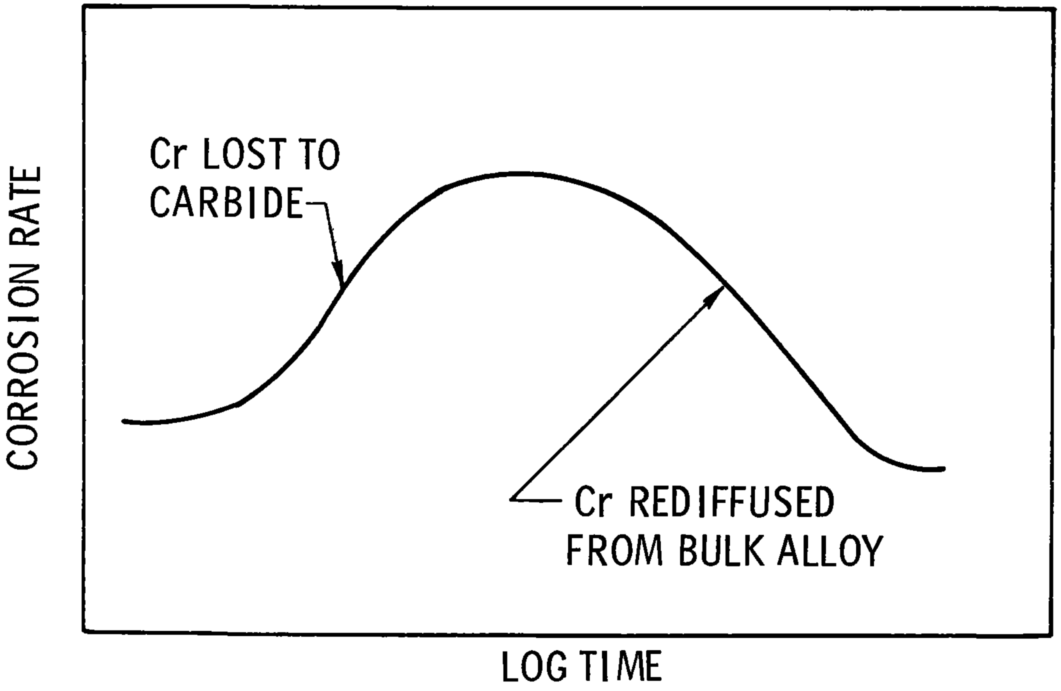
SENSITIZATION

9-N7-129-21

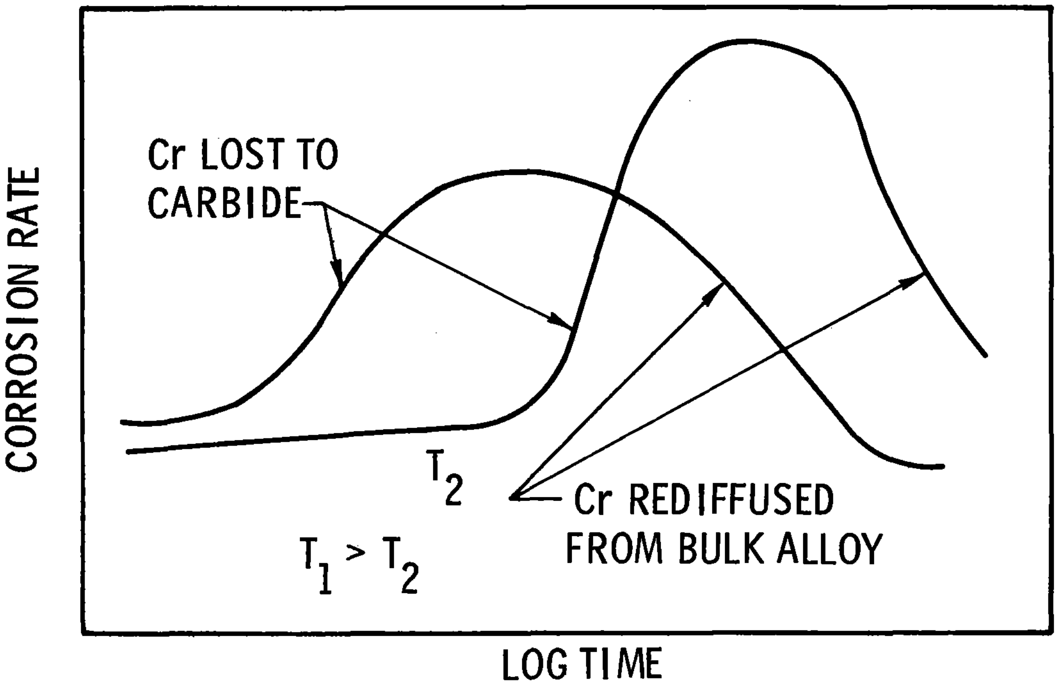
SENSITIZATION



9-N7-129-22


CORROSION RATE
Cr LOST TO CARBIDE
Cr REDIFFUSED FROM BULK ALLOY
LOG TIME

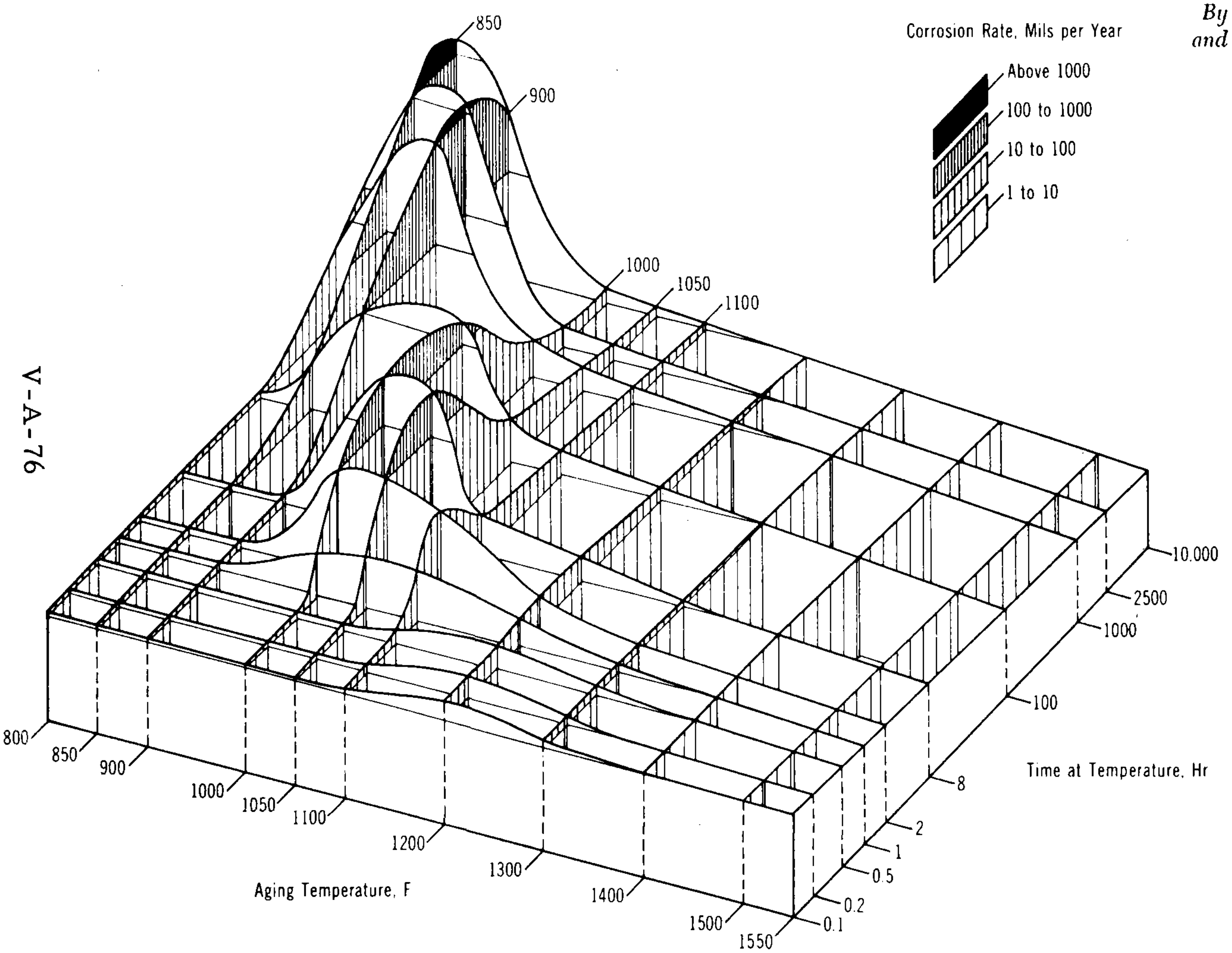
70-MA1-48-361



70-MA1-48-361A

How Sensitization Affects the Corrosion of Stainless Weld Metal

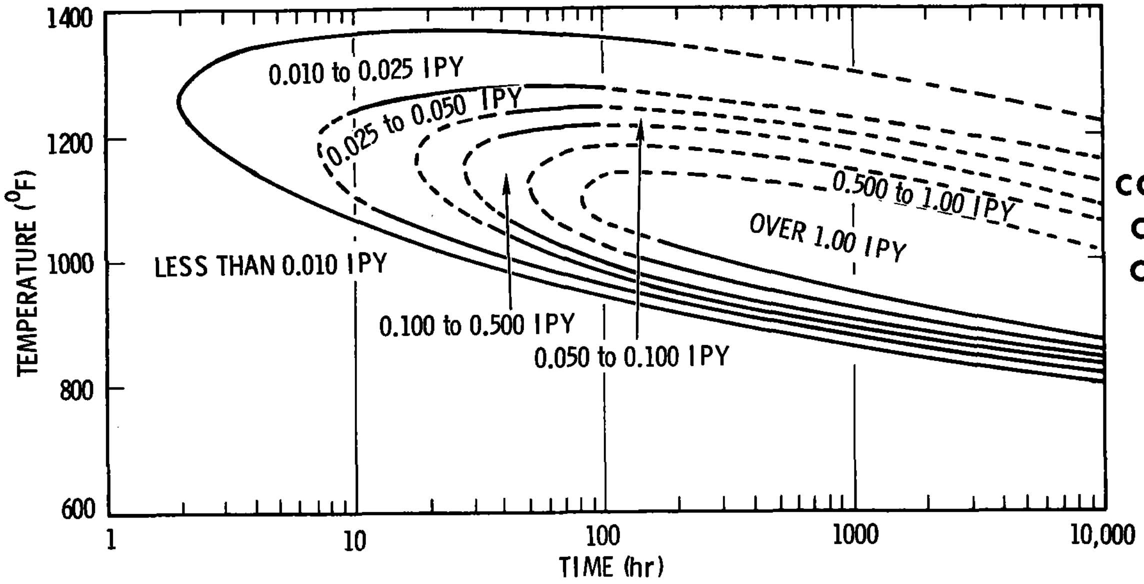
By RUSSELL B. GUNIA
*and THOMAS J. MOORE**



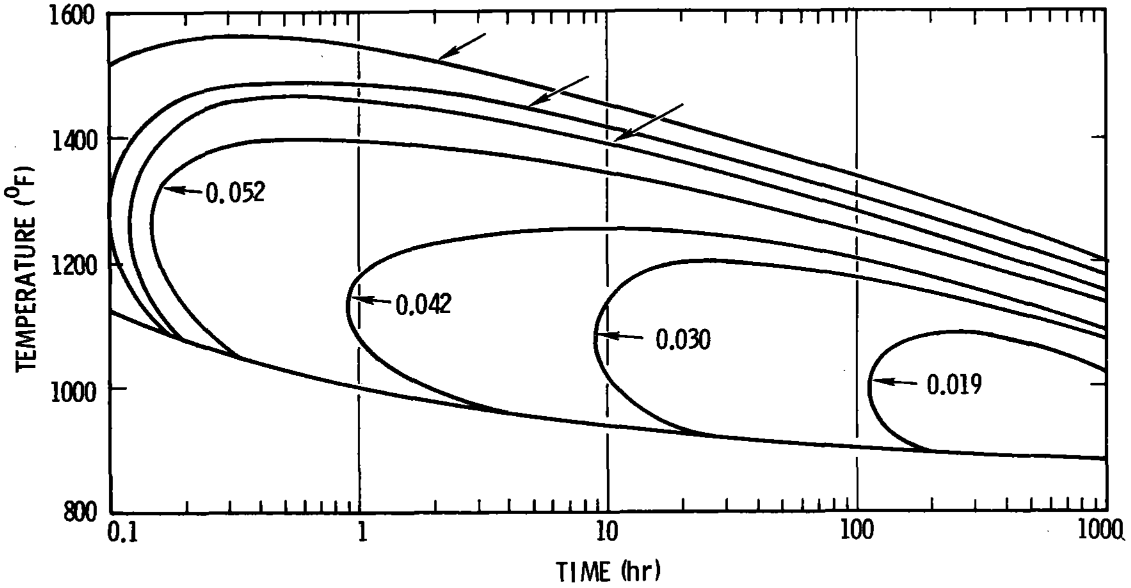
This three-dimensional drawing illustrates the time-temperature-sensitization relationship for 18-8 weld metal (0.036% C) which was aged in the as-welded condition before being corrosion tested in boiling nitric acid. (The vertical scale is logarithmic with the same base as the time scale.)

*Mr. Gunia is manager, stainless steel metallurgy, United States Steel Corp., Pittsburgh, and Mr. Moore is assistant director of research, Arcos Corp., Philadelphia.

TIME-TEMPERATURE-SENSITIZATION DIAGRAMS FOR AUSTENITIC STAINLESS STEEL



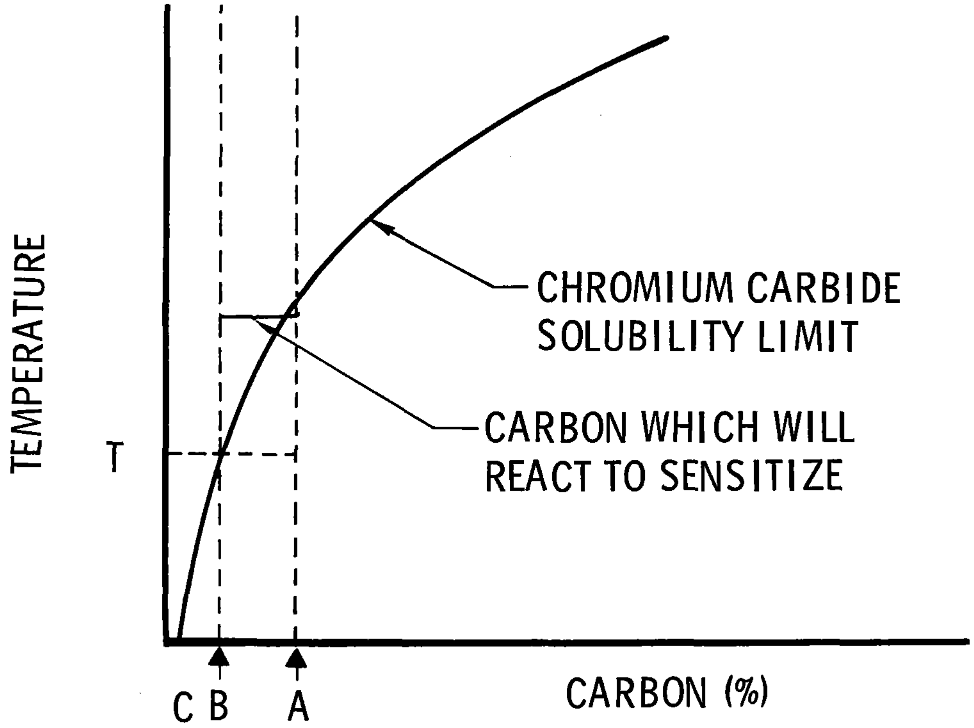
CONSTANT CARBON CONTENT



CONSTANT CORROSION RATE

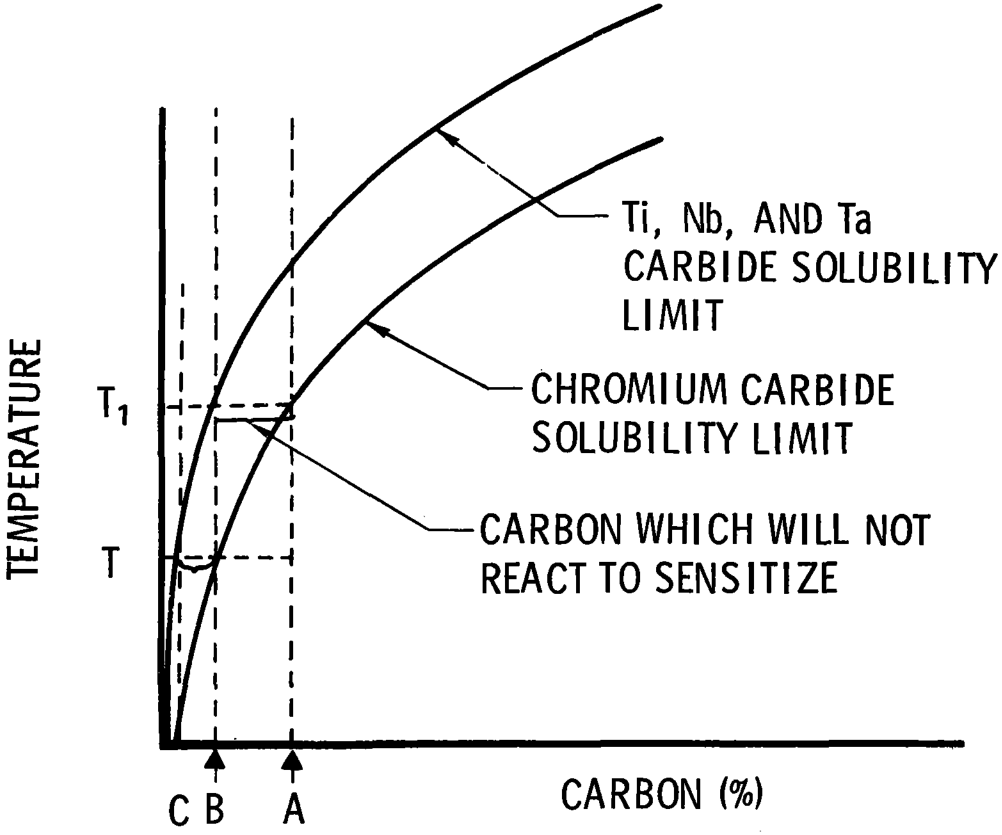
70-MA1-48-374

PSUEDO PHASE DIAGRAM: STAINLESS STEEL CARBON

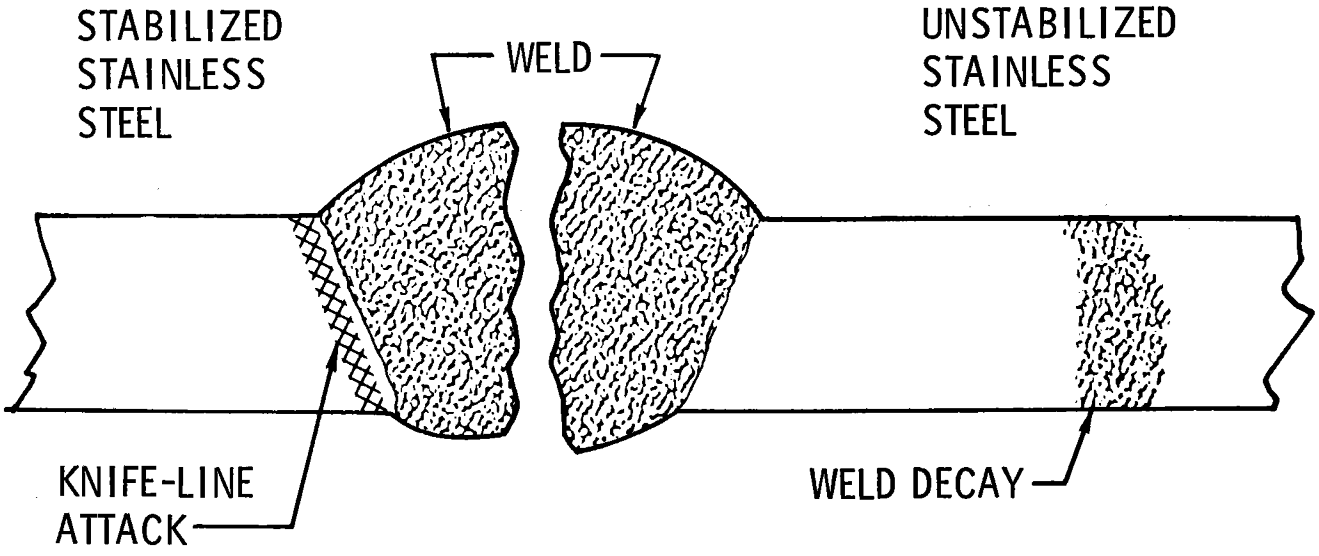


70-MA1-48-348

PSUEDO PHASE DIAGRAM: STAINLESS STEEL CARBON



70-MA1-48-348A



NARROW REGION
(2000 to 2600°F)

Nb, Ti CARBIDES
DISSOLVED; DID
NOT PRECIPITATE
ON REHEATING

WIDER REGION
(900 to 1400°F)

CHROMIUM CARBIDE
PRECIPITATES:

STEEL IS SENSITIZED

70-MA1-48-359

TO RESIST SENSITIZATION:

- OPERATE ABOVE 1200°F
- SOLUTION ANNEAL AND OPERATE BELOW 800°F
- REDUCE CARBON (e.g. 304L) — LOSE STRENGTH
- ADD STRONG CARBIDE-FORMERS SUCH AS Ti(321) OR Cb(347) –
  - LESS WELDABLE
  - SUBJECT TO KNIFE-LINE ATTACK
  - WILL SENSITIZE EVENTUALLY

9-N7-129-24

SENSITIZATION

SENSITIZATION

- HAS NO EFFECT ON STRENGTH
- HAS NEGLIGIBLE EFFECT ON DUCTILITY
- HAS MINOR EFFECT ON IMPACT STRENGTH AT LOW TEMPERATURES
- HAS NO EFFECT ON OXIDATION RESISTANCE
- HAS NO EFFECT ON SODIUM COMPATIBILITY

9-N7-129-26

STRESS CORROSION

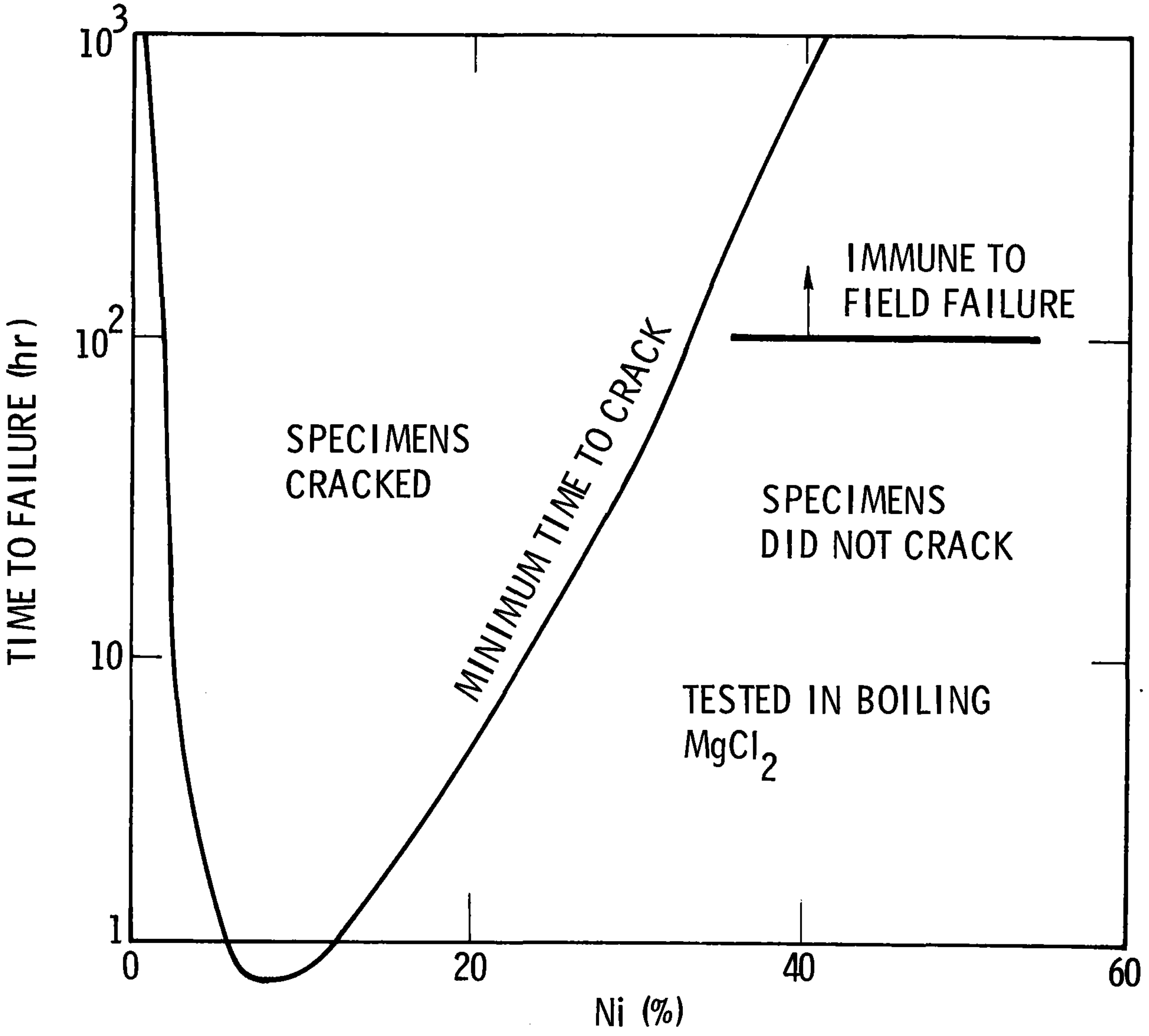
9-N7-129-27

STRESS CORROSION CRACKING

- VERY RAPID CRACK FORMATION AND PROPAGATION UNDER SPECIFIC CONDITIONS
  - FOR AUSTENITIC STAINLESSES USUALLY
    - TENSILE STRESS – TRANSGRANULAR CRACKS
    - HALIDE ION – USUALLY CHLORIDE-WATER
    - ABOVE AMBIENT TEMPERATURE

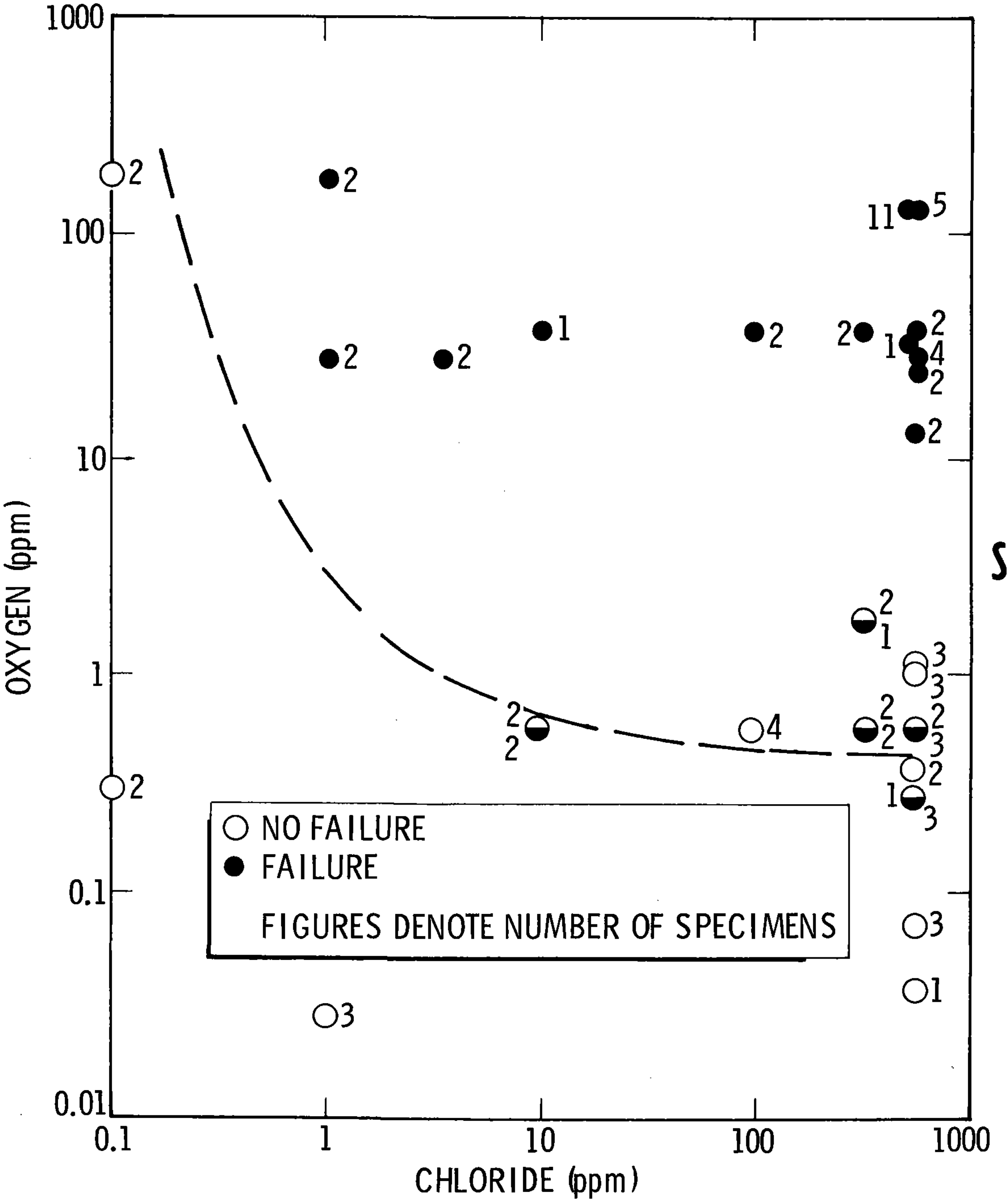
70-MA1-48-354

Ni ALLOY STRESS CORROSION



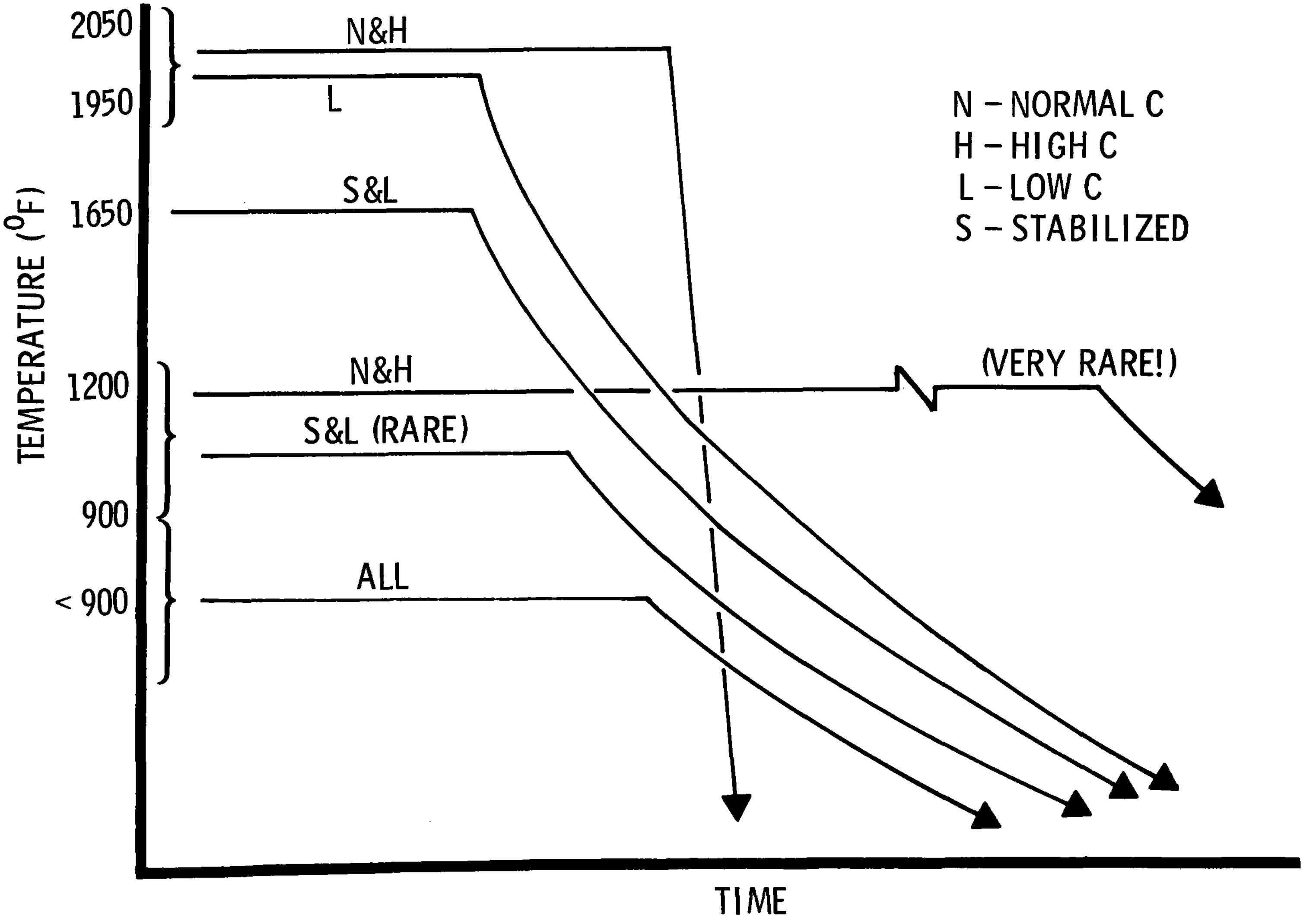
70-MA1-48-346

SYNERGISTIC EFFECT
OF
CHLORIDE & OXYGEN
ON
STRESS CORROSION CRACKING
OF
STAINLESS STEEL



70-MA1-48-344

HEAT TREATMENTS FOR AUSTENITIC STAINLESS STEELS



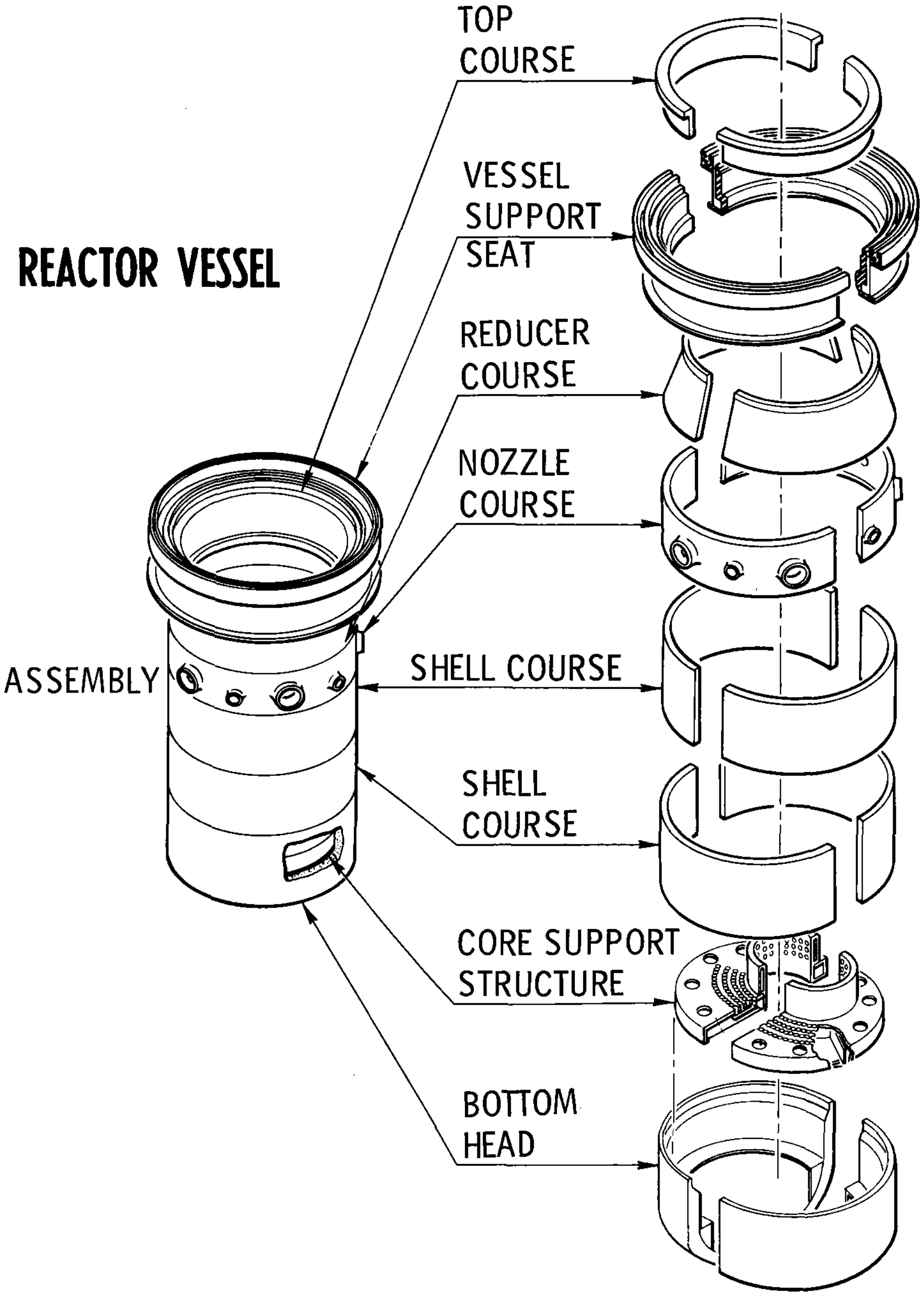
V-A-87

70-MA1-48-345

CASE HISTORIES

VESSEL MATERIAL SELECTION

ASSEMBLY & BREAKDOWN OF REACTOR VESSEL



70-MA1-48-294

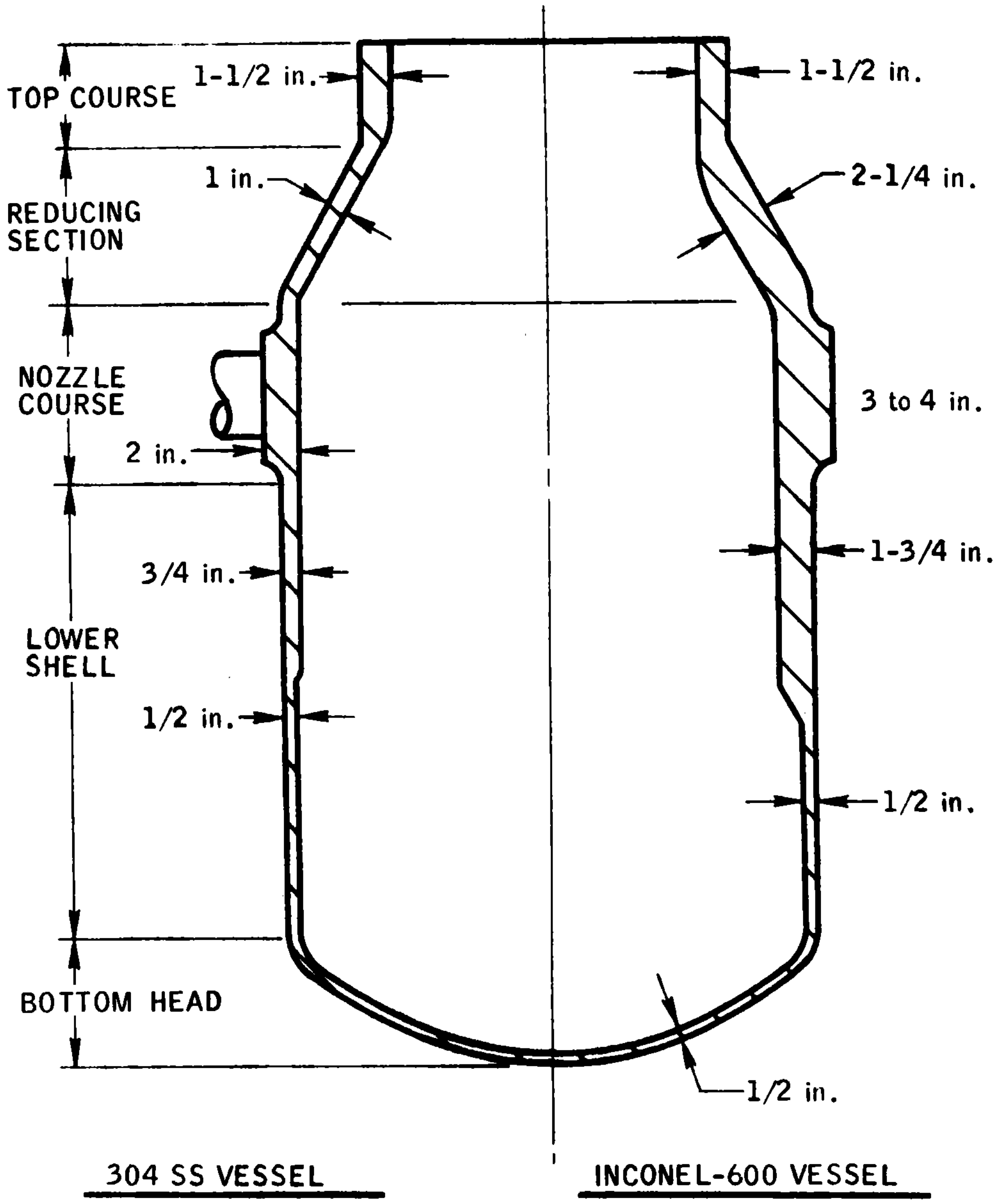
ENVIRONMENTAL ANALYSIS

- FABRICATION, SHIPPING, AND STORAGE
- INSTALLATION AND ERECTION AND STORAGE
- OPERATION AND MAINTENANCE
- ABNORMAL OPERATION AND MAINTENANCE
- SHUTDOWN AND RETIREMENT

SHOP FABRICATION

ENVIRONMENT	EFFECT	POSSIBLE COUNTERMEASURES
● FABRICATION – WELDING		
CONTAMINATION	MATERIAL CONTAMINATION C, Pb, S HALOGENS	ESTABLISH REQUIREMENTS
OIL, DUST, ETC.	RESIDUAL STRESS	APPROVE PROCEDURES
MOISTURE	CORROSION	IN-PROCESS CONTROL
METAL CHIPS	STRESS CORROSION	PROPER CLEANING
MARKING PENCILS, ETC.	WELD POROSITY	CONTROL MATERIALS
WELDING MATERIAL	WELD CRACKS	ANNEAL IF POSSIBLE
FLUXES	MECHANICAL PROPERTIES	STRESS RELIEF IF POSSIBLE
TEMPERATURE	LOW TEMPERATURE EMBRITTLEMENT	TAG SENSITIZED COMPONENTS
NDT FLUIDS		CONTROL ENVIRONMENT
COUPLANTS		
DYES		
● STORAGE AND SHIPMENT		
CONTAMINATION	OXIDATION	SPECIFIC REQUIREMENTS
NATURE	CORROSION	APPROVE PROCEDURES
BLOOD, SWEAT, AND TEARS	STRESS CORROSION	CONTROL ENVIRONMENT
DUNNAGE AND CRATING	SCRATCHES AND DINGS	
	DEFORMATION	

FBR REACTOR VESSEL



70-MA1-48-263

LIQUID METAL REACTOR EXPERIENCE

FACILITY	LOCATION	POWER (Mwt)	COOLANT	COMPONENT	MATERIAL	TEMPERATURE (°F)		OPERATION
						DESIGN	MAXIMUM OPERATIONAL	
EBR-II	IDAHO	45	Na	CORE VESSEL PIPING IHX SHELL	304 SS 304 SS 304 SS	1000 1000 1000	880 880 880	1964 TO PRESENT
FERMI	MICHIGAN	100	Na	CORE VESSEL PIPING IHX SHELL	304 SS 304 SS 304 SS	1000 1000 1000	825 825 825	1963 TO 1966
SEFOR	ARKANSAS	24	Na	CORE VESSEL	304 SS		820	1968 TO PRESENT
DFR	SCOTLAND	60	NaK	CORE VESSEL PIPING IHX SHELL	321 SS 321 SS 321 SS		780 780 620	1962 TO 1967; 1969
RAPSODIE	FRANCE	24	Na	CORE VESSEL PIPING IHX SHELL	316 SS 316 SS 316 SS		1000 1000 950	1967 TO PRESENT
SRE	CALIFORNIA	20	NA	CORE VESSEL PIPING IHX SHELL	304 SS 304 SS 304 SS	1500 1200 1200	1030 1030 1000	1957 TO 1964 (>37,000 hr)
HNPF	NEBRASKA	240	Na	CORE VESSEL PIPING IHX SHELL	304 SS 304 SS 304 SS	1000 1000 1000	945 945 895	1963 TO 1965
BR-5	USSR	5	Na PRIMARY NaK SECONDARY	CORE VESSEL PIPING IHX SHELL	321 SS 321 SS		840 840 800	1959 to ? (38,000 hr TO JULY 1967)
EBR-1	IDAHO	1.4	NaK	CORE VESSEL PIPING IHX SHELL	347 SS 347 SS A-NICKEL		610 610 580	1951TO 1963
SNAP 2 (DR & ER)	AI	0.06	NaK	CORE VESSEL PIPING IHX SHELL	316 SS 304 SS 316 SS	1300 1300 1300	1200 1200 1200	~ 3000 hr EACH
SNAP 8 (DR & ER)	AI	0.6	NaK	CORE VESSEL PIPING IHX SHELL	316 SS 316 SS 316 SS	1400 1400 1400	1300 1300 1250	S8ER - 10,000 hr S8DR - 1500 hr TO PRESENT
SNAP 10 (FS-3, FS-4)	AI	0.03 0.04	NaK	CORE VESSEL PIPING	316 SS 316 SS	1050 1050	1010 1010	FS-3 - 10,000 hr FS-4 - 1,000 hr
ARE	TENNESSEE	2.5	Na	CORE VESSEL PIPING	INCONEL INCONEL		1300	220 hr

70-MA1-48-362

SUMMARY OF PERFORMANCE FACTORS FOR GPU-AI FBR

VESSEL MATERIAL SELECTION

	304	316	321	347	INCONEL 600	INCOLOY 800
TECHNICAL						
MECHANICAL PROPERTIES	A	A	A	A	C	C
PHYSICAL PROPERTIES	A	A	A	A	A	A
METALLURGICAL PROPERTIES						
THERMAL	A	B	A	A	A	A
IRRADIATION	A	A	A	A	A	A
FABRICABILITY	A	A	A	A	A	A
WELDABILITY	A	A	B	C	C	C
CHEMICAL						
SODIUM COMPATIBILITY	A	A	A	A	C	B
GENERAL CORROSION	B	B	B	B	A	A
ECONOMIC						
COST/AVAILABILITY	A	A	A	A	C	B
FABRICATION COST	A	A	A	C	C	C
QC COST	A	A	A	C	C	C
RISK						
FABRICATION EXPERIENCE	A	B	B	B	C	C
REACTOR EXPERIENCE	A	A	B	B	*	NONE
SODIUM EXPERIENCE	A	A	B	B	C	C
IRRADIATION EXPERIENCE	A	A	B	B	C	C

A – GOOD
B – ACCEPTABLE
C – PROBABLY ACCEPTABLE
*USED IN THE AIRCRAFT REACTOR EXPERIMENT AT ORNL, A SODIUM COOLED, MOLTEN SALT FUELED REACTOR, 2.5 Mwt, 1300°F, 220 hr TOTAL LIFETIME

70-MA1-48-369

REACTOR VESSEL CONCLUSION

- TECHNICALLY
  - ALL CANDIDATE MATERIALS COULD BE USED
  - NICKEL ALLOY
    - INCREASED THERMAL STRESS
    - SENSITIVE TO CONTAMINATION
  - STAINLESS STEEL ALLOY
    - SENSITIVE TO STRESS CORROSION
- RISK AND UNCERTAINTIES
  - EXPERIENCE FAVORS 304 STAINLESS STEEL FOR SODIUM SERVICE
- ECONOMICS
  - FAVORS 304 STAINLESS STEEL
- CONCLUSIONS
  - 304 STAINLESS STEEL IS EQUAL TO OR SUPERIOR TO ALTERNATE ALLOYS IN ALL FACTORS EXCEPT ONE – i.e., STRESS CORROSION IN AQUEOUS MEDIA
  - A POSITIVE PROGRAM TO COMBAT THIS OBVIOUS DEFICIENCY WOULD BE MORE EFFECTIVE THAN EFFORT TO QUALIFY A NICKEL ALLOY

70-MA1-48-352

CLADDING MATERIAL SELECTION

REQUIREMENTS OF CLADDING

- CLOSE DIMENSIONAL TOLERANCE THIN-WALLED TUBING
- CONTAINMENT INTEGRITY FOR FUEL AND FISSION PRODUCT GASES
  - LIQUID SODIUM ENVIRONMENT
  - TEMPERATURES TO 1200°F
  - 1-1/2-yr SERVICE LIFE
  - HIGH FAST NEUTRON FLUX
  - INTERNAL GAS PRESSURE
  - STRESSES EXERTED BY SWELLING FUEL

70-MA1-48-351

FACTORS AFFECTING CLADDING MATERIAL SELECTION

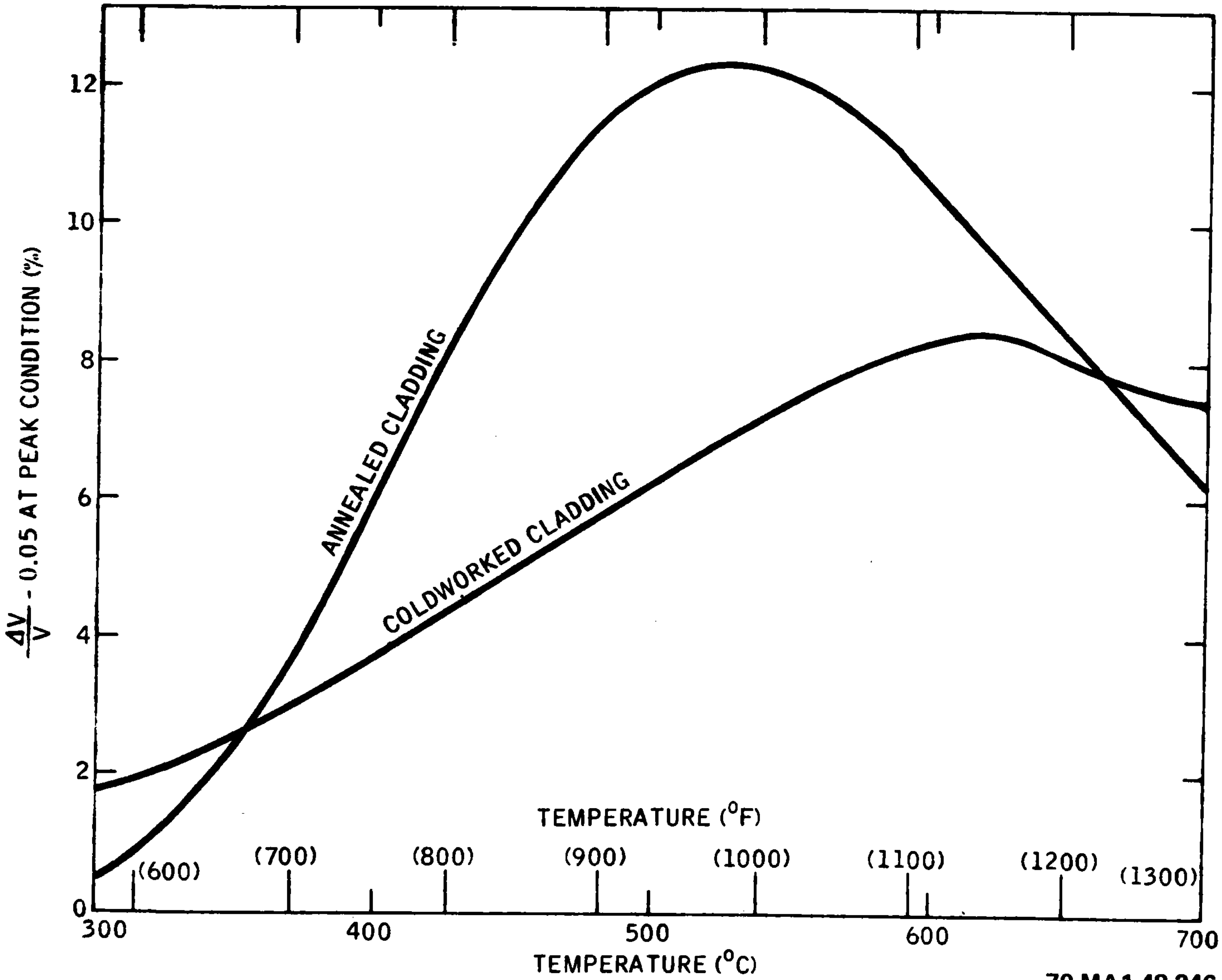
1. FABRICABILITY AND HANDLING
2. MECHANICAL PROPERTIES
3. THERMAL STABILITY
4. IRRADIATION STABILITY
5. SODIUM CORROSION

COMPARISON OF RUPTURE STRENGTH

CW 316 SS	HIGHEST
ST 304 SS	↓
ST 316 SS	↓
CW 304 SS	LOWEST

9-N7-130-10

CORRECTED SWELLING STRAIN vs TEMPERATURE



70-MA1-48-246

SODIUM CORROSION OF CLADDING MATERIALS

- SURFACE RECESSION
  - ST 304 SS, ST 316 SS, CW 304 SS, CW 316 SS EQUIVALENT (GE, UK, AND AI)
- FERRITE LAYER FORMATION
  - ST 316 SS AND CW 316 SS MORE RESISTANT THAN ST 304 SS AND CW 304 SS (AI LMFBR)
- CARBON TRANSFER (DECARBURIZATION)
  - LOSS OF RUPTURE STRENGTH OF CW 304 SS GREATER THAN THAT OF MILL ANNEALED 316 SS (AI LMFBR)
  - LOWER STRENGTH OF M316L SS vs M316 SS (UK)
  - TENDENCY FOR DECARBURIZATION OF 316 SS GREATER THAN THAT OF 304 SS IN 304 SS LMFBR Na SYSTEM

70-MA1-48-250

EVALUATION OF
CLAD MATERIAL PERFORMANCE RATING FACTOR

	RUPTURE STRENGTH	DUCTILITY	SWELLING RESISTANCE	Na CORROSION RESISTANCE	DECARBURIZATION RESISTANCE	FABRICATION AND HANDLING
CW 316 SS	1	1	1	1	5	1
ST 316 SS	3	1	3	1	5	5
CW 304 SS	5	5	3	5	1	1
ST 304 SS	3	5	5	5	1	5

RATING: 1 HIGHEST, 5 LOWEST
SELECTION: COLD WORKED 316 SS

70-MA1-48-349

CONTROL ROD
TRIP LATCH
MATERIAL SELECTION

70-MA1-48-261

CONTROL AND SAFETY ROD TRIP LATCH

FUNCTION

- SUPPORT NEUTRON ABSORBER SECTION AND RELEASE WHEN REQUIRED

REQUIREMENTS

• LIFE	10 yr, 500 TRIPS	
• IRRADIATION	3.4×10^{20} n/cm^2 $>$ 1 Mev	
• ENVIRONMENT	REACTOR Na FLOW $<$ 1 ft/sec	
• TEMPERATURE	OPERATION	1200^0F
	REFUELING	600^0F
	MAINTENANCE	350^0F
• STRESS	NORMALLY VERY LOW 90,000 psi AT 1200^0F POSSIBLE DURING TRIP	

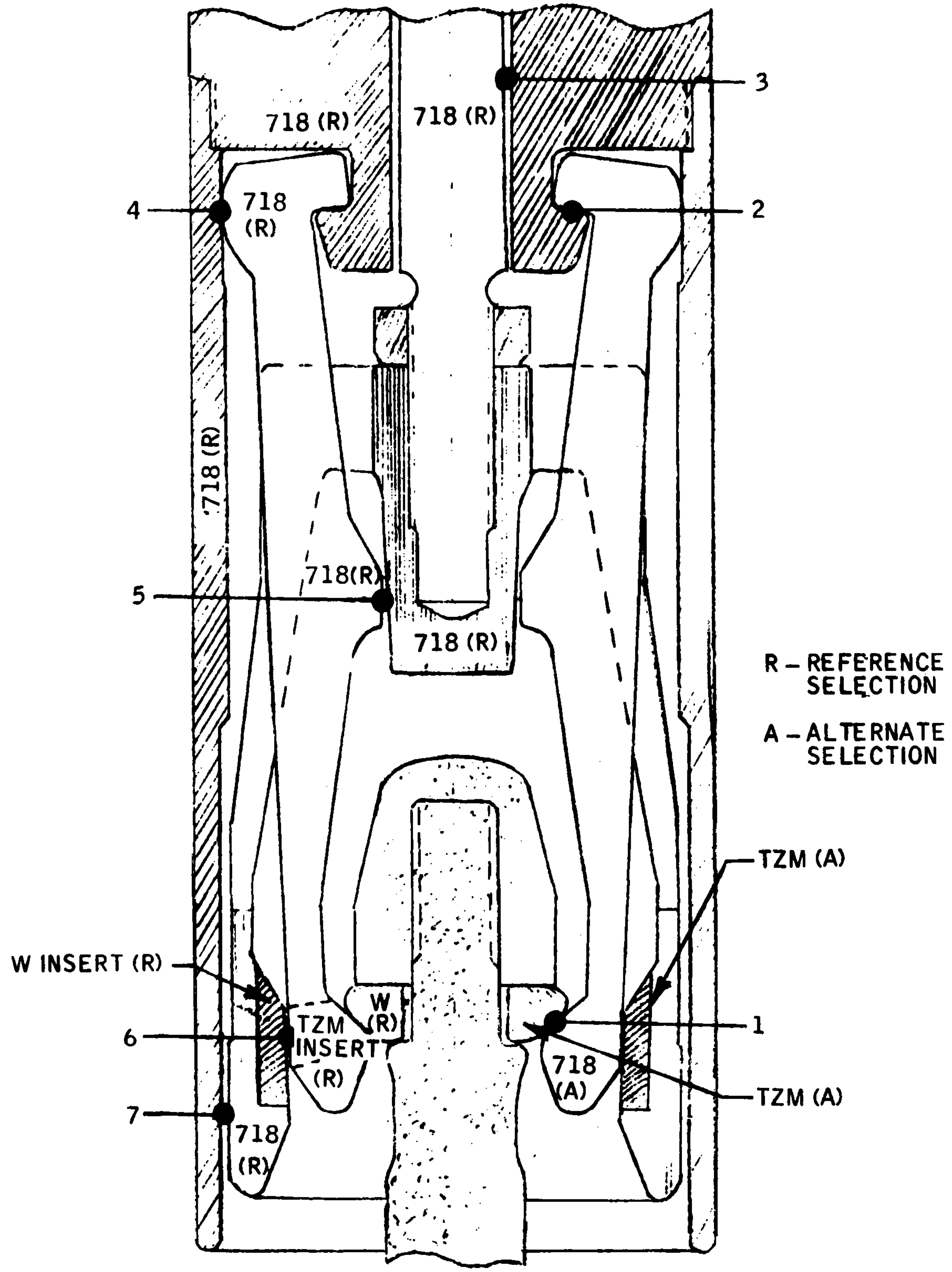
70-MA1-48-357

TRIP LATCH MATERIALS
DOMINANT SELECTION CRITERIA

- STRENGTH
- SELF-WELDING
- NEUTRON DAMAGE
- SODIUM CORROSION
- FRICTION

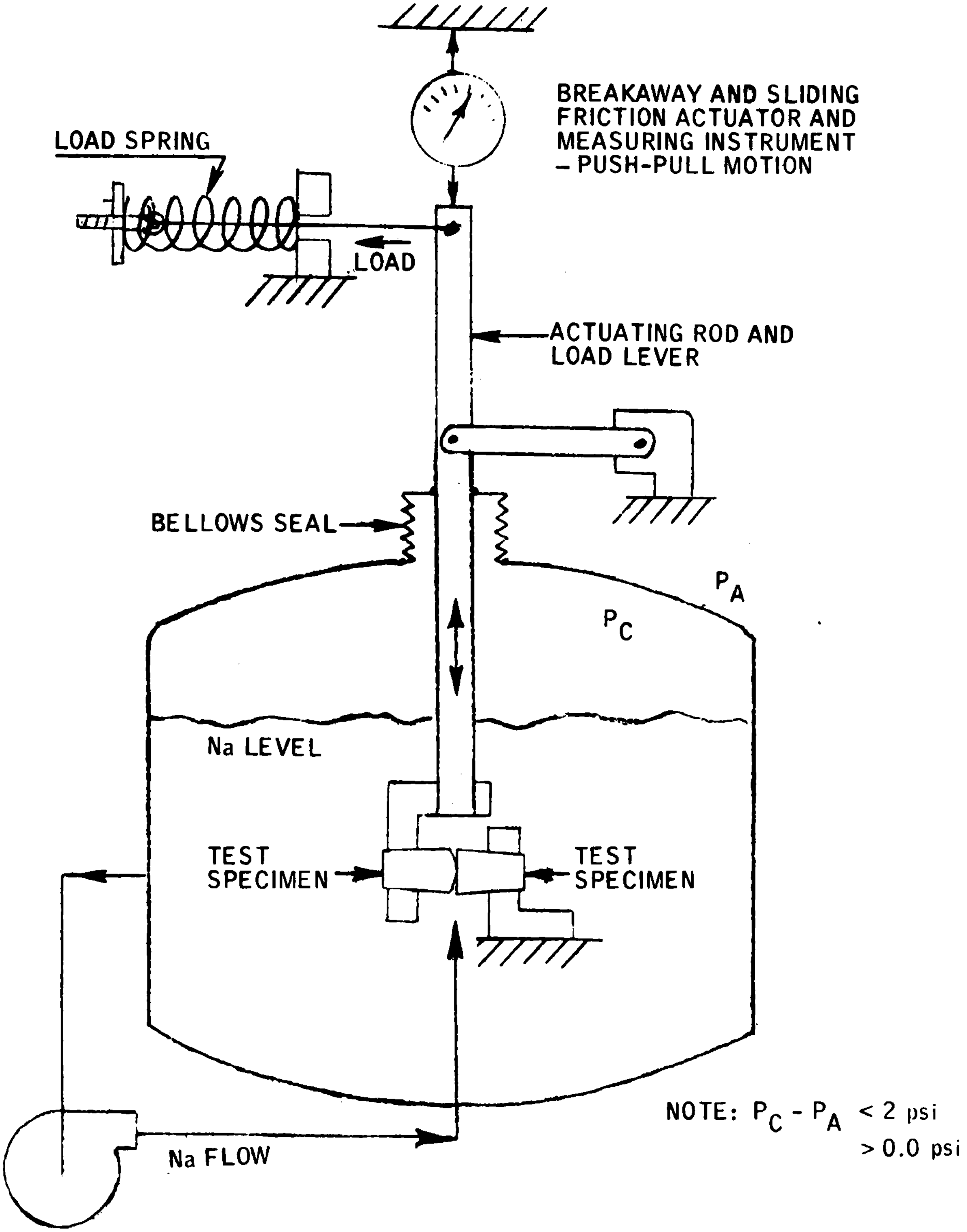
9-N7-130-17

FRICTION AND ADHESION COUPLE LOCATION



9-N7-130-18

TRIP LATCH TEST CONCEPT



NOTE: $P_C - P_A$ < 2 psi
> 0.0 psi

RECOMMENDED TEST PROGRAM ADHESION TEST COUPLES

● TUNGSTEN	vs	TZM (Mo ALLOY)
● 718	vs	718
● 718	vs	TZM (Mo ALLOY)
● 718	vs	W
● 718	vs	Nb-BONDED TiC
● 718	vs	STELLITE STAR J
● TZM	vs	Nb-BONDED TiC
● TZM	vs	TZM
● 304 SS	vs	304 SS

9-N7-130-19

STEAM GENERATOR
MATERIAL SELECTION

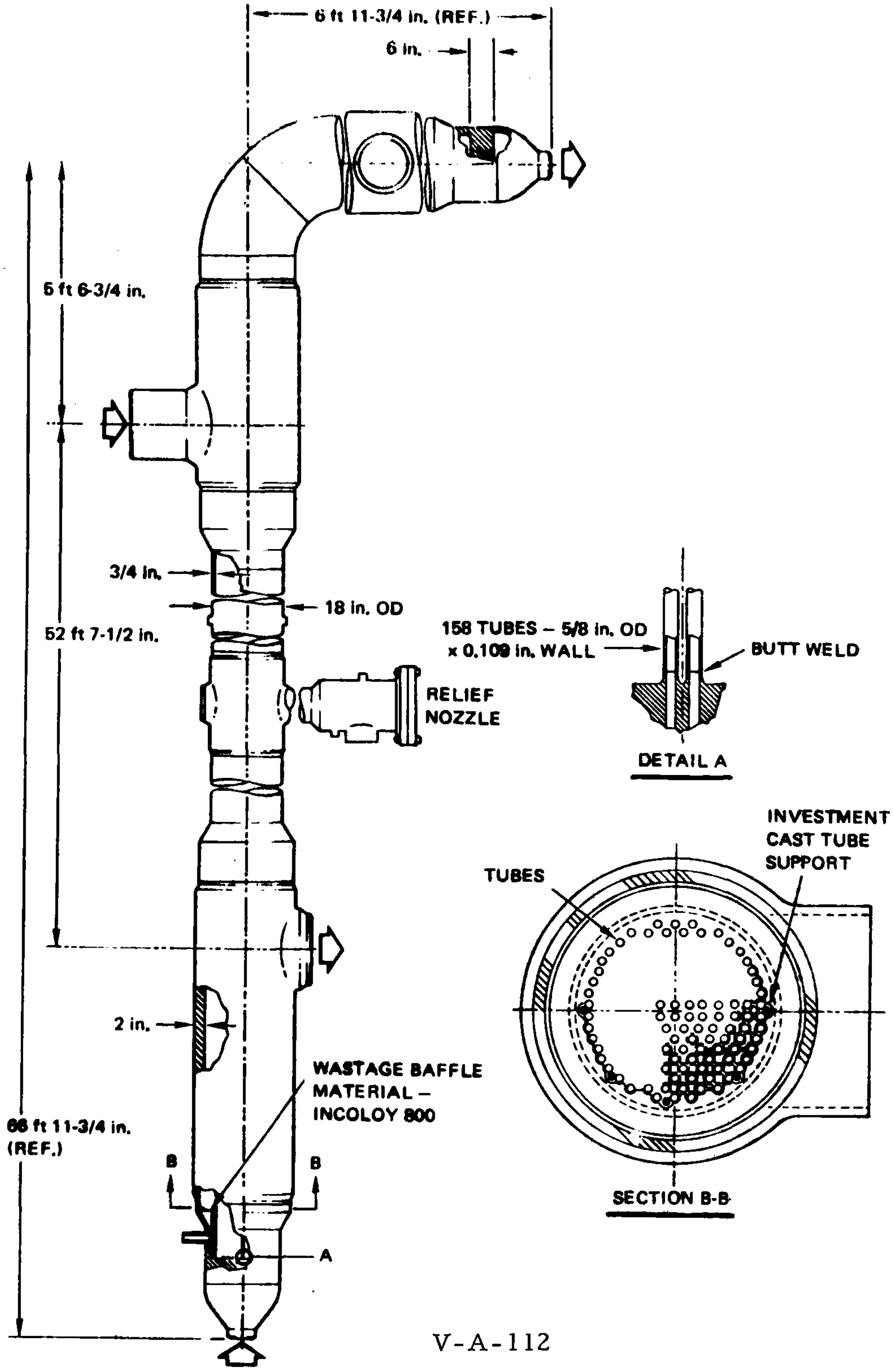
70-MA1-48-252

STEAM GENERATOR DESIGN REQUIREMENTS

● SODIUM TEMPERATURE	950°F
● STEAM TEMPERATURE	905°F
● SODIUM PRESSURE (MAXIMUM)	240 psia
● STEAM PRESSURE	3125 psia
● DESIGN LIFE	30 yr
● OXYGEN IN SODIUM	10 to 20 ppm
● WATER PURITY	150 ppb
● ASME STAMP?	YES
● IHX MATERIAL	304 SS

9-N7-130-22

STEAM GENERATOR



MATERIAL SUMMARY

MATERIAL	RELATIVE COST OF RAW MATERIALS	ALLOWABLE ASME STRESS AT 950°F (psi)	STRESS CORROSION	THERMAL STABILITY	CORROSION			FABRICABILITY
					SODIUM	STEAM	AIR	
2-1/4 Cr - 1 Mo	0.15	11,000	IMMUNE	GOOD	GENERAL CORROSION ON LOW OXIDE SODIUM APPEARS TO BE VERY LOW FOR ALL OF THE ALLOYS CONSIDERED. LIMITED DATA ON INCOLOY 800; HOWEVER DUE TO COMPOSITION, ITS RESISTANCE SHOULD BE NO WORSE THAN INCONEL	ALL MATERIAL APPEARS TO HAVE ADEQUATE RESISTANCE TO GENERAL CORROSION BY STEAM; HOWEVER THE GENERAL CORROSION APPEARS TO BE RELATED TO THE CHROMIUM CONTENT OF THE SURFACE. IF CHROMIUM IS AT SURFACE MATERIAL FORMS PROTECTIVE LAYER	RESISTANCE TO OXIDATION BY AIR INCREASES WITH INCREASING CHROMIUM CONTENT	ESTABLISHED TECHNOLOGY
5 Cr - 1/2 Mo	0.2	10,000	IMMUNE	GOOD				REQUIRES PRE- AND POST-HEAT OR WELDS
304 SS	0.90	9,750	SUSCEPTIBLE	WILL SENSITIZE AT TEMPERATURES ABOVE 800°F				WELL ESTABLISHED TECHNOLOGY
316 SS	1.00	10,100	SUSCEPTIBLE	MAY DEVELOP SOME SIGMA PHASE AT ELEVATED TEMPERATURES				WELL ESTABLISHED TECHNOLOGY
321 SS	1.00	11,200	SUSCEPTIBLE	SAME AS 316 SS				SAME AS 316 SS
INCOLOY 800 CLASS I CLASS II	1.20	 14,000 9,000	50 TO 300 TIMES MORE RESISTANCE UNDER LABORATORY CONDITION THAN 300 SERIES	MINIMUM DUCTILITY (20%) OCCURS AFTER 6 mo AT 1200°F, DUCTILITY INCREASES TO 24% AFTER 18 mo. LOWER SUSCEPTIBILITY TO SIGMA FORMATION THAN 300 SERIES				LIMITED FABRICATION EXPERIENCE. ALLOY BEHAVIOR IS SIMILAR TO 300 SERIES SS
INCONEL 600	1.46	11,500	RELATIVE IMMUNITY IN FIELD EXPERIENCE	MINIMUM DUCTILITY (28%) AFTER 6 mo AT 1200°F. DUCTILITY REMAINED CONSTANT UP TO 18 mo.				WELDING OF THICK SECTIONS MAY RESULT IN MICROFISSURING

70-MA1-48-373

STEAM GENERATOR

MATERIAL SELECTED: 2-1/4 Cr - 1% Mo

PRIMARILY DUE TO RESISTANCE TO CHLORIDE STRESS CORROSION CRACKING

70-MA1-48-358

SUMMARY

KNOW YOUR REQUIREMENTS

KNOW YOUR MATERIALS

THEN FIT THEM

SOURCES OF DATA

- LMIC
- FFTF MATERIALS DESIGN DATA BNWL-891
- BNWL REPORTS
- AI-FBR MATERIALS HANDBOOK (IN PPN)
- LIQUID METALS HANDBOOK
- REACTOR HANDBOOK
- AEROSPACE STRUCTURAL MATERIALS HANDBOOK
- MECHANICAL PROPERTIES DATA CENTER
- CORROSION ENGINEERING (TEXTBOOK)
- METALS HANDBOOK
- ASME BOILER AND PRESSURE VESSEL CODE
- ASTM SPECIAL PUBLICATIONS

9-N7-129-30

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SODIUM TECHNOLOGY COURSE, SESSION VI
SODIUM INSTRUMENTATION AND ELECTRICAL SYSTEMS
E. Matlin

This is the third lecture in which some aspects of sodium instrumentation have been covered. By way of review of the other lectures, I have listed four characteristics which I think define the unique requirements of sodium instrumentation. First, as has been mentioned on several occasions, absolute containment is essential. Second, the instruments are characterized by the fact that they must operate at high temperatures. The hot leg temperatures of many systems are 1200° and higher. Third, maintenance is invariably difficult. The instruments are either located in and about the reactor or the reactor gallery, or in some other spot where they cannot be maintained, or where maintenance would be extremely difficult. This means, of course, that a remote readout is normally required. Finally, the instruments must be designed to be very tolerant of the plugging of annuli and cavities with either frozen sodium or sodium oxide. This discussion will be primarily limited to what I consider to be the four most important sodium instruments, namely, flowmeters, level devices, pressure instruments, and temperature measuring devices.

A. FLOWMETERS

1. Electromagnetic Permanent Magnet

Let's start with flowmeters. The simplest type of flowmeter for sodium service, and the one which is most widely used is the permanent magnet EM flowmeter. It operates on the principle that where a moving conductor passes through a magnetic field, a voltage will be generated at electrodes located mutually perpendicular to the axis of flow and to the axis of the magnetic field. See Figure 1. The output will be generally described by E = a constant times BLV, where B is the flux density, L is the length of the conductor, and V is the flow velocity (Figure 2). Because of the electrical shunting effect of the pipe that contains the sodium, and other effects which I'll discuss presently, a more accurate relationship requires additional terms, as seen in Figure 3. In the second equation, the product of velocity and conductor length has been replaced by flowrate divided by pipe ID, and in addition, four constants have been added. K1 corrects for the pipe wall shunting, which causes a voltage drop to occur across the generator resistance, resulting in a drop in terminal voltage. It includes, in addition to the dimensions of the pipe, the ratio of the resistivity of the sodium to the pipe wall. K2 is the corrective factor to account for the nonhomogeneity of the flux in the axial direction if the magnet length is not several pipe diameters in length. The value of K is a function of pole face length to pipe diameter, and must be determined experimentally. Figure 3 shows a plot of this factor. K3 is the factor that compensates for changes in the magnet temperature, and is also shown plotted in Figure 3. Data for this plot must be obtained for the specific magnet material used. The effect plotted must be distinguished from permanent magnet strength degradation, which will initially result from exposure of the magnet to temperature. K4 is a pipe expansion factor and follows the usual expression for the linear expansion of materials. The effect is to increase the diameter factor, d.

Figure 4 illustrates the accuracy which can be obtained in using Equation 1. The data were taken on Hallam flowmeters in sizes of 1, 2, 3, 6, and 14 in. The "difference" column indicates the difference between the calculated output and the actual measured output. As you can see, for 1, 2, and 3 in. flowmeters, the calculated output was within a few percent of the actual measured output. However, in 6-in. and larger flowmeters, rather large deviations occurred. The reason for the discrepancies is related to difficulty in obtaining homogeneous fluxes for large diameter pipes, and in obtaining good average flux values. Also, Equation 1, as will be discussed below, does not consider the effect of eddy currents, which become important in large diameter pipes. Other important data which show up on this chart are the actual outputs per gallons per minute which were obtained for practical sized magnets. It is seen that for a 1-in. flowmeter, the output is ~1 mv/gpm. Since 1 mv represents about the minimum desirable full scale readout instrument range, a 1-in. flowmeter should not be used when the maximum flow is <1 gpm. Similarly, a 6-in. flowmeter should not be used for full scale outputs of <22 gpm, etc.

As mentioned previously, Equation 1 does not take into consideration the effects of eddy currents which are quite important in large size flowmeters. These currents will flow both axially and circumferentially. As seen in Figure 4, the axial eddy currents flow in generally rectangular patterns under the influence of the voltage generated in the sodium. The field generated by the currents will act to either add to or reduce the main dc field. The field will be reduced at the entrance to the flowmeter and aided at the exit. As seen in Figure 5 the effect of the flow is to reduce the peak flux density and to shift the point at which it occurs downstream. Since the flux density varies with flow, the sensitivity will vary with flow, i.e., the output will be non-linear. As seen in Figure 6, the linearity of the output will be better or worse, depending upon where the electrodes are located relative to the pole pieces. From experimental data it has been found that optimum linearity is approached with the electrodes located near the downstream edge of the magnet. Conversely, as seen in the Figure, the greatest non-linearity occurs with electrode pairs located near the flowmeter entrance. If the flow is symmetrical in the pipe, the D-shaped circumferential eddy currents do not affect linearity.

In Figure 7, output vs flow for a 14-in. flowmeter is plotted at two different temperatures, 350 and 950°F. As would be expected, both linearity and sensitivity improve at the higher temperature. This occurs because the resistivity of the sodium increases with temperature, reducing the magnitude of the eddy current shunting and flux distortion.

In order to initially calculate the flowmeter output and later recalibrate the flowmeter in service, it is necessary to measure flux density. Prior to flowmeter installation, this can be done by inserting any of a variety of flux meter probes into the pipe bore at the magnet centerline and reading the flux density out directly. Once the flowmeter is installed in a loop, however, the main gap flux can no longer be directly measured. It is possible, generally, to measure fringe flux, and if the ratio of fringe flux to main gap flux has been previously determined, the latter may be inferred. For this reason, it is desirable, when actually calibrating a flowmeter in a loop, to measure the fringe flux so that the flowmeter can be later recalibrated in situ. Where the flowmeter is installed in an inaccessible location it is desirable to be able to remotely monitor flux. A convenient way of doing this is to employ a flip coil mounted to the magnet frame so that the coil, when rotated, cuts lines of fringe flux. The flip coil is connected to a ballistic galvanometer. Rotation is accomplished by using a rotary solenoid. If the radiation level is excessively high, both the rotary solenoid coil and the flip coil must be wound with inorganic insulation.

A source of error which can affect flowmeter accuracy after calibration is lack of wetting. If wetting of the pipe by the liquid metal is not complete a high source impedance will result, and the output will be reduced. Figure 8 illustrates percentage of wetting as determined by flowmeter readings for various time and pipe treatments. It is seen from Curve 3 that above 800°F, complete wetting will take place even on an untreated section of pipe. Prior operation at room temperature will reduce the temperature somewhat at which complete wetting will take place. As seen from the other curves, treatment of the pipe with various acids and alkaline solutions will further accelerate the process. As a general rule, at least 24 hr should be allowed for wetting for initial operation below 500°F.

Another possible source of error is the generation of thermoelectric potentials if the electrode material is not carefully matched to the pipe material. Experiments have shown that thermoelectric potentials as high as 50 mv can be generated at 1200°F with stainless steel electrodes welded to stainless steel pipe. If the full scale flowmeter output was as low as 1 mv this would represent a 5% error.

The response time of an electromagnetic flowmeter will be determined by the equivalent source L/R time constant. If it were not for eddy current paths, the source impedance would appear as a very low resistance. In small flowmeters (up to 6 in.) where eddy currents are less important, this condition exists and low response times result (<50 ms). In larger flowmeters, preliminary analysis indicates that response times may be much longer, as long as 2 or 3 sec for a 36-in. pipe size. The analysis required to calculate response time is quite sophisticated and so, the calculated values may be quite pessimistic. Attempts to actually measure response times on a 10-in. flowmeter using noise analysis have been unsuccessful due to instrument problems, so the actual values of response time for large flowmeters is still very much in doubt.

An installation problem which must be considered for all types of flowmeters is the influence of upstream disturbances on flowmeter output. Recent studies have shown for a 10-in. flowmeter installed ~24-in. downstream of an elbow, that $< 1\%$ noise was added by the elbow. Further, this noise can be eliminated by orienting the pole faces parallel to the plane of curvature of the elbow.

2. ac Electromagnetic Flowmeters

It is theoretically possible to design an ac EM flowmeter similar in construction to the permanent magnet dc flowmeter in which the magnetic material is replaced by ferromagnetic material around which coils are wound. If the coils are excited with ac, the output at the electrodes will then be ac. This type of flowmeter has the advantage of an easily amplified output signal and consequently a lower field strength can be used. The disadvantages are that (1) a well regulated input current must be supplied, (2) eddy currents in the fluid will be large, detracting from the output and making the output highly temperature sensitive, and (3) the frequency must be selected low enough to assure field penetration but high enough to provide adequate frequency response and ease of amplification. In the rare instances where a generation type ac flowmeter has been used, the field coils have been of the transverse type, that is of a rectangular shape located on either side of the pipe but curved to fit the pipe diameter to form a saddle configuration. In this form the coil insulation must be designed to survive the pipe surface temperature.

Another approach to the use of ac is to utilize the distortion of an ac field caused by the flow of a moving conductor. A typical configuration for this type of flowmeter, usually referred to as an "eddy current" flowmeter, is shown in Figure 9. This type of configuration originally patented by Lehde & Lang, consists of a group of solenoid coils around which, as in the figure, or through which (in alternate concepts) the liquid metal, whose flow is to be metered, is passed. The coils are arranged alternately of primaries and secondaries such, that with the secondaries connected in series opposition, there is no net output with no flow. When flow is introduced, the interaction of the eddy current generated field and the primary field results in a distortion of the resulting field such as to unbalance the secondary outputs and produce an output which is quite linear with flow. A considerable amount of analytical work has been performed on this type of flowmeter at ANL and testing has been done at ANL, and to a lesser extent at BNW and Atomics International. The optimum excitation frequency goes down as the desired fluid penetration distance goes up because of the skin effect; thus, this type of flowmeter tends to be most attractive for small pipe sizes or reactor core fuel exit channel flow monitoring.

Figure 10 illustrates the results of testing eddy current type flowmeter coil assemblies by simulating the flowing sodium by the use of metal cylinders, dropped over the coil assemblies. Different materials were used to determine the effect on output of changes in fluid conductivity. An important thing to be seen from Figure 10 is that it is possible to obtain rather large outputs for reasonable inputs (say, 1 amp) with simulated fluid velocities in the range of 5 to 10 ft/sec. The outputs, as you see, are in the range of 50 to 60 mv ac. The frequency used was 400 Hz. The outputs for a given material are quite linear with flow. But note that the output is not linear with conductivity. Copper, which has the highest conductivity of the materials used, does not give the highest output, although stainless steel, with the lowest conductivity yields the lowest output. The reason for this is that, with an extremely low conductivity device, there is little disturbance of the field, and consequently a low output. On the other hand, if the conductivity is very good, penetration of the field will be reduced and output will be affected. Sodium has a resistivity at 1200°F of $\sim$35 μ-ohm-cm as against lead with 20 μ-ohm-cm at room temperature.

Another form of eddy current flowmeter is the so-called E-core flowmeter. This device has the shape of an "E" transformer lamination and is wound with a primary coil on the center leg and with two balanced secondaries connected in series opposition of the outside legs. The coil assembly is installed with its legs adjacent to the pipe surface. Because of the field pattern, the output will be most sensitive to flow at the surface of the pipe where the flowmeter is installed. Output will thus be substantially affected by changes in flow distribution in the pipe. Also, high temperature insulation is required. Because of these shortcomings, the E-core device usage has been limited to flow switch application.

Summarizing, electromagnetic flowmeters offer the following advantages:

1) High reliability due to simplicity and absence of pipe penetration
2) In small sizes provide good linearity
3) Can provide convenient outputs requiring a minimum of signal conditioning
4) Generally provide negligible pressure loss
5) Low response time, except in very large sizes.

3. Differential Head Devices

Differential head devices are the type of flowmeters most commonly used in most conventional process systems. Into this category fall the Venturi meter, orificemeter, and the flow tube. Figure 11 shows schematic views of these devices. As seen, each consists of a flow restriction and low pressure and high pressure taps. In actual practice, a differential pressure device would be used rather than two pressure indicators.

The equation for the output of these devices follows the general form shown in Figure 12 which happens to be an equation for an orifice type meter. You can see that the flow is proportional to an orifice constant, times orifice area, times the square root of 2g x ΔP over the density of the fluid. Here, ΔP is the generated differential head. It can be seen from Equation 2, what the disadvantages are when this type of unit is used in a sodium system. First, the output is related to the density of the fluid which changes with temperature. Secondly, the output is not linear, dp is proportional to the square of the flow. Thirdly, a differential pressure device operating at very low pressures is required, which is very difficult to come by for use with sodium, as we will see later. Fourthly, the dimensions of the orifice plate will change with temperature, possibly through erosion by the fluid. Finally, some nonrecoverable pressure loss is required, increasing pump horsepower.

Experimentally, it has been found that there is a temperature shift of ~10% in going from 300 to 1200°F with these type devices. The attractive feature of differential head type flowmeters is that they can be calibrated very accurately for water and, if the measured calibration can be corrected accurately for a second fluid used at a higher temperature, a highly accurate flowmeter will result. Because of the vast experience in the use of conventional differential head devices, outputs can be calculated to within 1% without actual test calibration. When actually calibrated, the accuracy will depend on the capability of the test facility, but accuracies are normally better than 0.25% for line sizes to 12 in. and 0.5% for 12 to 48-in. lines. In theory the correction of the water calibration to sodium ought to be as accurate as the hydraulic characteristics of the sodium at operating temperatures are known. However, there is little experimental data to verify the accuracy of the correction factors and there is evidence of errors as great as 2% for constant Reynolds numbers. Nevertheless, differential head type flowmeters in both small and medium sizes (1 to 12 in.) have been used in calibration loops and in conjunction with EM flowmeters.

4. Thermal Flowmeters

Thermal flowmeters have also been used in sodium systems. AI is using several in the Advanced Zirconium Hydride Program at the present time. They operate on the principle that if heat is added to a section of pipe, the mass flowrate is proportional to the heat added minus the heat losses over the specific heat of the fluid, times th rise in temperature. This relationship is shown in Figure 13, Equation 3. Thus, if electrical heat is applied to a pipe section, the flow can be obtained by applying a scale factor to differentially connected upstream and downstream thermocouples. The disadvantage in this kind of system is that, in order to get a substantial ΔT, it is necessary to put in very substantial power and this power requirement becomes excessive for lines much larger than 1 or 2 in. Even in small flowmeters the output tends to be noisy. Further, as you see from Equation 3, the output is a function of specific heat and, that parameter will change with temperature – ~1 to 1-1/2%, in the range of 400 to 1000°F. A further disadvantage is that of a relatively slow response time. The response time will be controlled by the time for heat transfer equilibrium to be established and by the time constant of the thermocouples. The result is a time constant in seconds.

The advantages of this type of flowmeter are: (1) no pressure loss, (2) direct mass flow measurement, and (3) theoretically the ability to analytically calibrate the device. Work has been done on estimating the probable error of these devices and it has been set at 2%; however, experimentally, this figure has not been verified. By way of example, Figure 14 illustrates typical discrepancies in calibration which show up in testing different types of flowmeters. The outputs of three different kinds of flowmeters, all located in the same line, are shown on this curve. The solid dot represents a purchased MSA permanent magnet flowmeter; the squares, an AI EM flowmeter thrown together with a radar magnet; and the triangles, an AI designed thermal flowmeter. As you can see, although it has been stated that both the EM flowmeters and the thermal flowmeters ought to be accurate to a few percent, you will notice that there is a difference in the output of at least ~6 or 8%. Therefore, one of the other of these flowmeters is obviously not living up to its expectations. Subsequent data indicated the EM flowmeters to be the more accurate.

5. Transit Time Flowmeters

Another method of measuring liquid metal flow is by using a transit time flowmeter. In this device the fluid velocity is measured by determining the time required for a disturbance to travel a known distance along the pipe. The disturbance may be introduced artificially by a sound transmitter or heater, or the speed of existing random fluctuations may be measured. These latter signals tend to be very low in amplitude with respect to background and instrument noise, hence "noise analysis techniques" must be employed. The advantages of this type of flowmeter are that simple transmitters and sensors can be designed, ideally not penetrating the pipe or vessels, and good accuracy can be obtained. The disadvantages are that the time response is characteristically slow and often, very sophisticated signal conditioning equipment is required.

B. LEVEL INSTRUMENTS

There are probably more different methods of measuring level in a sodium tank than there are methods for measuring any other liquid metal parameter. One can use the conductivity property of the fluid or, force of displacement can be measured using a float; one can measure hydraulic pressure. Sonar techniques and radar techniques can be used. Finally, the tank can simply be weighed and the tare subtracted. In practice, although there are many ways of doing it, none of the techniques have proved 100% successful. Conductivity methods will be discussed first, since the conductivity property techniques are the most commonly used.

1. Conductivity Probe

The simplest way of measuring level in a sodium tank is to use a conductivity probe; that is a conductor of some kind which is insulated from the tank and which extends into the tank. The sodium being a conductor, if the level rises above the bottom of the probe, a contact will be made completing a circuit to a light or a meter. This elementary system is illustrated in Figure 15. Unfortunately, no insulators have been demonstrated to withstand sodium or sodium vapor for reasonable periods of time although it is reported in the literature that high purity alumina has proven quite resistant to attack. Even if a material can be found impervious to the environment, the problem of condensation of the sodium, and consequent shorting of the probe remains. Therefore, this technique has not been used very successfully. However, these shortcomings can be overcome by installing the conductor in a reentrant thimble. In this configuration, a low resistance path through the thimble and tank will always exist, but since the sodium is a much better conductor than the stainless steel thimble, a large change in circuit resistance will take place when the sodium level reaches the bottom of the thimble.

2. Resistance Probe

A slight modification of the probe design allows continuous readout of level. This device, shown in Figure 16, only requires, in addition to the power lead connected to the bottom of the thimble, a voltage lead also brought to the bottom and returned to the power source through a meter. This power source can be ac or dc but, because of the low voltage high current required, it is convenient to use ac transformed down. Tracing through the schematic, it is seen that, as the sodium rises, it shorts out part of the thimble and the overall resistance in the circuit is reduced.

The voltmeter reads the voltage across the portion of the thimble not in contact with sodium which, for a constant source current is proportional to its resistance. As we have said before, resistance varies inversely with level. Ignoring the shunting effect of the tank wall and making the assumption that the resistance of the sodium is much less than the resistance of the stainless steel thimble, the voltmeter output will be

$$V_o = IR\left(1 - \frac{H_L}{L_T}\right), \qquad \text{. . . Equation 4}$$

where

V_o = output voltage
I = applied current
R_T = thimble resistance
H_L = sodium level
L_T = thimble length

Ordinarily, the assumption that the sodium resistance is much less than the thimble resistance is valid, but generally the tank shunting cannot be ignored, and the result is a nonlinear output. It can also be seen that the thimble resistance will vary with temperature for a constant level, and thus, this device will be temperature sensitive.

To avoid the shunting of the thimble resistance path by the tank, some units have been designed where the tube is installed from the bottom of the tank, as shown in Figure 17. If this circuit is analyzed it will be seen that the shunting of the tank has been avoided and Equation 4 is valid. Once again, however, this type of device is temperature sensitive for the reasons discussed previously. To avoid locating the probe in the bottom of the tank, but still retain the linear output, the so-called "J" type level probe has been designed and used widely. Examining Figure 18 it is seen that the active portion of the device is the portion of the thimble extending from the closed thimble on the right, to the bottom of the probe. The "I" section of the "J" series acts merely to support the active section in the sodium and to provide an electrical conduit. The performance will be similar then to the probe installed from the bottom, and will have a linear output but will be temperature sensitive if a constant current is applied. A substantial measure of temperature compensation can be obtained by applying a constant voltage to the probe instead of a constant current and selecting the power lead wire material, feeding the probe so that the lead wire resistance is much higher than the active thimble resistance and also of the same material as the thimble, so that the lead wire and thimble resistance will change at the same rate, assuming they are at the same temperature. Substituting these conditions into Equation 4 yields

$$V_o = \frac{V_i R_T}{R_T + R_g}\left(1 - \frac{H_L}{L_T}\right) = \frac{V_i R_T}{R_g}\left(1 - \frac{H_L}{L_T}\right)$$

$$\cong R V_i \left(1 - \frac{H_L}{L_T}\right), \qquad \text{. . . Equation 5}$$

where

V_i = input voltage

R_g = lead wire resistance.

Thus, the remaining temperature effects are secondary order geometry change effects. In actual practice, temperature sensitivities of $<1/2\%$, and accuracies of 1% have been reported.

3. Induction Probes

A second type of level device which has been fairly widely used, particularly in the Hallam reactor is the so-called induction probe. Here again, the conductivity property of sodium is utilized but utilized in a different way. Figure 19 shows a very schematic diagram of a simple induction level probe circuit. It consists of a long solenoid type coil installed in a thimble which is immersed in the sodium. The coil is fed by a source of ac and the voltage across the coil is measured. As the level of sodium increases around the coil, it will act as a shorted turn on the secondary of this coil. The result will be a reduction in the coil inductance and Q. This will show up as a reduction in the voltage out if a constant current is applied.

One of the disadvantages of this system, as with the simple resistance probe, is that with temperature, the resistance of the coil will change and the resistance of the sodium, which is shunting the coil, will change. Therefore, this output will be a function of temperature as well as level. To reduce the temperature sensitivity normally, these coils are used in a bridge circuit with a reference coil. This arrangement is shown in Figure 20. The reference coil must be located in an environment such, that the temperature of the reference coil and the active coil are nearly equal and vary together. In such a case, changes in only temperature will not unbalance the bridge and will not cause an apparent level change. This type of temperature compensated device works well for coils < 1 ft, however, a long coil probe becomes very inaccurate in terms of absolute accuracy. For instance, if a total accuracy, including temperature effects of ±0.5% can be achieved, the absolute accuracy for a 5-ft probe would be ±3 in. To avoid that kind of inaccuracy, normally long probes are designed as an assembly of individual coils, rather than one coil, and with a manual selector switch or automatic selecting systems so that only the coil, which is near the interface, is in the circuit. With a multicoil arrangement accuracies of ±1 in. or less have been obtained.

Since the induction coil thimble is immersed in the liquid sodium the coil materials must withstand the temperature and radiation environment of the fluid which, for reactor service, may approach 1200°F, gamma doses of 10^{11}R and fast neutron fluences of 10^{20}R. Obviously only inorganic materials can be used. Very good results have been obtained in reactor service (Hallam) using glass-served Constantan wire wound on a mild steel bobbin insulated with glass tape. The glass serving and tape must be carefully baked out in air prior to winding to drive out all organics, or carbonization of the organic will take place with severe degradation of insulation resustance. The Constantan conductor was chosen because of its very low temperature coefficient of resistance and high temperature capabilities. The mild steel bobbin was selected over a ceramic bobbin to obtain maximum sensitivity, although the temperature sensitivity suffered. Based on AEC-sponsored coil development work performed in the past as part of the SNAP program (Systems for Nuclear Auxiliary Power) and current coil development as part of the Zirconium Hydride Program, conductors of stainless-steel-clad copper, nickel-clad silver and possibly dispersion hardened copper may also prove satisfactory. Processes for winding, encapsulating, and curing coils of these materials have been thoroughly developed.

4. Tri-Coil Dipstick

A somewhat different type of inductive or transformer level probe has been used extensively at AI and by other; a device referred to as a dipstick or tri-coil probe. In this system an assembly of three small solenoid coils is installed in a metallic tube. The center coil is the primary, and around it are wound two secondary coils. The primary is excited with ac and the secondaries are connected in series opposition as shown in Figure 21. This whole assembly is installed in a reentrant thimble and manually positioned or servo driven to a position where the unbalance is maximized. At this point the centerline of the coil assembly will be near the liquid gas interface with one secondary coil under the surface and one above. The level is read by measuring the distance the probe extension rod is extended into the tank thimble. This device, will be slightly temperature sensitive since it is impossible for the secondary coils to be perfectly symmetrical, and changes in temperature will unbalance the coils.

5. Differential Pressure

It would be theoretically possible to measure the level of sodium as the level of many other fluids are measured, i.e., by measuring the difference in pressure between an elevation near the bottom of the tank and the cover gas. The level would be computed by dividing the difference in pressure between the cover gas and sensor by the density of the fluid. This relationship indicates one of the shortcomings of this approach, namely, that the density will vary with temperature and therefore, the device will be sensitive to temperature, (as a level sensor but not as a weight sensor). A more important shortcoming, is that it is necessary to have a dp cell which will operate with sodium and will measure rather small pressures. For instance, an inch of sodium is equivalent to 0.03 psi, so it is obvious that a very sensitive differential pressure cell is required to obtain good accuracy. The other disadvantage to this system is that the pressure device must be located in the bottom of the sodium tank or in a stand pipe, which makes for a very inconvenient method of installation and imposes difficult maintenance problems. If the fluid pressure sensor is located remotely from the tank the difference in density in the connecting line must be compensated for unless it is mounted at the same elevation as the line leaving the tank. Figure 22 illustrates the system in very schematic form. As shown it has had very little application. Actually, there would not be two pressure gages but one differential pressure cell. A modification of this scheme has, however, achieved a certain amount of success.

In the modified approach, referred to as a gas bubbler system, a standpipe is installed in the tank with its base located at the lowest level desired to be measured. Gas is bubbled through the standpipe at a low constant flow. The differential pressure between that required to establish the flow and the cover gas is a measure of the tank level. The advantage of this system is that the differential pressure cell can be located remotely from the tank and some measure of inhibition of the diffusion of sodium vapor is obtained by the purge flow. However, the control of the back diffusion of the vapor has not been complete and in time the capillary tubing between the dp cell and tank plugs with sodium and sodium oxides.

6. Miscellaneous Others

As I have mentioned before, there are a number of other devices that have been used for level indication at various times and for various installations. Mechanical floats which are linked to either pneumatic transmitters or differential transformers, and which measure either force or displacement have been used. In fact, the SCTI facility of the LMEC has one or two of these devices in operation. Apparently they have worked with some success; the problem is, of course, the classical one of operating mechanisms in sodium. Radiation absorption has been used wherein a radioactive source is located on one side of the tank and a radiation detection device is located on the opposite side and the difference in absorption of the radiation is measured. Of course, this is limited to nonradioactive tanks. Sonar devices have been used in which the interface between the fluid and the gas is detected by measuring the time it takes the sonar pulse to travel from the transmitted reflect off the surface and return or travel through the liquid and return. Finally it is perfectly possible, under proper circumstances, to measure the level of the sodium in the tank by weighing it. Once again, level will have to be calculated as a function of the density which is a function of temperature. Of course, a method of taking out the tank weight, pipe reactions and other forces must be found.

C. PRESSURE INSTRUMENTS

There is a large graveyard of abandoned pressure instruments that have been designed to operate directly in the sodium. Generally, these approaches were extensions of commercial devices which were upgraded in temperature in an attempt to meet operating temperatures. These devices where the transmitting elements are in contact with sodium or sodium vapor have failed due to: (1) plugging of cavities with oxides, (2) malfunctions of mechanical parts, or (3) failure of electrical coils because of the high temperatures or changes in the geometry of mechanical control components or in the properties of electrical components. Gas transmission systems have been used with some success; that is, a standpipe is provided in the side of a tank and a gas line transmits the pressure above the sodium level to a pressure transmitter or detector located in the cool region. Generally speaking this type of device does not work well because in time these lines plug with sodium. Cover gases, however, are regularly measured with a gas transmission system, in conjunction with a vapor trap. This type of installation has worked out fairly successfully. I have already mentioned the gas bubbler technique. Briefly, I will review for historical purposes, some of the direct immersion devices, which, as I have said, have not worked well.

Figure 23 illustrates a pneumatic transmission device. It is comprised of a flapper valve arrangement in which a flapper is mechanically coupled to the sodium pressure through a diaphragm. Gas is introduced at the supply nozzle and exhausted at the bleed nozzle. In operation, an equilibrium will be established such that the pressure above the diaphragm just equals the sodium pressure. This occurs since, if the pressure in the upper housing exceeds the Na pressure, the diaphragm will move down, opening up the flapper valve and relieving the pressure, and vice versa. The sodium pressure is read out by measuring the supply pressure. This type of transmitter, as I have said, has not worked out well. It has been quite unreliable because of the critical nature of the flapper valve, and there have been large drifts in output with temperature and time. These drifts have been due, in addition to the problems with the flapper valve, to changes in the characteristics of the diaphragm, which will affect calibration.

Figure 24 illustrates another approach to direct measurement of sodium pressure. In this device, the sodium pressure to be measured is converted into a force by a plate connected to a bellows. This force is transmitted to a cooler region by the use of a rod. The force, in turn, is converted into a displacement when reacted against by calibrated springs located in the cooler region. The displacement is measured by a differential transformer, which communicates electrically to a remote readout device. This electrical pressure sensor has suffered in the past from high variable transmission rod friction, calibration spring shifts and failure of the differential transformer coil winding. It is possible that today, with improvements in high temperature technology, that this device could be made to work, but maintainability would remain a problem.

1. NaK Filled Systems

Presently, the old reliable standby for pressure instrumentation is the use of a NaK transmission system. Schematically it is as seen in Figure 25. It consists of a fitting which is welded into the sodium system containing a single-ply or multi-ply bellows which seals off the sodium; a NaK filled capillary tube that communicates with a bellows, diaphragm or Bourdon element which transforms this pressure into an electrical or pneumatic signal. The advantages of NaK as a transmitting fluid are that: (1) the freezing point is very low — 12°F, (2) the boiling point is quite high — over 1400°F, (3) the vapor pressure is quite low — 0.7 psi at 1000°F. This is particularly important because the vapor pressure of the NaK limits the minimum range at which these units can operate: (4) a low volumetric coefficient of expansion. A 16% change in volume occurs for a 1000°F change in temperature. From these data it is seen that NaK can generally cover the pressure and temperature ranges in which we are interested. The temperature sensitivity can be held in check because of the low vapor pressure and because of the low volumetric change with temperature.

To obtain the minimum temperature sensitivity, it is desirable to limit the amount of NaK which is contained in the sensing element as compared to the NaK located in the transmission system and in the Bourdon element where temperature changes are low. Thus, changes in the volume of the NaK located in the sensor will not have a very significant effect on the overall volume. This is accomplished by the use of a nested double diaphragm. In order that the change in spring rate of the bellows will not be reflected in the output, it is desirable to have the sensor diaphragm spring rate rather low compared to the spring rate of the Bourdon element. This also insures that the change in volume of NaK in the sensor element, as the pressure range is traversed, will be small, and the spring constants of the sensor element bellows will not influence the output greatly. If these techniques are adhered to it is possible to achieve <1% full range temperature shift and obtain accuracies in the range of a few percent.

Problems in the use of the NaK filled systems have been primarily those of evacuating and filling with clean NaK, and welding. Of course, the routing of NaK filled armored capillary tubes, in and out of galleries, increases the installation costs and presents some hazard. A major practical problem has been in getting companies interested enough to build these things. Because the total requirement for sodium instruments has been rather low and fabrication techniques necessarily exacting, many of the companies who are competent to fabricate the sensors are not interested in supplying instruments for the low quantities that are normally required. AI has gone through two or three suppliers and, at this point, I am not certain how many suppliers are interested in furnishing these kind of units; particularly to RTD specifications. I believe the LMEC is acquiring these data. Regarding the electrical or mechanical transmitting device, strain gages, linear differential transmitters, pneumatic flapper valves and direct mechanical linkages have been used with bellows, diaphragms, and Bourdon elements.

Figure 26 shows a typical differential pressure transmitter that has been used very successfully on the SCTI. It is a modification of a commercial double bellows dp cell. As you can see, it has two bellows which are mechanically coupled to each other, and whose outsides are surrounded with NaK in separated cavities. These cavities are connected to the NaK filled capsules through capillary tubes and any difference in pressure between these two capsules results in motion of the linkage. That motion, in turn, is coupled to a gear sector which transmits the rotary motion to a shaft which can be coupled to an indicator, a pneumatic transmitter, or to an LVDT or other type of electrical transducer.

2. Force Balance Type Miniature Pressure Detector

Figure 27 shows a sketch of a miniature type force balance pressure transducer that has been designed by Atomics International for measuring pressures in fuel elements and in-pile experiments at temperatures up to 1500°F. It operates on the principle of direct pressure balance. The pressure to be measured causes a force to be exerted through a bellows on a coupling disc causing the disc to move upward. A balancing pressure is applied to the coupling disc from an external source through an opposing bellows. This external pressure is adjusted so that a contact between the coupling disc and an insulated thermocouple is just made. When this condition exists, the balancing pressure is read. The thermocouple also provides a temperature readout. Because of the basic simplicity of this device it has operated quite successfully at very high temperatures for at least short periods of time.

D. TEMPERATURE INSTRUMENTS

Generally speaking the techniques that are used in temperature measurement are not different for sodium systems from the techniques which are used in any other high temperature application, with the exception that in sodium systems the conductors must be completely sheathed so that they are not shorted out by the sodium. Of the many potential techniques which could be used in sodium systems, only two have had any wide spread application. One is the use of the thermocouple, the other is the use of RTD's. Of the two, thermocouples have had the widest application.

Figure 28 illustrates the operating temperature range of a number of temperature measuring devices. The shaded portion indicates the temperature range of interest. It is seen that except for copper-Constantan, most of the conventional thermocouple materials such as iron-Constantan, chromel-Constantan, and chromel-alumel are suitable, although iron-Constantan is marginal, and thus sees little use. Platinum platinum-rhodium would be suitable but appears to be less stable in a long term high temperature radiation environment than chromel-alumel or chromel-Constantan. The output of tungsten-rhenium is lower than the others, and at temperatures below 2000°F, there is little incentive to use refractory materials. Of the resistance devices, only platinum will meet the temperature requirements. I will discuss the testing of some of these units shortly. The temperature range of filled systems is too low for most applications and they suffer from long response times. Pyrometry and visual techniques are limited to very special applications.

1. Thermocouples

Figure 29 is a view of a typical thermocouple for high temperature application and applicable for sodium use. As you see, it contains a metal jacket, usually stainless steel, but sometimes Inconel or other material with an insulator, usually MgO, spacing and insulating the thermocouple material. The magnesium oxide has been compressed or swaged inside the sheath. Normally, thermocouple fabrication will start with material that is anywhere from two or four times the diameter of the final resulting sheath.

There are two basic methods of terminating thermocouples. One method is the grounded junction in which the wires are brought out to the end of the thermocouple and a plug weld is made which incorporates the thermocouple wires and the sheath. This kind of installation will provide relatively fast response, and in some circumstances, may be more accurate than the type of installation in which the thermocouple junction is made below the plug and is electrically insulated from the thermocouple tip. This second type or junction, shown on the right in Figure 29, has the advantage of greater reliability, particularly in the thermal cycle mode. This, because differential expansion between the conductors and the sheath will not impose direct stress on the conductors at the junction. An electrically insulated junction also provides greater flexibility in the readout instrumentation. Figure 30 indicates the limits of error that are available from commercial thermocouples. For chromel-alumel, it is seen that above 530°F temperature, the accuracy of commercial stock is ±3/4% of reading. It is possible to obtain premium stock in which the accuracy would be ±1/4%. If greater accuracies are required, then it is necessary to calibrate each individual thermocouple. Probably, the best transfer accuracy that can be obtained would be 2 or 3°F.

2. RTD's

As I mentioned before, resistance thermometer devices, or RTD's, have had a certain amount of application in liquid metal systems. AI has used them to measure the inlet-outlet temperature at Hallam, and more recently we have designed some units for use in controlling the reflector drums in the SNAP reactors, and in particular, the SNAP 8 reactor. Figure 31 represents the specifications for that particular RTD. We were shooting for an accuracy of ±4 °F with a maximum operating temperature of nearly 1400 °F so, percentage-wise that's very small. We were attempting to obtain a 12,000-hr life and 5 sec response time. Also, a drift rate after 1000 hr of 36 μ-ohm/hr and a total drift rate in 12,000 hr of 160 Ω-ohm. 50 Ω-ohm was equivalent to $\sim$1 °F, so this is about 3 °F of drift in 12,000 hr. We were unable to achieve that kind of performance.

Figure 32 illustrates what those devices look like. They were bent so that they could be welded into the pipe lines. The probe consisted of an outer sheath of stainless steel and an inner sheath of platinum inside of which was contained the platinum element bundle. The individual elements were made up of platinum inside of which was contained the platinum element bundle. The individual elements were made up of platinum coils, and several conductors were brought out so the unit could be used in a three-wire bridge circuit.

Figure 33 represents actual performance of a number of RTD's plotted against thermocouples. Shown is a plot of the drift in °F at 1300° vs elapsed time, out to 10,000 hr. From this curve it can be seen that at least for the first 8,000 hr, RTD's after initial drift were considerably more stable than some of the more exotic thermocouple materials. However, chromel-alumel thermocouples turned out to be much more stable than the RTD's, particularly beyond 8,000 hr. We have also had problems in failure of these devices after a number of thermocycles. We were never able to meet the 160 Ω-ohm total drift that we were attempting to meet on the SNAP 8 program, and unfortunately, we have not been able to continue that development program.

E. LEAK DETECTORS

Because of the potential hazard to personnel, which could result from leakage of sodium out of piping and equipment in exposed secondary systems, and the effect on system performance in primary systems, most sodium installations have incorporated some form of leak detector. These devices are in two basic forms. Detection of leaks in piping is usually attempted by installing insulated conductors directly below the pipe such, that they will be shorted out when contacted with sodium. The conductors are usually separated and insulated with ceramic beads, although glass braided insulation has also been used. To direct the flow of the sodium to the conductor/bead assembly, shim stock is wrapped around the pipe under the insulation. This type of assembly has proven fairly effective in detecting leaks when they have occurred, but many installations have been plagued by erroneous indication of shorts due to shorting of the conductors on the shimstock, or pipe. By proper design of beads and site installation and inspection techniques, false indications should be minimized.

The second type of leak detector used in reactor cavities, pump heater cavities and the like, is a conductivity probe. These probes are ordinarily made up of mineral insulated cables containing one or more conductors or made up with thermocouple cables. It is necessary that the ends be sealed to prevent entrance of moisture during installation which could later give a false indication of a short. Since these units are not normally exposed to sodium vapor, the sealant need not be resistant to sodium vapor. In fact, operation will be enhanced if the sealant is attacked by sodium or sodium vapor. The seal must, of course, withstand the temperature environment and thus generally, only inorganics can be used. When properly made these probes have performed very reliably. Sketches of both types of systems are shown in Figure 34.

F. MISCELLANEOUS INSTALLATION DETAILS

1. General

Each type of instrument and application will present its own peculiar installation requirements, however, there are a few practices and considerations which have general application, as noted here.

a. Containment

Pressure pickups, integral EM flowmeters, level thimbles and some types of thermocouple wells will pierce the primary containment of the sodium system they monitor. Thus, the codes and standards which apply to the pipes, vessels, and equipment must be applied to these instruments. This may present some problems, as for instance, a NaK filled bulb where the containment may consist of a 0.005-in. stainless steel diaphragm backed up by a 0.080-in. capillary tube wall. Similarly, containment criteria may impose difficulty in obtaining desired response times in immersion thermocouples.

b. Capillary Lines

Filled systems must be factory filled with NaK, sealed and calibrated. This means that the capillary tubing which is invariably armored, and the transmitter must be carefully protected during sensor installation, then routed out of pipe galleries through a bulkhead seal. This operation requires careful planning in the design of the gallery seals and tubing installations.

c. Wiring

It goes without saying that high temperature and/or radiation resistant wiring is required to feed the electrical type pickups. This implies the use of either mineral insulated cable or inorganically insulated wire, the later usually a glass or asbestos insulated, nickel-plated copper. The MI cable is more rugged, but expensive, and imposes sealing and termination problems. The inorganic insulated cable is subject, initially, to moisture pickup and would be damaged if unprotected in the event of contact with sodium or sodium vapor.

d. Redundancy

Because of the inaccessibility of most instrument installations, redundant installations are often made. In the case of flowmeters, this usually takes the form of redundant electrodes. The approach with pressure instruments is generally to locate sufficient sensors in a given loop so that the pressure at any point in the loop can be inferred from other sensors if one unit is lost. Direct redundancy is applied for level detectors in critical applications, such as the reactor tank. The same applies for thermocouples.

2. Electromagnetic Flowmeters

1) Small flowmeter magnet assemblies are generally supported directly on pipe. Large flowmeter magnets require independent support. Vibration of the magnet relative to the pipe will cause output noise.

2) It if is desired that flowmeter detect gas bubbles, optimum location of electrode axis is vertical. This may conflict with optimum location for minimum elbow noise.

3) Ordinarily, unshielded twisted pairs are adquate as lead wire. Where EMI is high, shielded wire may be required.

4) A thermocouple is usually installed on magnet face for correcting magnet flux density.

3. Level

1) If "J" tube is used, the excitation transformer is generally located at the first accessible spot. Twisted shielded wires are usually used for output.

2) On inductance probes, twisted shielded wire is used throughout.

4. Pressure

1) To avoid trapping gas, or collecting solids, the sensor is ordinarily side-mounted.

SODIUM INSTRUMENTATION REVIEW

- ABSOLUTE CONTAINMENT
- HIGH TEMPERATURE – POSSIBLY RADIATION
- MAINTENANCE DIFFICULT – REMOTE READOUT GEN. REQUIRED
- AVOIDANCE OF PLUGGING

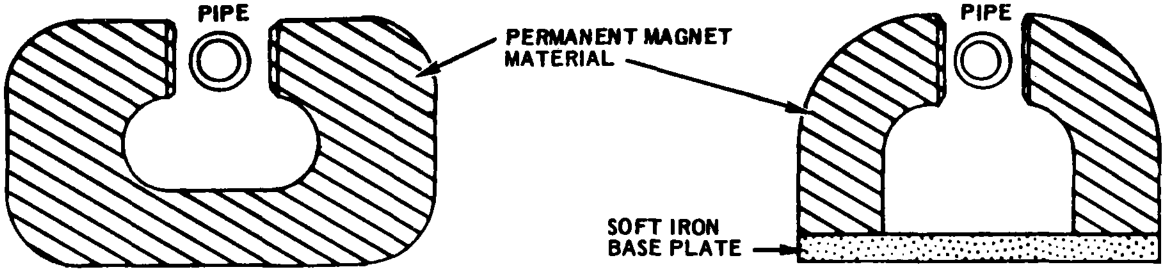
70-MA1-48-295

E/M FLOWMETERS

- PERMANENT MAGNET MOST WIDELY USED
- E = KBLV (BUT PIPE SHUNTING)
- SIMPLE CONSTRUCTION
- CONVENIENT ELECTRICAL OUTPUT
- GOOD LINEARITY
- LOW PRESSURE DROP

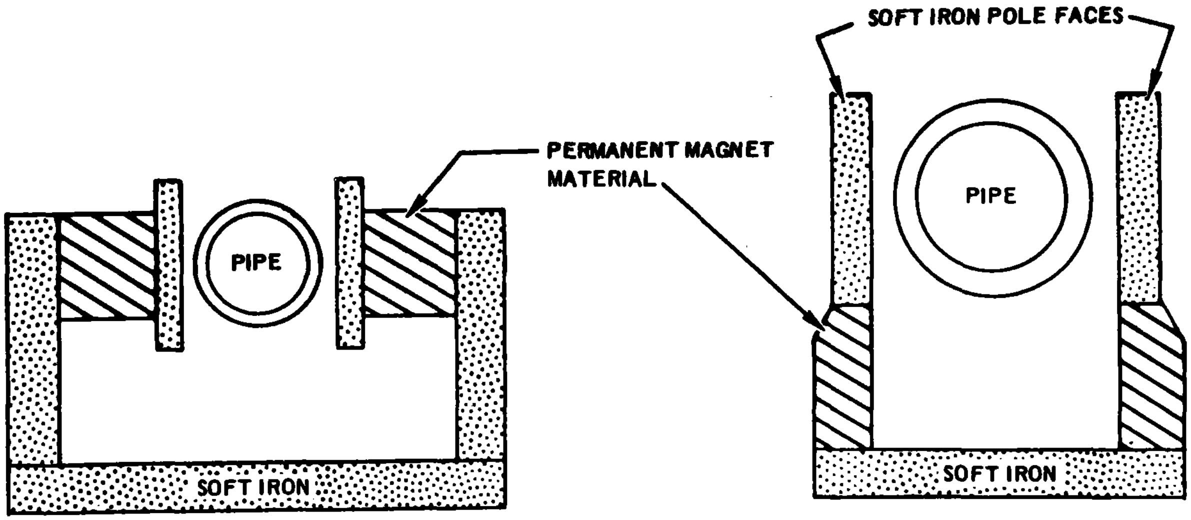
70-MA1-48-296

FLOWMETER MAGNET CONFIGURATIONS



(a) "C" MAGNET

(b) "HORN" MAGNET



(c) MAGNET ASSEMBLY

(d) MAGNET ASSEMBLY

70-MA1-48-379

E/M FLOWMETER OUTPUT

$$\boxed{E = \frac{Q \times BK_1K_2K_3}{3162dK_4}} \qquad \text{EQ. 1}$$

Q = FLOWRATE (gpm)
E = OUTPUT SIGNAL (Mv)
d = PIPE ID (in.)
B = FLUX DENSITY (gauss)

K_1 = PIPE WALL SHUNTING FACTOR $= \dfrac{2dD}{D^2 + d^2 + \frac{\rho f}{\rho W}(D^2 - d^2)}$

D = PIPE OD $\frac{\rho f}{\rho W}$ = RATIO OF RESISTIVITIES

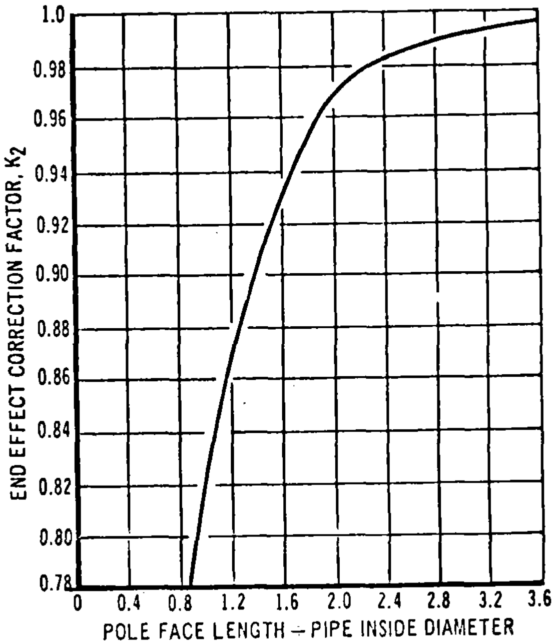
K_2 = END EFFECT FACTOR (SEE CURVE)

K_3 = MAGNET TEMPERATURE FACTOR (SEE CURVE)

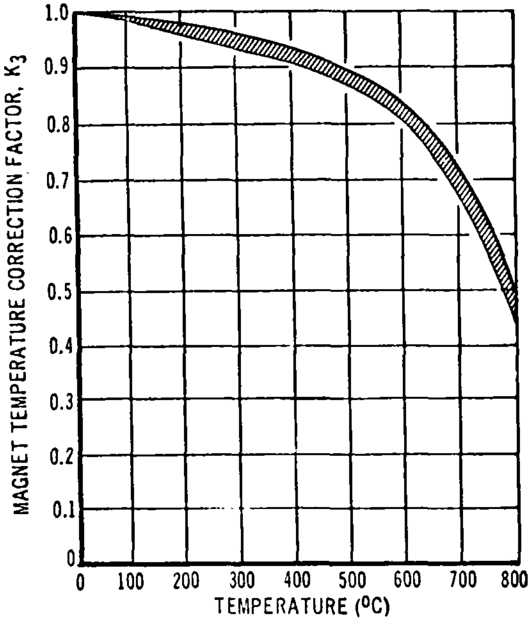
K_4 = PIPE EXPANSION FACTOR $= 1 + \gamma\,(t - to)$

70-MA1-48-297

E/M FLOWMETER CORRECTION FACTORS



END EFFECT CORRECTION



MAGNET TEMPERATURE
CORRECTION

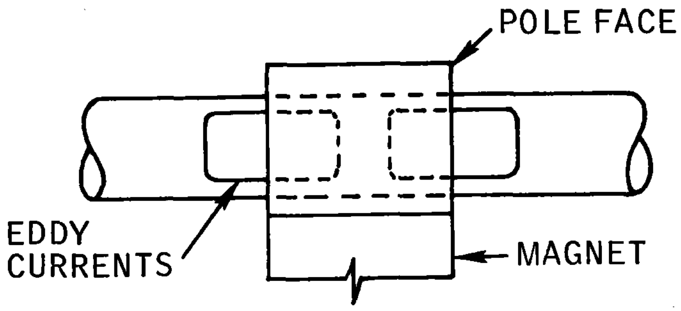
70-MA1-48-342

CALIBRATION SUMMARY

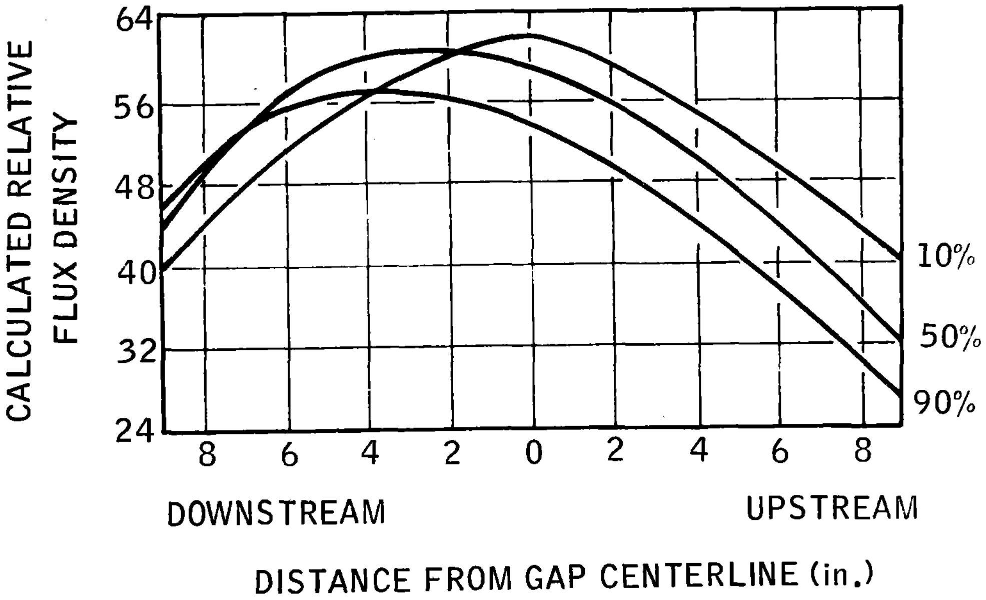
SIZE (in.)	CALIBRATION (Mv/gpm)	FLUX DENSITY (gauss)	CALCULATED (Mv/gpm)	DIFFERENCE (%)	SODIUM TEMP (^{0}F)
1	1.016	3830	1.03	-1.36	450
1	0.983	3830	1.01	-2.67	960
2	0.1565	1180	0.16	-2.19	450
2	0.1595	1180	0.1572	1.46	960
3	0.110	1205	0.108	1.85	400
3	0.109	1205	0.1075	1.4	700
3	0.109	1205	0.107	1.87	1000
6	0.0452	934	0.415	8.9	500
6	0.0448	934	0.0412	8.75	1000
14	-	277	0.00544	17.5	400
14	-	277	0.00543	3.71	700
14	-	277	0.00542	7.19	950

70-MA1-48-298

FLUX DISTRIBUTION



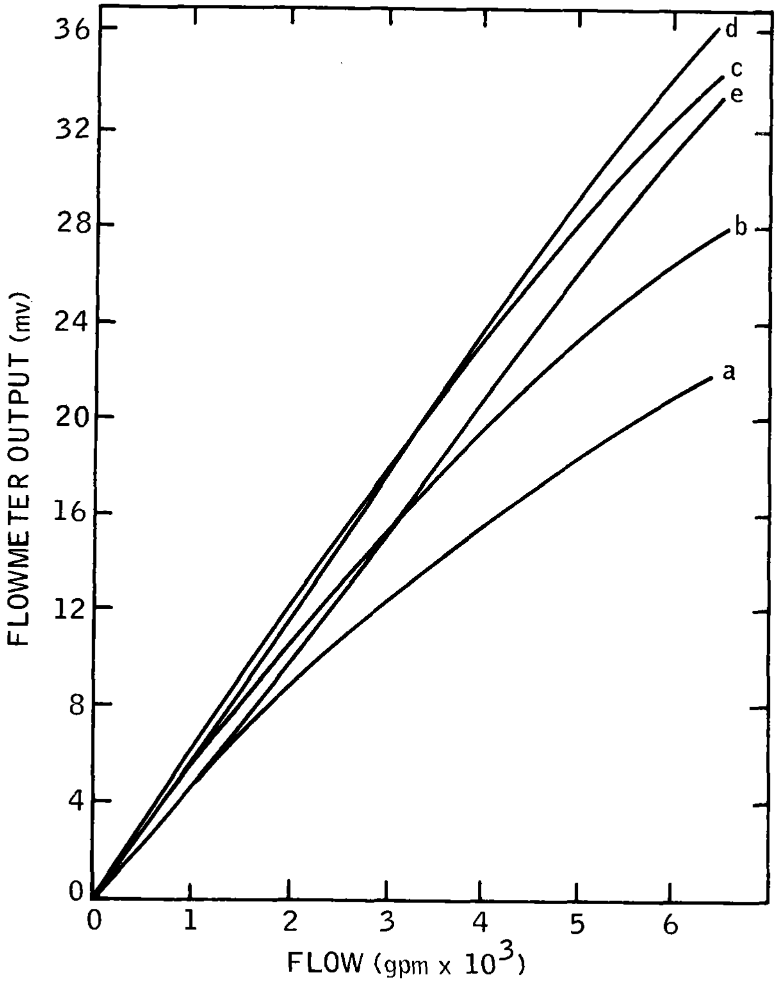
EDDY CURRENT PATHS

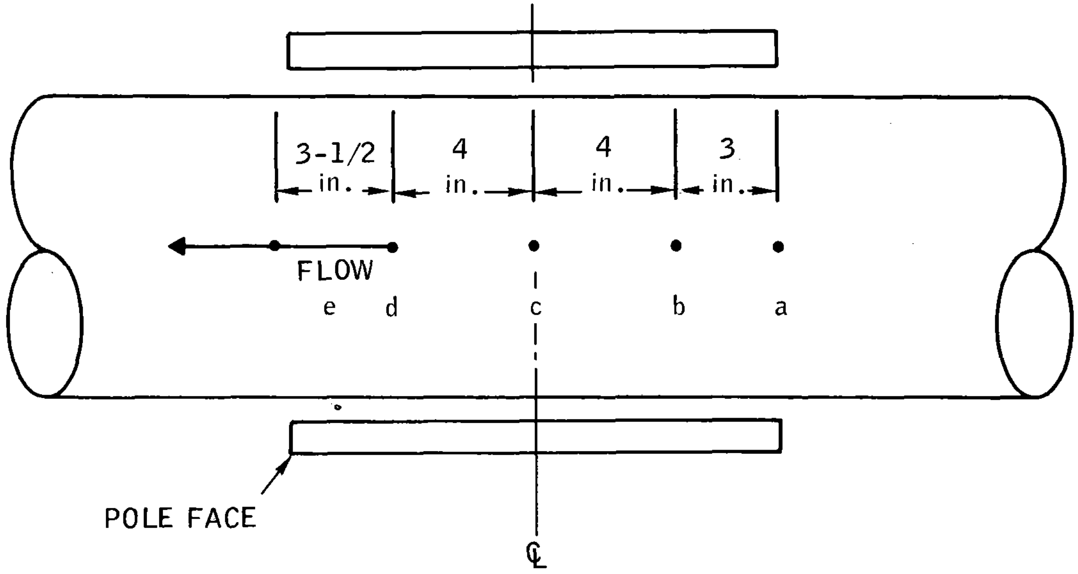


RESULTING FLUX SHIFTING

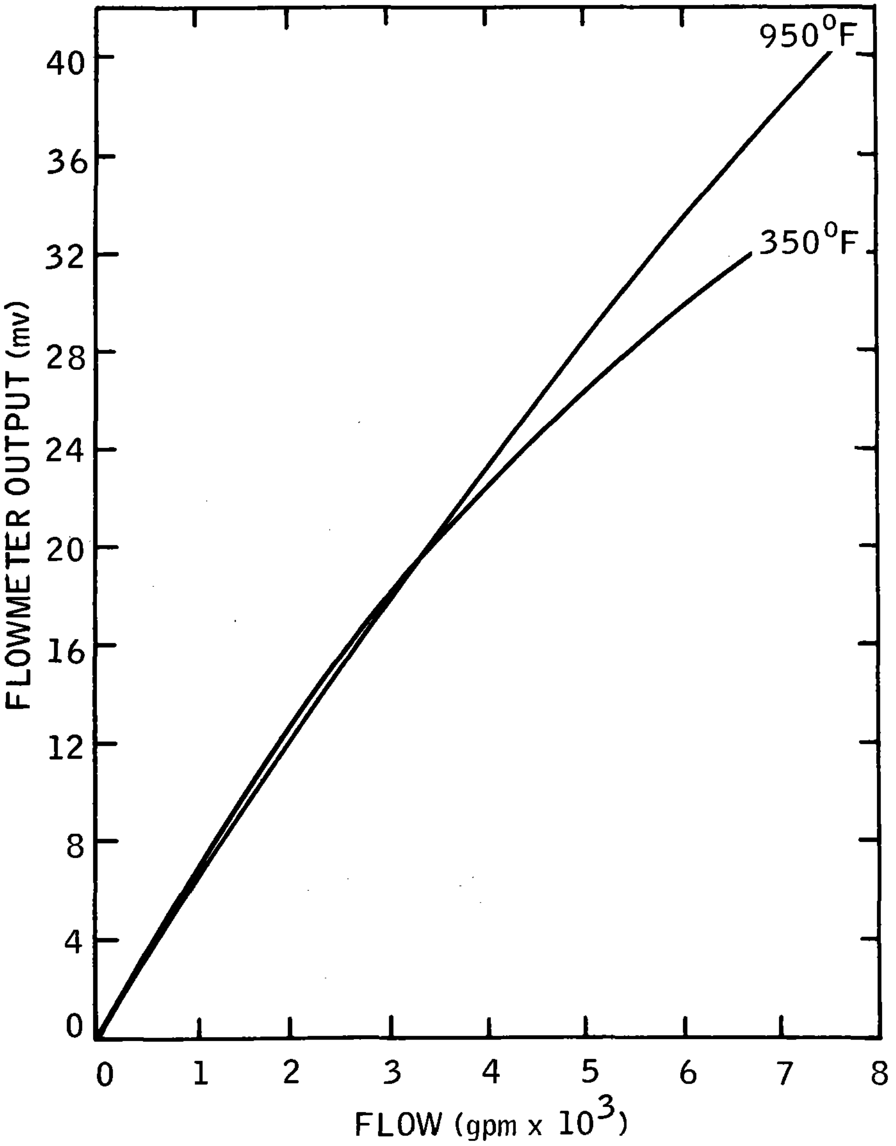
70-MA1-48-299

COMPARISON OF FLOWMETER OUTPUTS FROM FIVE ELECTRODE LOCATIONS





COMPARISON OF FLOWMETER OUTPUT FROM CENTER ELECTRODES AT 350° AND 950°F

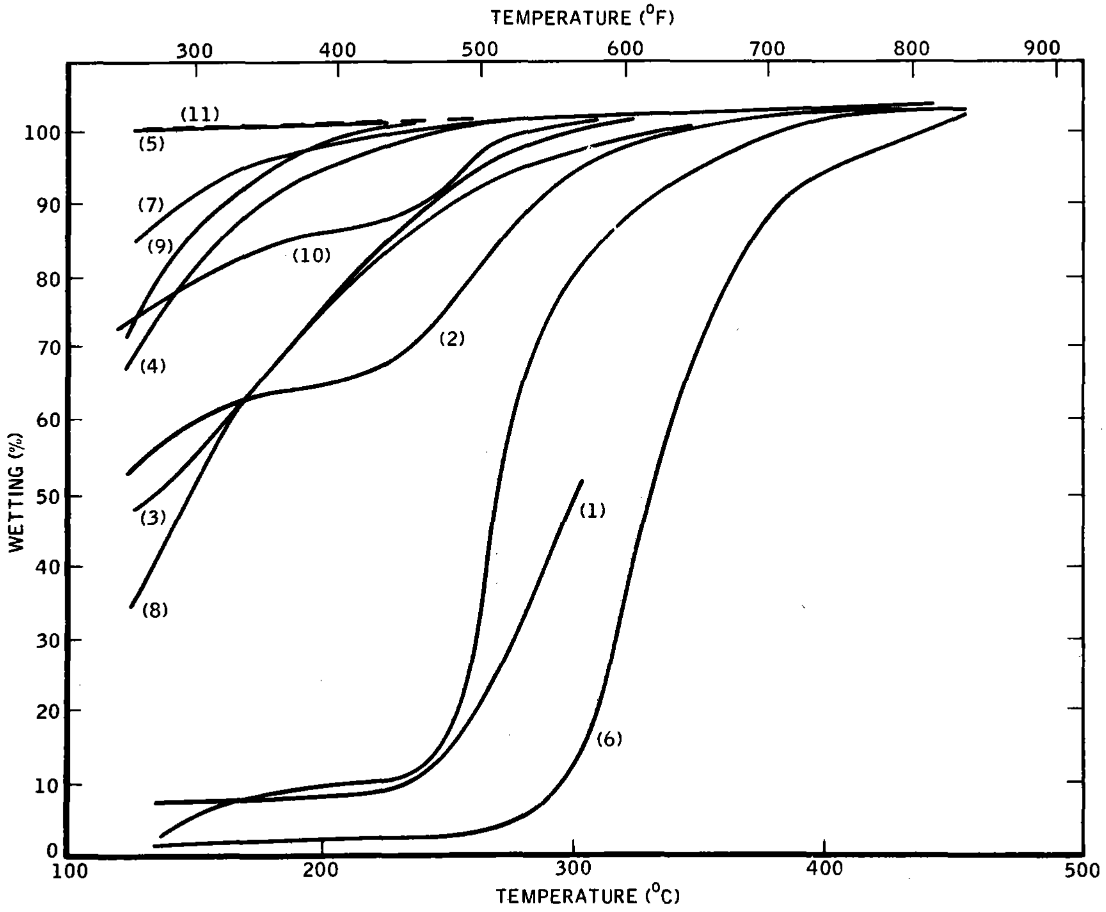


9-D1-129-86

E/M FLOWMETER

- RECALIBRATION REQUIRES MEASURING OF FLUX
  - HALL PROBE – FLIP COIL + BALLISTIC GALVANOMETER
- ELECTRODES MATCHED TO PIPE
- PIPE WETTING REQUIRED
- SHORT TIME CONSTANT – FLUID NOISE

WETTING SPEED



1 Specimen tested as cut from pipe (untreated).
2 Same as 1 after 19.5 hr at room temperature.
3 Same as 1
4 Treated; scrubbed with 60% trisodium phosphate, rinsed with H_2O, and evacuated to dryness.
5 Treated; filled with 50% NaOH (150-160°F) for 0.5 hr, rinsed with H_2O and evacuated to dryness.
6 Treated; filled with 3% H_2SO_3 for 30 min, rinsed with H_2O and evacuated to dryness.
7 Treated; electropolished, electrolyte $6H_3PO_4$-$2H_2O$ by weight. Current density 3 amp/in.^{2} for 30 min.
8 Same as 5
9 Same as 4
10 Treated; filled with 3 Hcl:1 HNO_3 (Aqua Regia) for 5 min, rinsed with H_2O and evacuated to dryness.
11 Same as 10

70-MA1-48-301

A C FLOWMETERS

VOLTAGE GENERATOR TYPE

- EASILY AMPLIFIED SIGNAL
- WELL REGULATED INPUT REQUIRED
- FREQUENCY CRITICAL
- TEMPERATURE SENSITIVE
- COIL TEMPERATURE LIMITATIONS

70-MA1-48-302

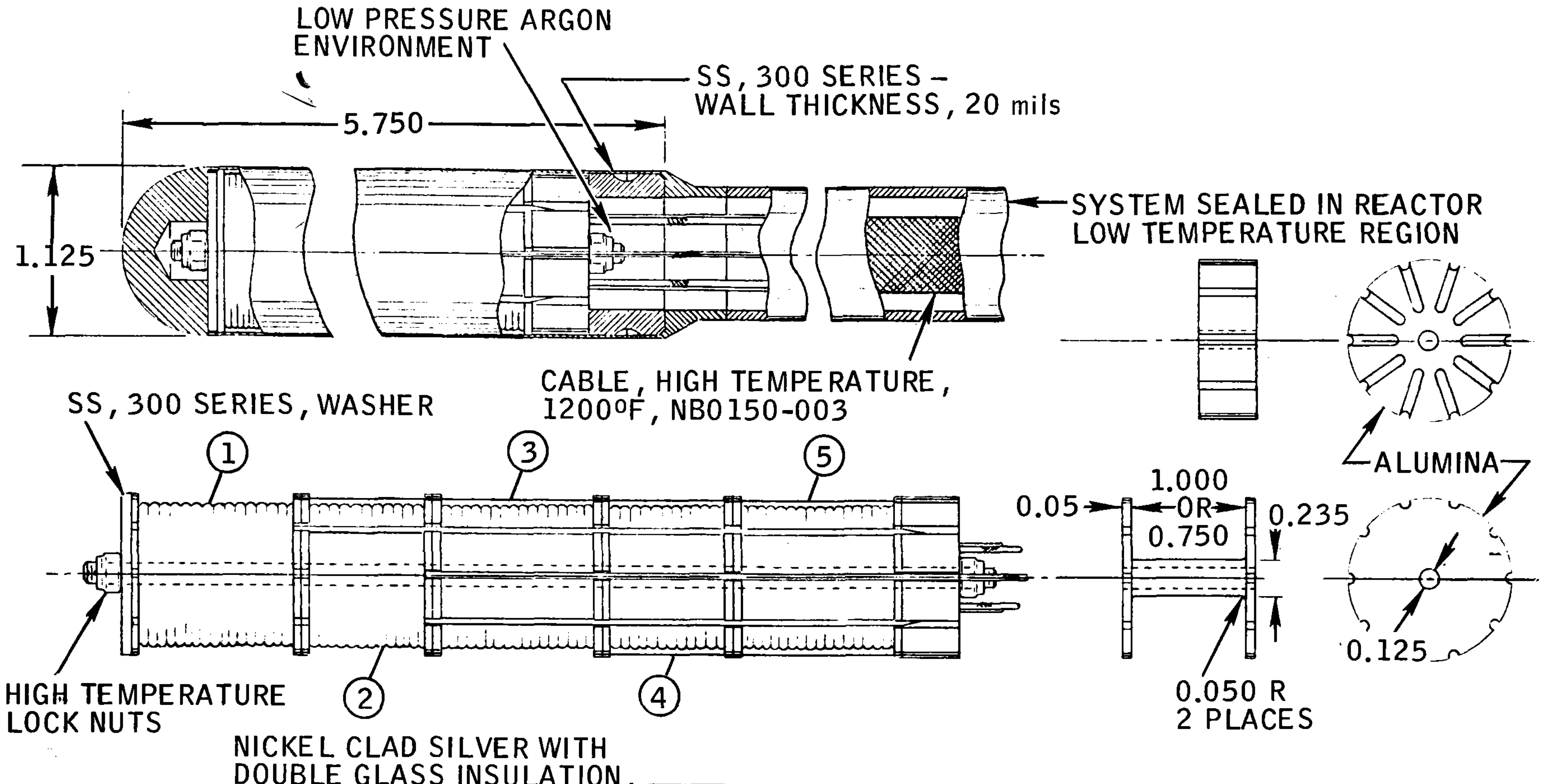
A-C FLOWMETERS

FLUX DISTORTION TYPE

- EDDY CURRENT
  - LIMITED IN PIPE SIZE
  - OUTPUT CAN BE HIGH AND LINEAR
  - TEMPERATURE SENSITIVE
  - HIGH TEMPERATURE COILS
- "E" COIL
  - SENSITIVE MAINLY TO SURFACE FLOW
  - HIGH TEMPERATURE INSULATION

70-MA1-48-303

CONCEPTUAL DESIGN FBR EDDY CURRENT FLOWMETER

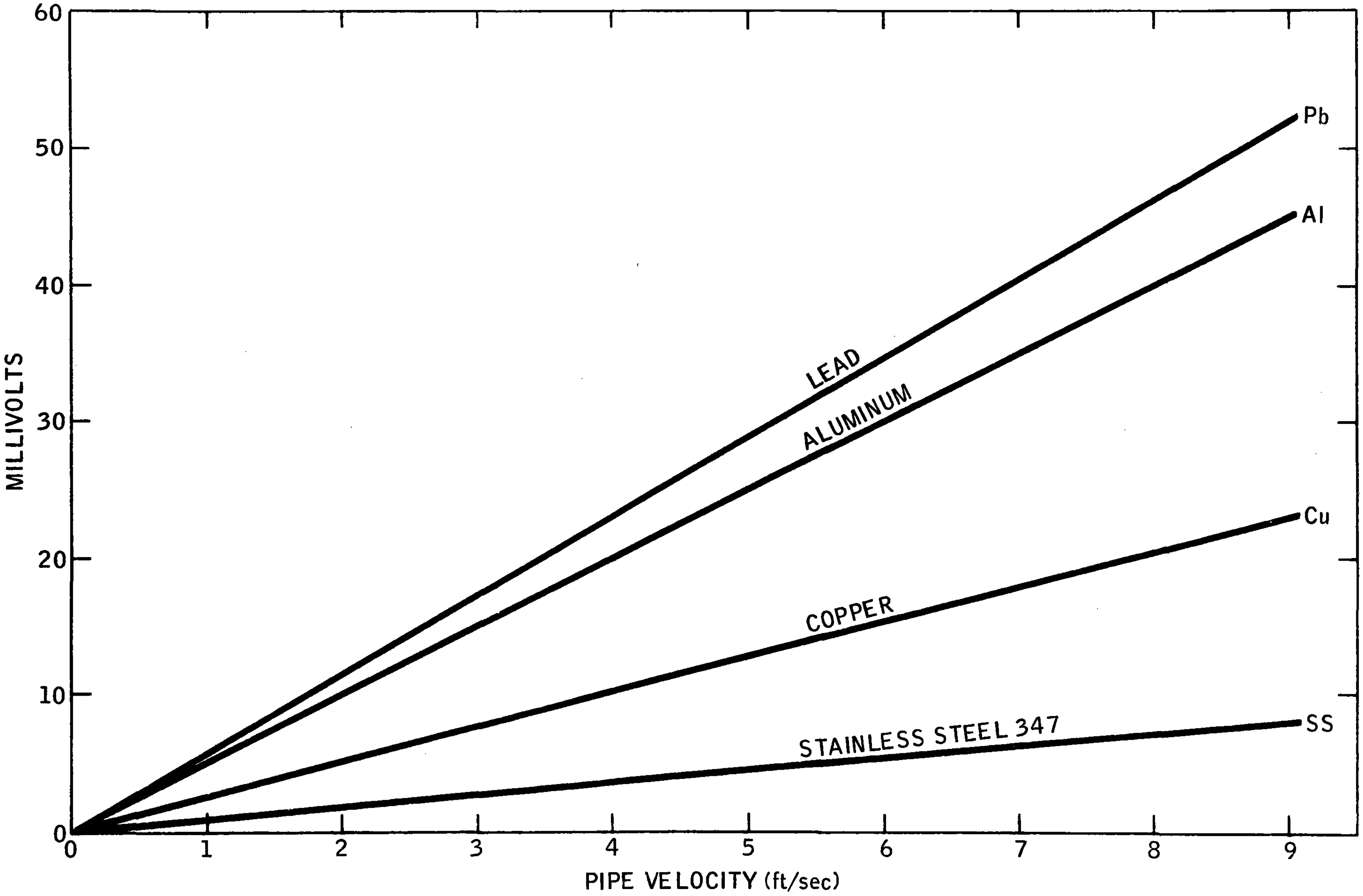


COIL NO.	AWG	TURNS	Ω 20°C	MH	Q	WIRE DIAM.
1, 3, 5	28	600	7.70	1.78	0.580	0.0263*
2, 4	32	865	27.50	4.25	0.388	0.01865*

*DIAMETER INCLUDES SLURRY DEPTH OF 15 mills. OTHER COIL DATA BASED ON TEST COILS WOUND WITH DOUBLE SILOTEX-180C AWG 24 AND 28.

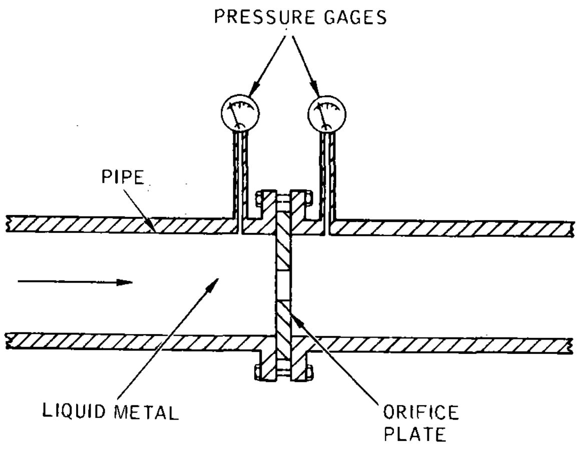
9-D1-129-89

TYPICAL OUTPUT vs PIPE VELOCITY SIMULATED FLOW METER

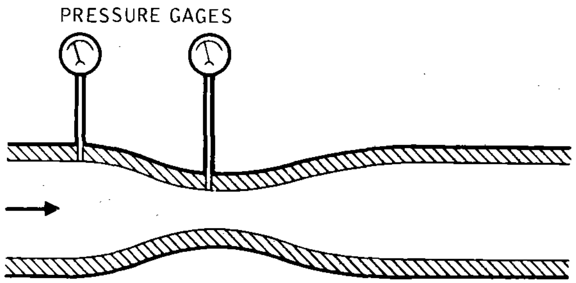


9-D1-129-90

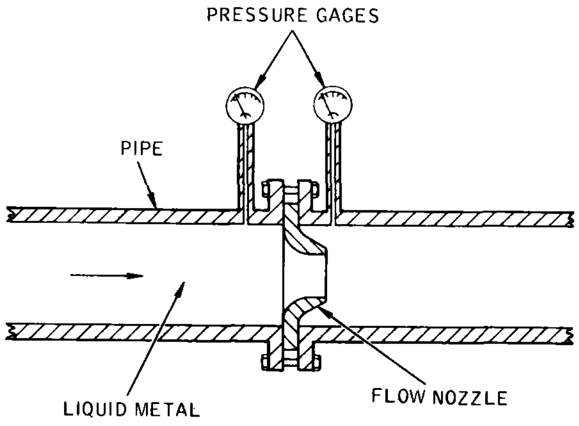
DIFFERENTIAL HEAD DEVICES



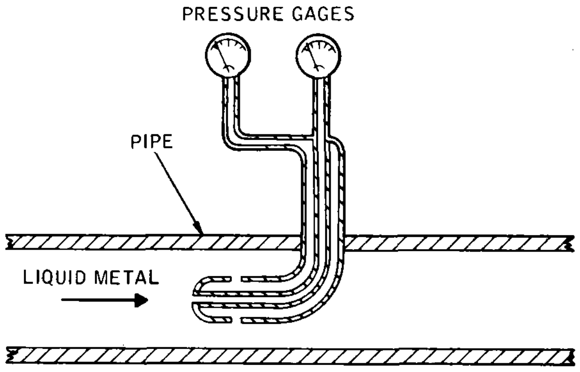
Orifice Plate Flowmeter



Venturi Flowmeter



Flow Nozzle Flowmeter



Pitot Tube Flowmeter

DIFFERENTIAL HEAD DEVICES

- VENTURI – ORIFICE – FLOW TUBE
- ORIFICE: $Q = CA\sqrt{\frac{2g\,\Delta\rho}{D}}$ EQ. 2

  C = ORIFICE CONSTANT
  A = ORIFICE AREA
  D = FLUID DENSITY
  Q = FLOW RATE
- USE LIMITED BY

  dp CELL LIMITATIONS

  HEAD LOSS

  TEMPERATURE DEPENDENCE - DENSITY/GEOMETRY
  (~10% 300-1200°F)

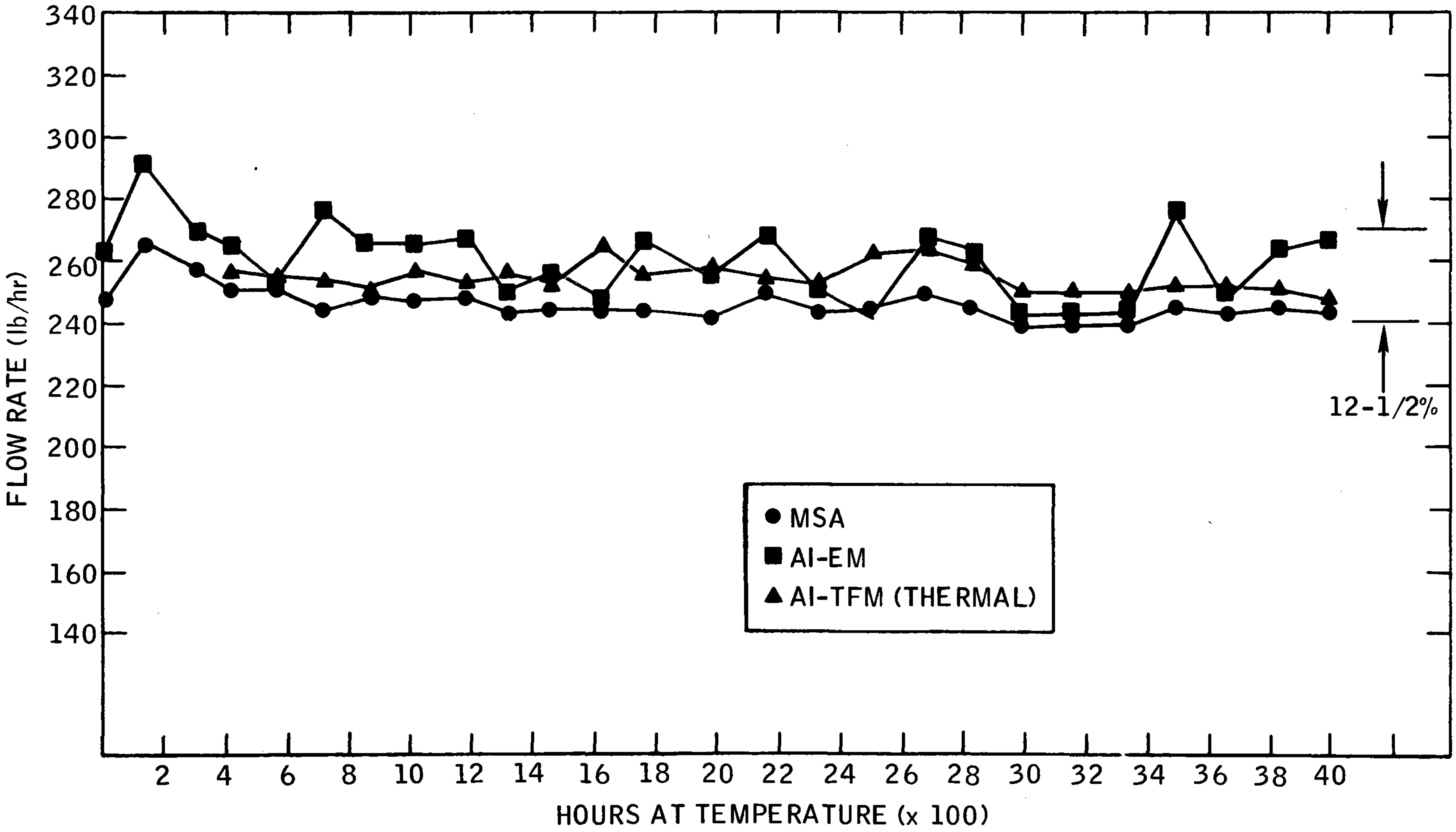
70-MA1-48-315

THERMAL FLOWMETERS

- $W = \frac{Q_i - Q_o}{C \Delta T}$ EQ 3
  - W = MASS FLOW RATE
  - Q_i = HEAT INPUT
  - Q_o = HEAT LOSS
  - C = SPECIFIC HEAT
  - T = TEMPERATURE RISE
- SMALL LINES ONLY OR EXCESSIVE POWER
- TEND TO BE NOISY
- DEPENDS ON CONSTANT SPECIFIC HEAT (1-1/2%, 400-1000^{o}F)
- NO HEAD LOSS
- ESTIMATED PROBABLE ERROR OF ± 2% NOT MET

70-MA1-48-316

TE TEST MODULE FLOW DATA



70-MA1-48-317

LEVEL INSTRUMENTS

WIDE VARIETY OF APPROACHES

- ELECTRICAL CONDUCTIVITY
- ELECTRICAL INDUCTANCE
- DIFFERENTIAL PRESSURE
- FLOAT – FORCE OR DISPLACEMENT
- RADIOACTIVITY ABSORPTION
- SONAR
- WEIGHT

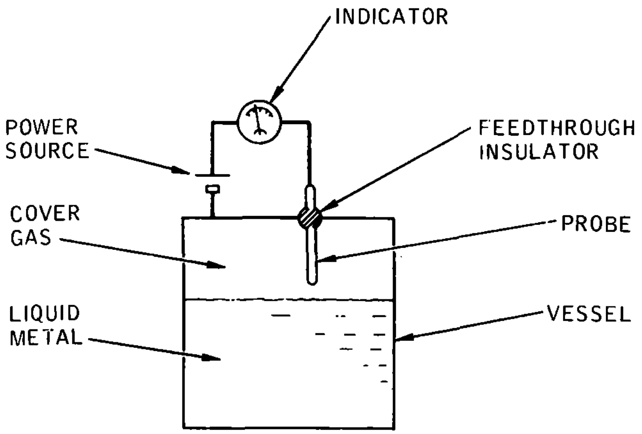
70-MA1-48-318

LEVEL INSTRUMENTS

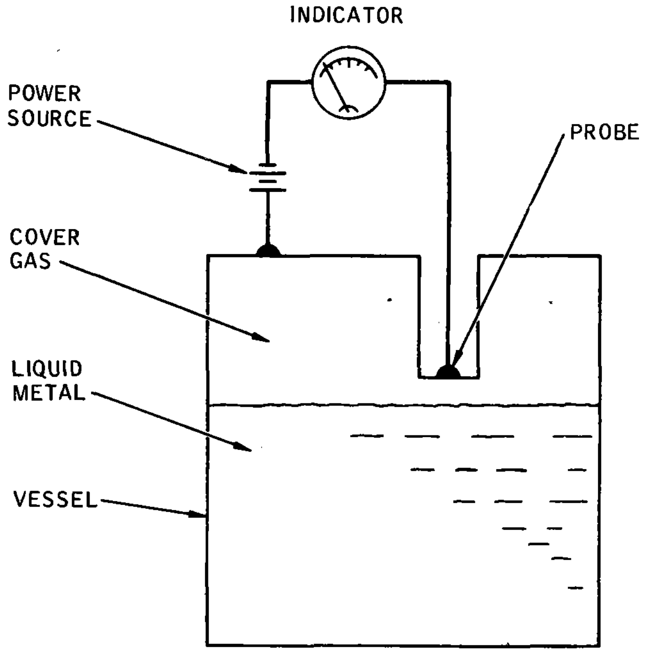
- CONDUCTIVITY PROBE
  - INSULATOR ATTACK
  - CONDENSED SODIUM
- CONTINUOUS RESISTANCE
  - WETTING REQUIRED
  - TEMPERATURE SENSITIVITY
  - LINEARITY

70-MA1-48-319

CONDUCTIVITY TYPE LEVEL PROBES



Level Probe

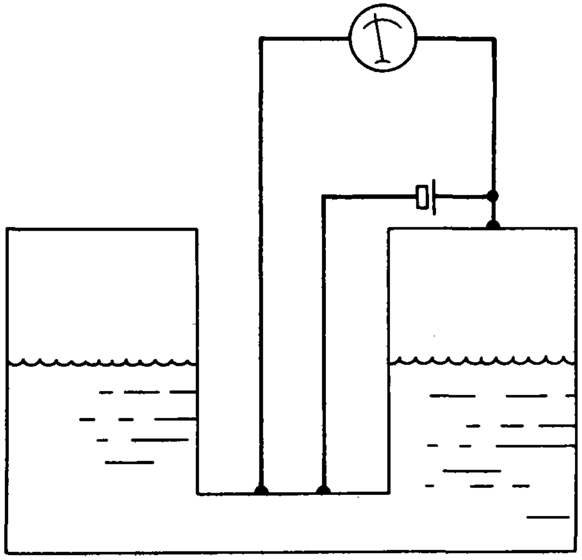


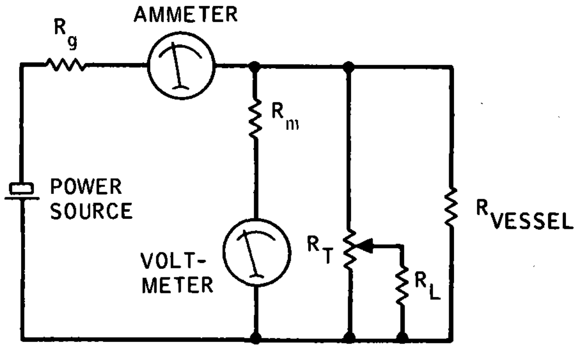
Level Probe,
Thimble Type

70-MA1-48-320

CONTINUOUS RESISTANCE PROBE

TOP MOUNTED



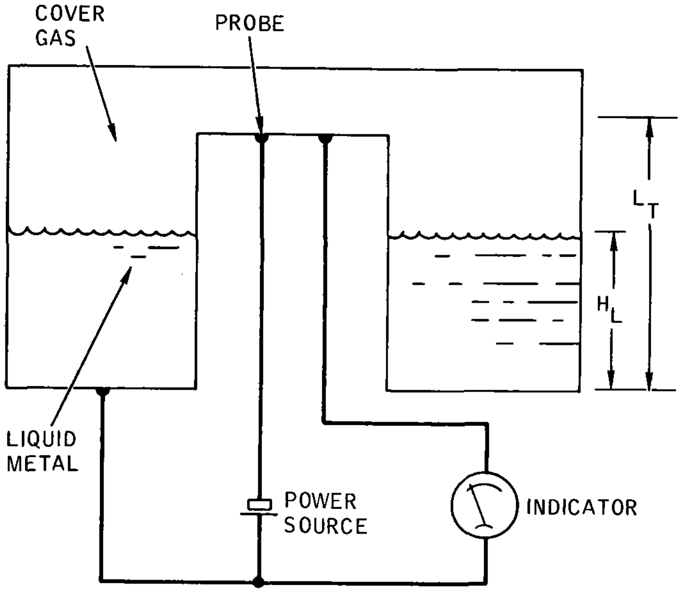


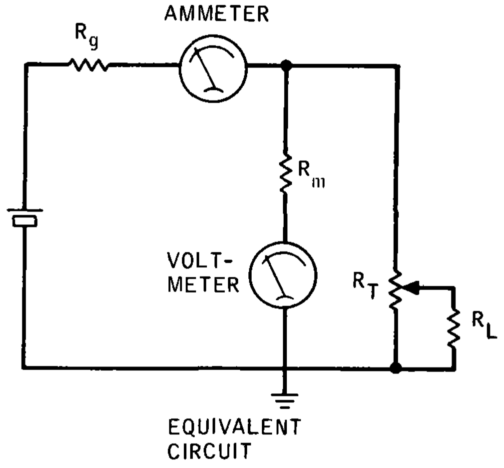
EQUIVALENT
CIRCUIT

70-MA1-48-321

CONTINUOUS RESISTANCE PROBE

BOTTOM MOUNTED





V_o = OUTPUT VOLTAGE

R_n = THIMBLE RESISTANCE

I = APPLIED CURRENT

H_L = SODIUM LEVEL

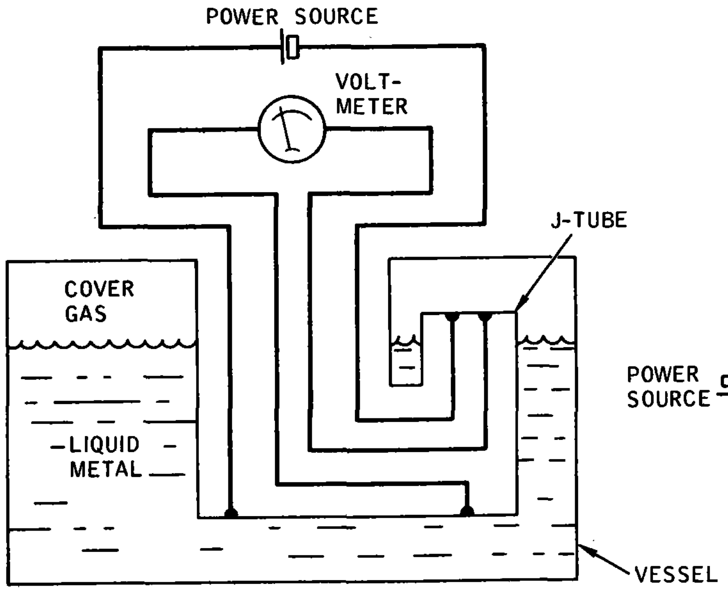
L_p = THIMBLE LENGTH

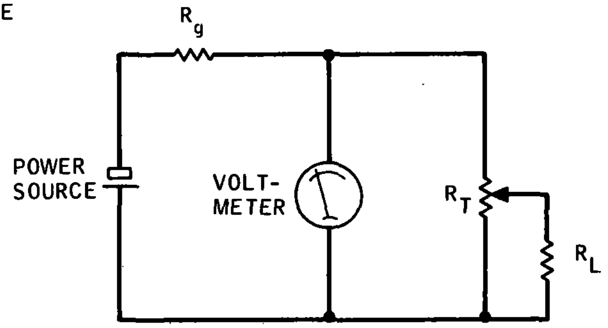
$$V_o = IR\left(1 - \frac{H_L}{L_T}\right)$$

70-MA1-48-322

CONTINUOUS RESISTANCE PROBE

"J" TUBE





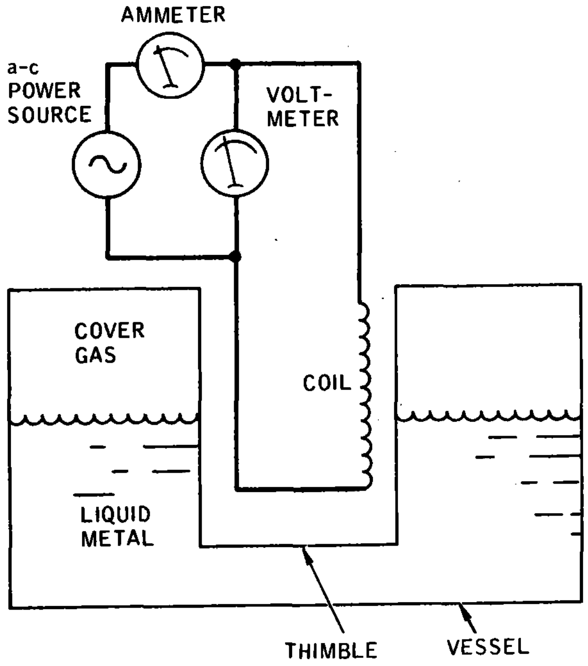
70-MA1-48-323

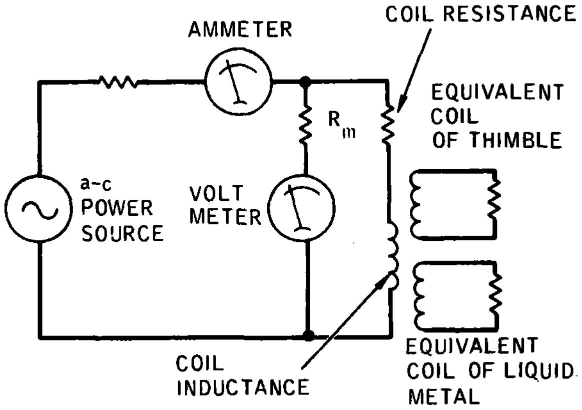
LEVEL INSTRUMENTS

INDUCTION PROBES

- Na ACTS AS SHORTED TURN, REDUCING "L" AND "Q"
- SINGLE COIL VERSION SENSITIVE TO Na AND WIRE TEMPERATURE
- TEMPERATURE SENSITIVITY REDUCED BY USE OF REFERENCE COIL
- ACCURACY AND LINEARITY IMPROVED BY SEGMENTING COILS (± 1/2 in. OBTAINABLE)
- "TRI-COIL" POSITIONED TO SENSE INTERFACE VERY USEFUL
- SNAP WIRING TECHNIQUES EXTEND RANGE TO 1200°F

LONG INDUCTION PROBE

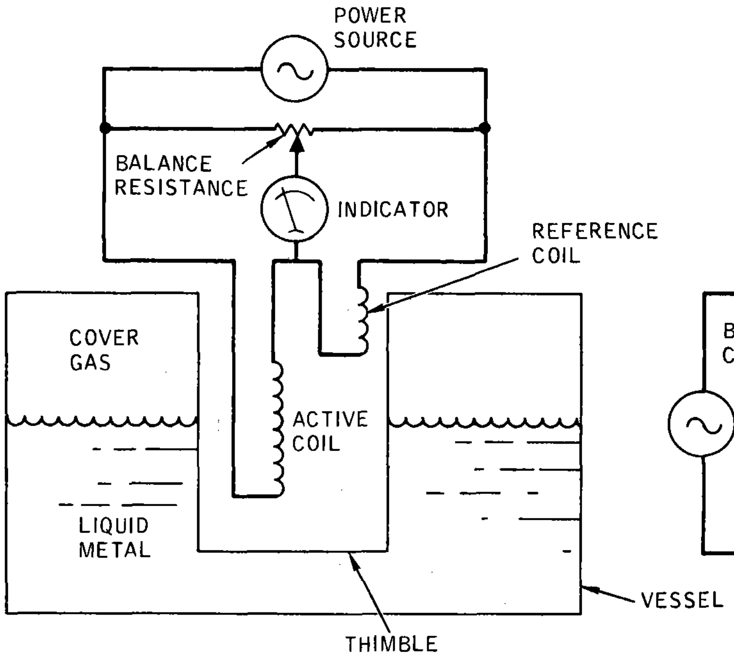


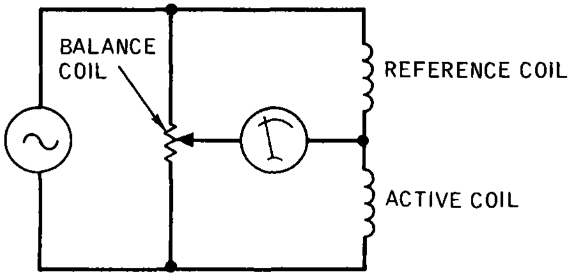


EQUIVALENT CIRCUIT

70-MA1-48-324

LONG INDUCTION PROBE
TEMPERATURE COMPENSATED





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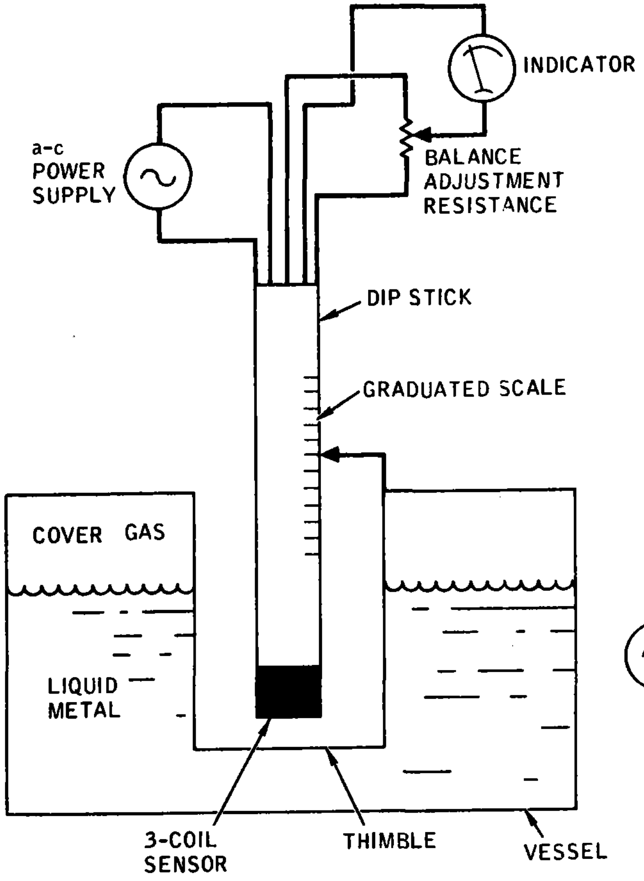
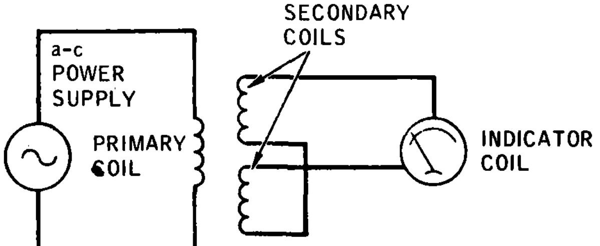
DIP-STICK PROBE





EQUIVALENT
CIRUCIT

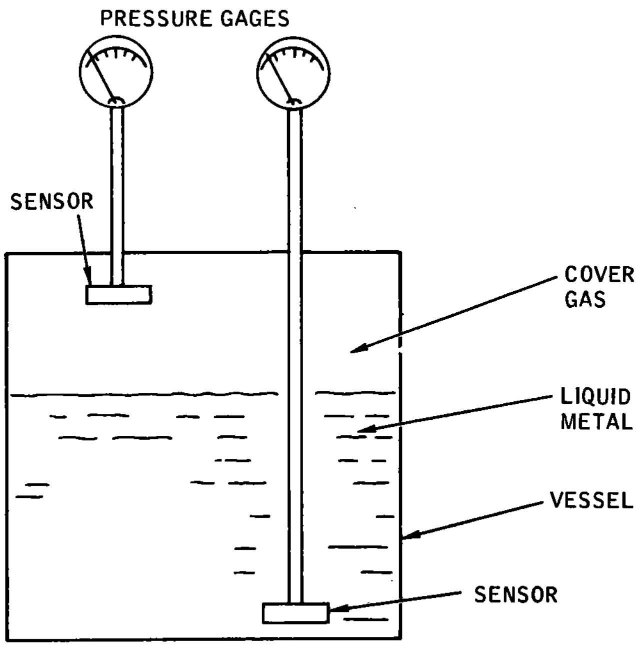
70-MA1-48-326

LEVEL INSTRUMENTS

DIFFER. HEAD $h = \frac{(P_{COVER\ GAS} - P_{SENSOR})}{DENSITY}$

- DENSITY CHANGES MUST BE COMPENSATED FOR
- ACCURATE RELIABLE dp CELLS REQUIRED
- INSTALLATION OF SENSOR NOT CONVENIENT
- GAS BUBBLER SHOULD ALLOW REMOTE LOCATION OF SENSOR BUT PLUGGING PROBLEMS

LEVEL MEASUREMENT BY DIFF. PRESSURE



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LEVEL INSTRUMENTS

MISCELLANEOUS OTHER

● FLOATS	MECHANICAL PROBLEMS, SEALS
● RADIATION ABSORPTION	LIMITED TO NON-RADIOACTIVE TANKS
● SONAR	COMPLICATED READOUT
● WEIGH TANK	TARE PROBLEMS

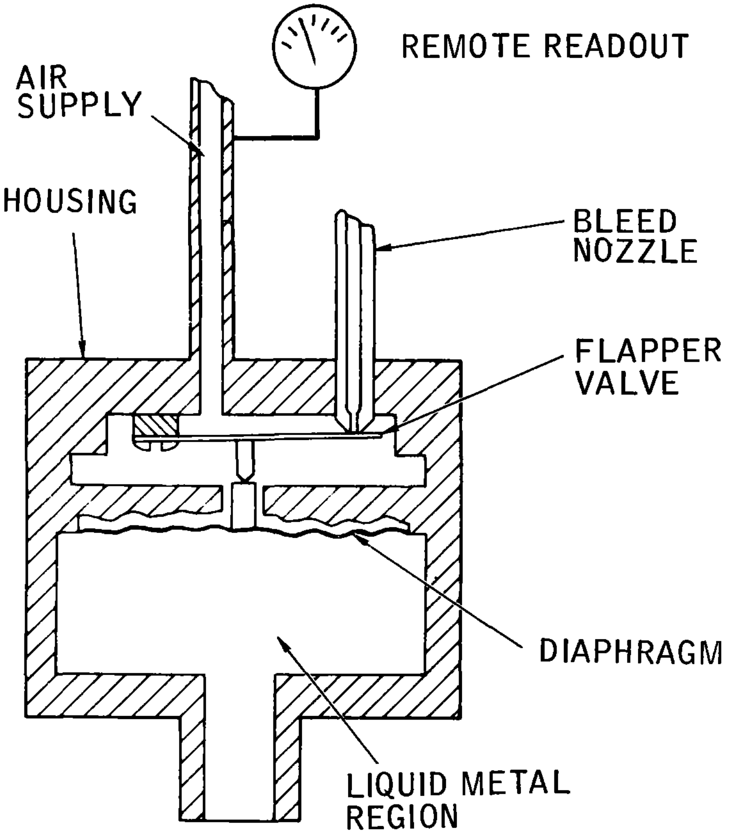
70-MA1-48-328

PRESSURE INSTRUMENTS

- DIRECT TRANSDUCING IN SODIUM SENSOR USUALLY FAILS
  - PLUGGING OF CAVITIES WITH OXIDES
  - HIGH TEMPERATURE MALFUNCTIONS OF MECHANICAL AND ELECTRICAL PARTS
  - CALIBRATION SHIFTS DUE TO TEMPERATURE CAUSED CHANGES IN GEOMETRY OR ELECTRIC PROPERTIES
- GAS TRANSMISSION SYSTEMS
  - OK FOR COVER GAS PRESSURE WITH VAPOR TRAP
  - GAS BUBBLER – LIMITED SUCCESS

70-MA1-48-329

FLAPPER VALVE TYPE PRESSURE SENSOR



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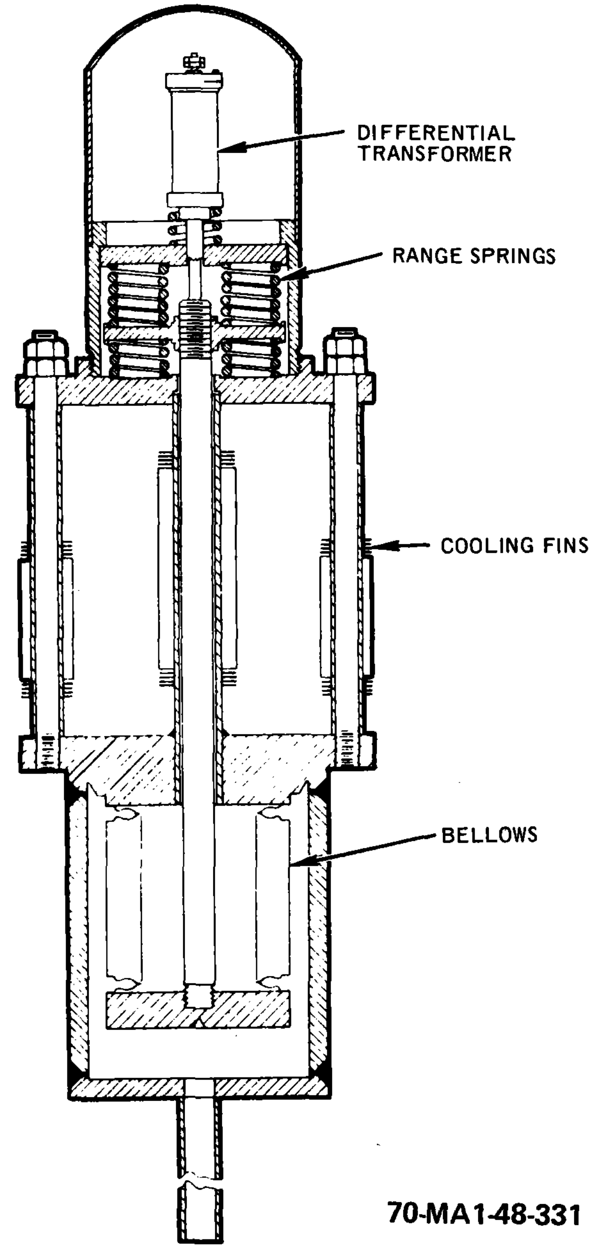
ELECTRICAL TYPE PRESSURE SENSOR
DIFFERENTIAL TRANSFORMER



70-MA1-48-331

PRESSURE INSTRUMENTS

NaK TRANSMISSION SYSTEMS – PRE-EMPS FIELD

FP – 12°F; BP – 1443°F; VP – 0.7 psia AT 1000°F; 16% $\Delta V/V$ FOR 1000°F CHANGE

FOR MINIMUM TEMPERATURE SENSITIVITY, SENSOR NaK LIMITED

DIAPHRAGM SPRING RATE $\ll$ BOURDON SPRING RATE

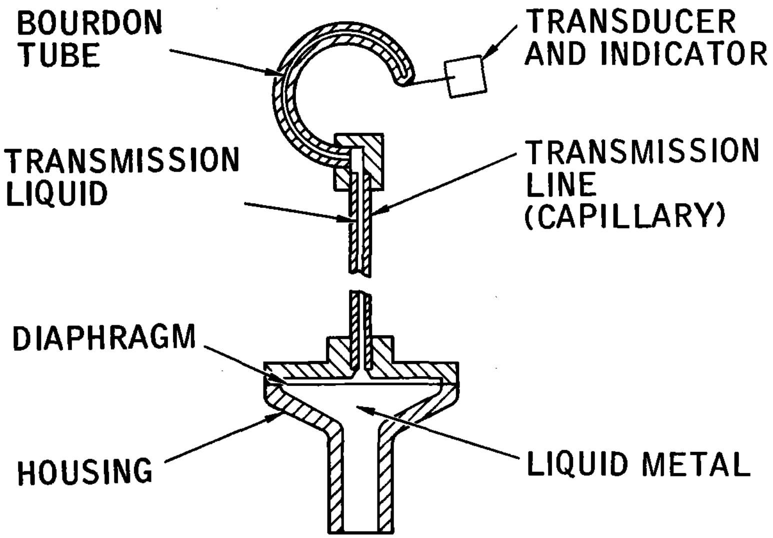
$<$ 1% FULL RANGE TEMPERATURE SHIFT ACHIEVED

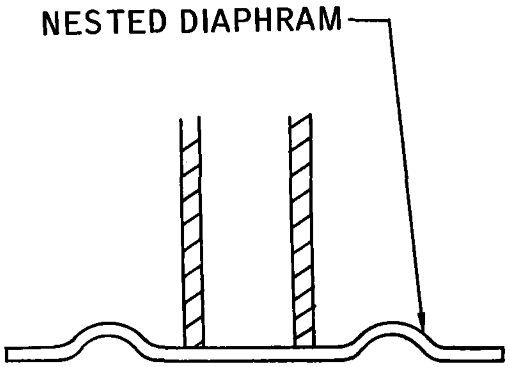
MAJOR PROBLEMS

EVACUATING, FILLING, WELDING, CLEANLINESS

70-MA1-48-333

NaK FILLED PRESSURE SENSOR





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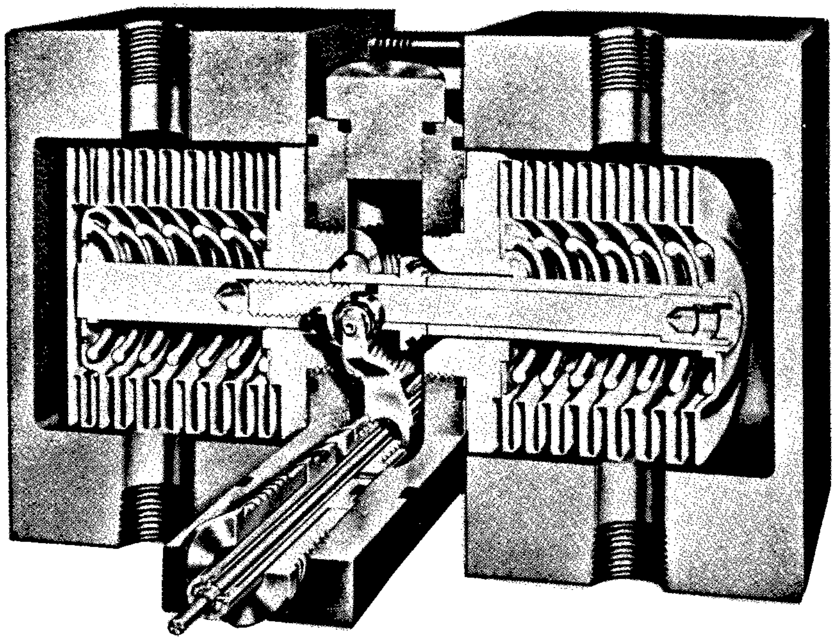
PRESSURE INSTRUMENTS

- NaK FILLED TRANSDUCERS
    - STRAIN GAGE
    - LVDT
    - PNEUMATIC
    - MECHANICAL LINKAGE

70-MA1-48-334

BELLOWS TYPE DIFFERENTIAL PRESSURE CELL FOR NaK SERVICE

BARTON MODEL 224 CUTAWAY



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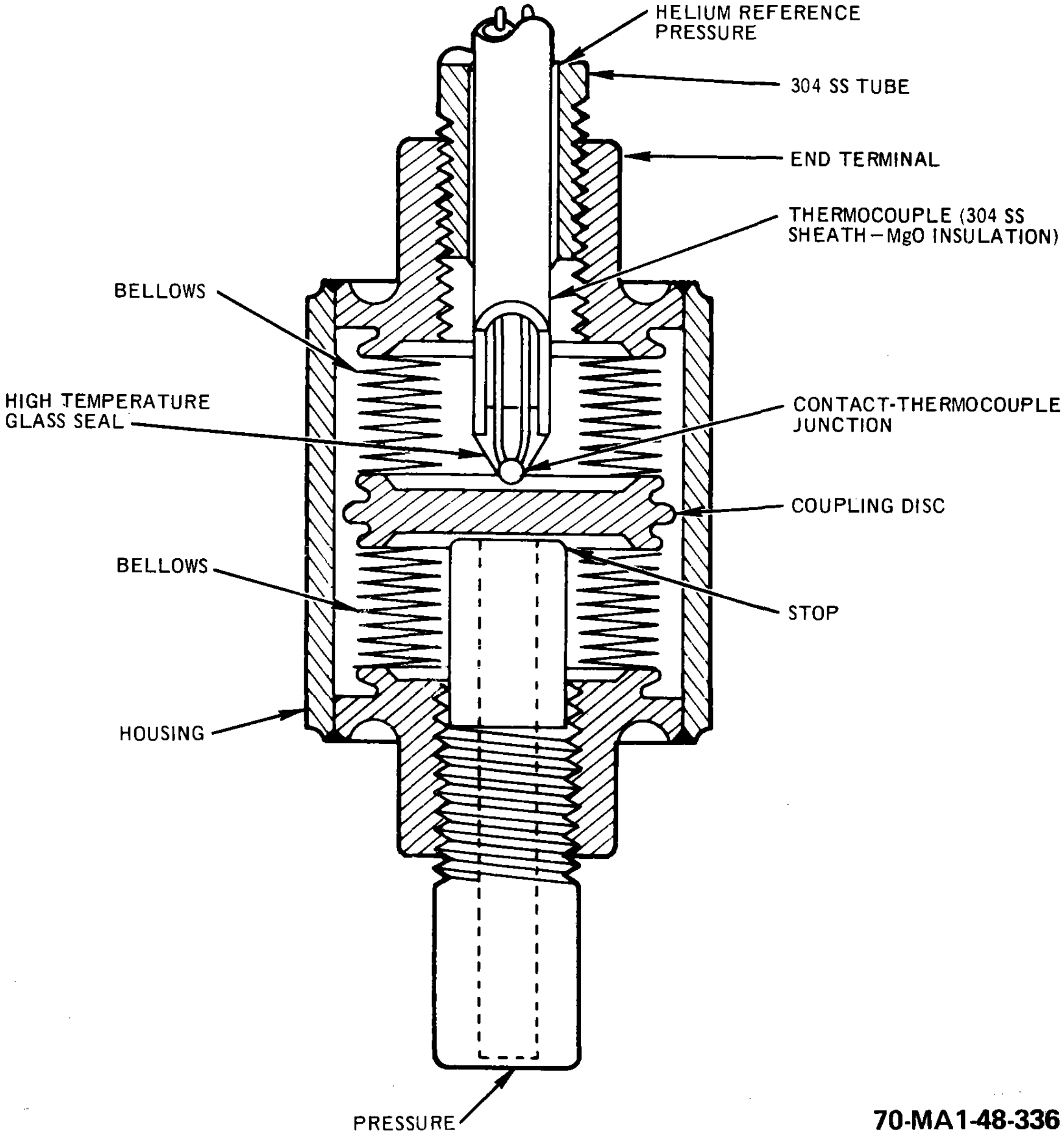
MINIATURE FORCE BALANCE PRESSURE CELL



70-MA1-48-336

TEMPERATURE INSTRUMENTS

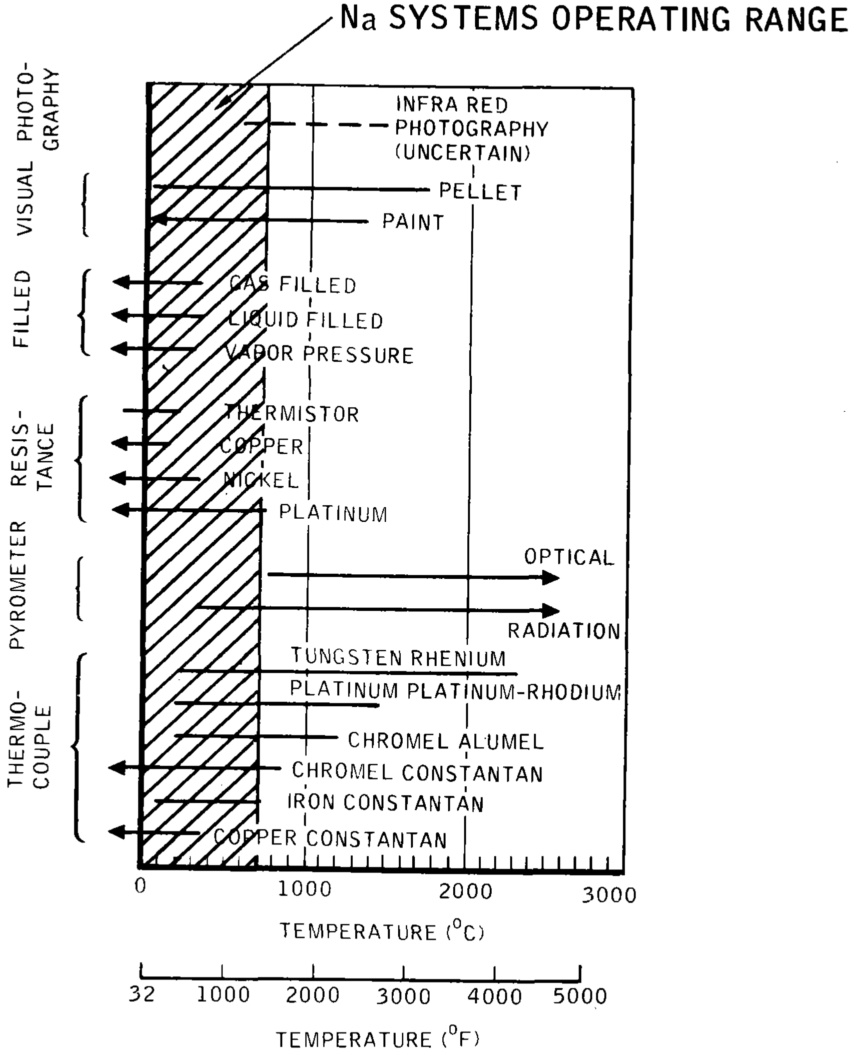
TC's, RTD's AND PYROMETERS AVAILABLE IN RANGE OF INTEREST

THERMOCOUPLES

- 3/4 OR 3/8% OF READING (C/A) UNLESS CALIBRATED
- METALLIC SHEATH REQUIRED WHERE EXPOSED TO Na OR Na VAPOR – GROUNDED JUNCTION FASTER RESPONSE BUT MORE PRONE TO FAILURE
- NEGLIGIBLE RADIATION DAMAGE TO 10^{20} nvt (C/A)

70-MA1-48-337

TEMPERATURE INSTRUMENT OPERATING RANGES



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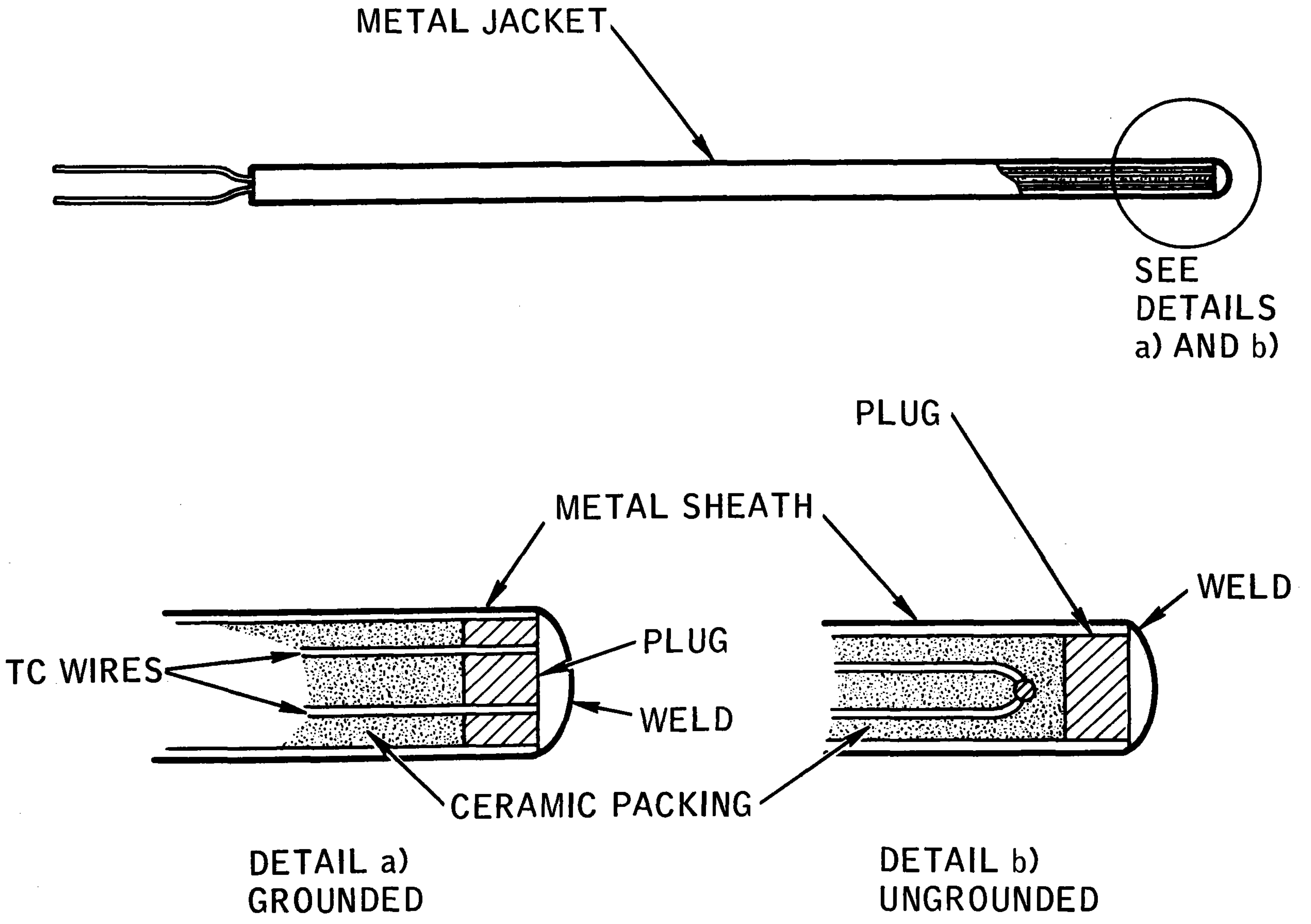
SHEATH THERMOCOUPLE CONSTRUCTION



70-MA1-48-339

TEMPERATURES AND LIMITS OF ERROR FOR COMMERCIAL THERMOCOUPLES

Type ASTM(14) Designation	Common Name	Limits of Error			Temperature-Wire Size Relation		
		Standard	Special	Temperature Range (°F)	Tempera-ture (°F)	Wire Size	
						AWG No.	Diameter (in.)
J	Iron-Constantan	±4°F ±3/4%	±2°F ±3/8%	32 to 530 530 to 1400	1400	8	0.128
					1100	14	0.064
					900	20	0.032
					700	24	0.020
					700	28	0.013
K	Chromel-Alumel	±4°F ±3/4%	±2°F ±3/8%	32 to 530 530 to 2300	2300	8	0.128
					2000	14	0.064
					1800	20	0.032
					1600	24	0.020
					1600	28	0.013
R S	Platinum 13% Rhodium-Platinum Platinum 10% Rhodium-Platinum	±5°F ±1/2%	±2-1/2% ±1/4%	32 to 1000 1000 to 2700	2700	24	0.020
T	Copper-Constantan	±1-1/2°F ±3/4%	±3/4°F ±3/8%	-75 to 200 200 to 700	700	14	0.064
					500	20	0.032
					400	24	0.020
					400	28	0.013
E	Chromel-Constantan	±3°F ±1/2%	±2-1/4°F ±3/8%	32 to 600 600 to 1600	1600	8	0.128
					1200	14	0.064
					1000	20	0.032
					800	24	0.020
					800	28	0.013
*	Tungsten 5% Rhenium + Tungsten 25% Rhenium	-	-	-	4200	18	0.040
					1800	20	0.032
					1600	24	0.020
					1600	28	0.013

*Note that last item has no ASTM designation

TEMPERATURE INSTRUMENTS

RTD's

- USED IN HALLAM AT 1000°F
- DEVELOPMENT TESTED TO 1300°F ON SNAP 8, BUT MECHANICAL FAILURES

70-MA1-48-340

S8DR RESISTANCE TEMPERATURE DETECTOR

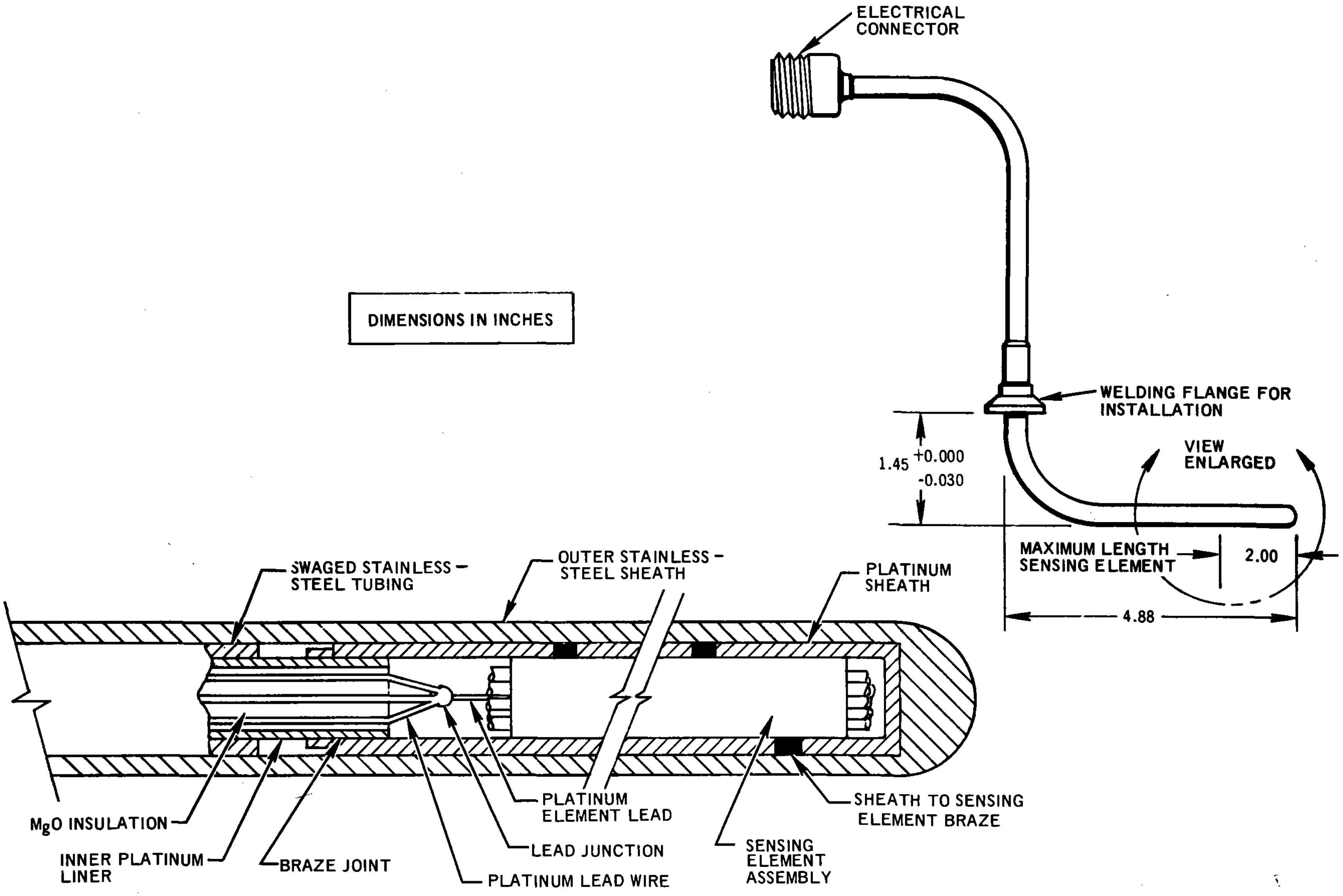
DESIGN REQUIREMENTS

- ACCURACY
  ±4°F
- MAXIMUM OPERATING TEMPERATURE
  1380°F
- OPERATIONAL LIFE
  12,000 hr
- RESPONSE TIME
  5 sec

- ICE POINT RESISTANCE
  24 ± 0.36 ohms
- ALUMINUM TO ICE POINT RESISTANCE RATIO
  ≥3.3539
- DRIFT RATE AFTER 1000 hr
  ±36 microhms/hr
- TOTAL DRIFT IN 12,000 hr
  ±160 milliohms

67-7695-023-77

RESISTANCE THERMOMETER DEVICE



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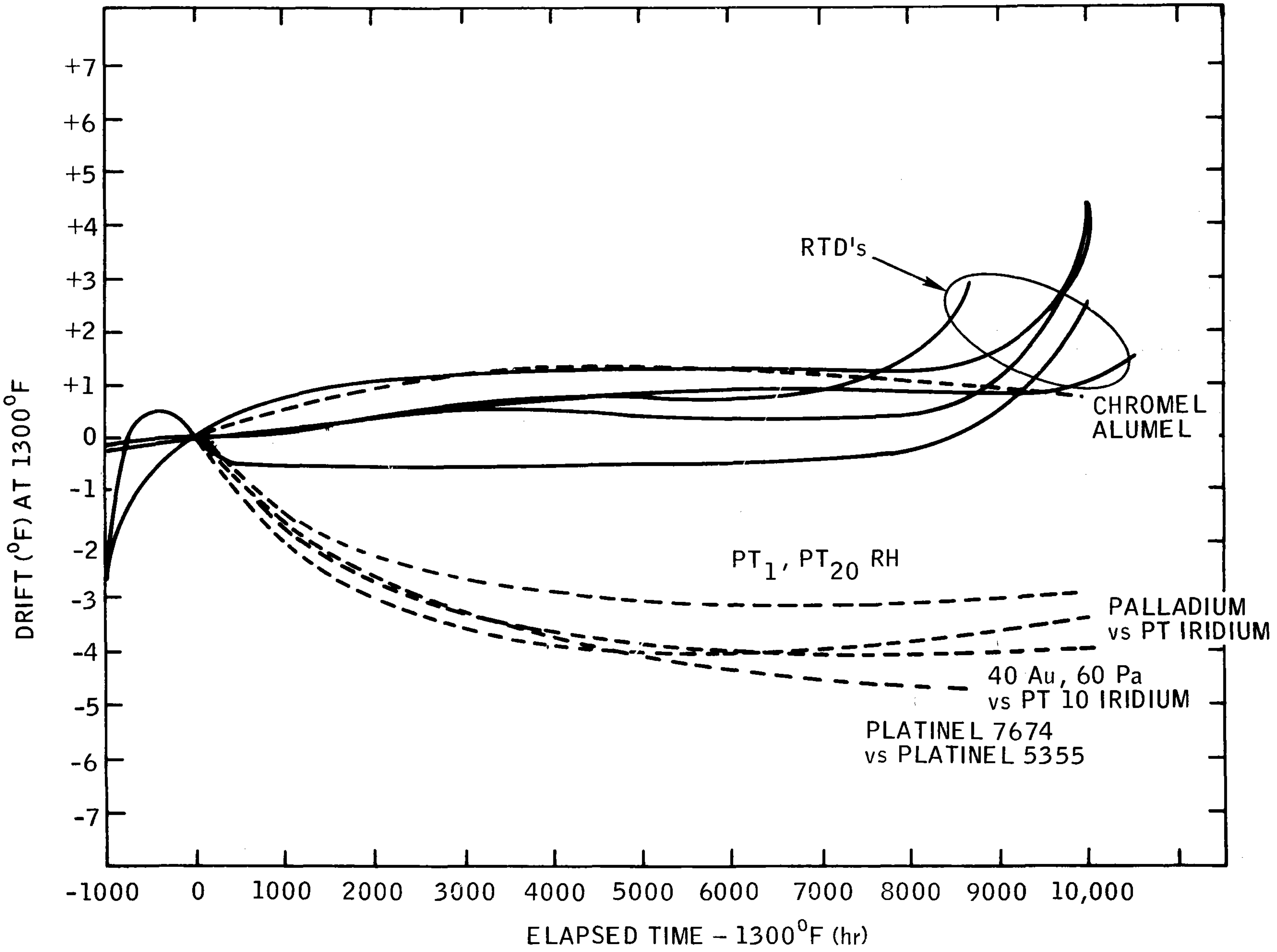
RTD AND T/C DRIFT RATE COMPARISON



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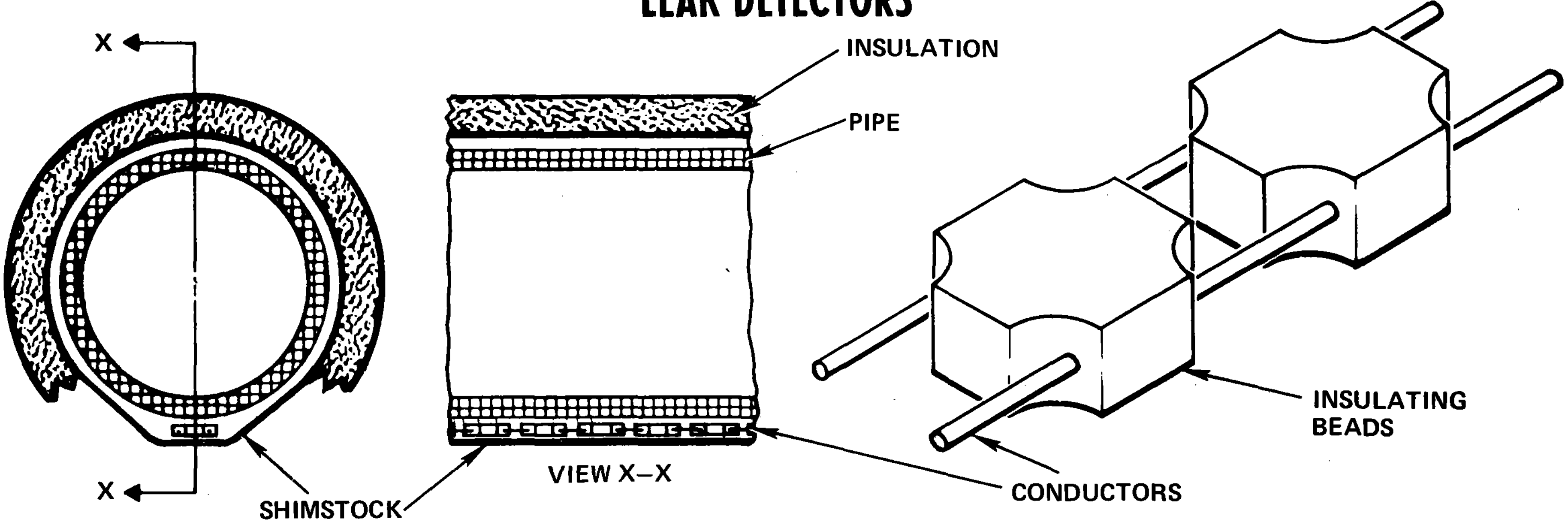
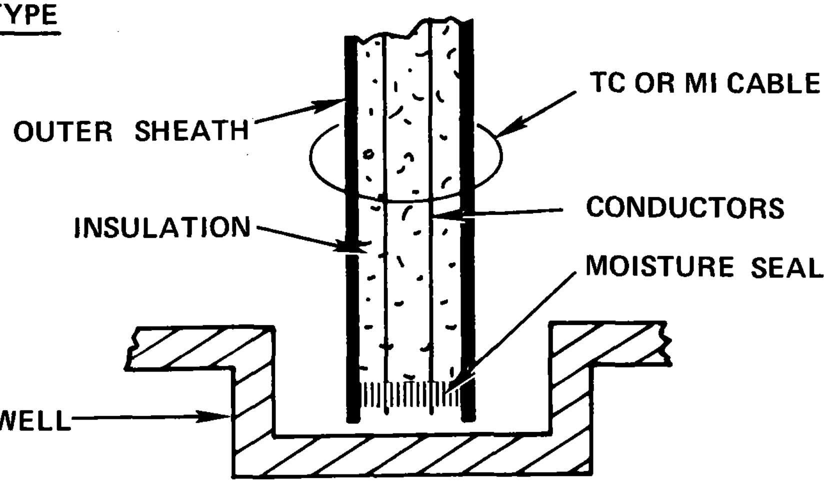
LEAK DETECTORS



PIPE TYPE



WELL TYPE

70-MA1-48-377

INSTALLATION PROBLEMS

GENERAL

- CONTAINMENT – CODES AND STANDARDS
- CAPILLARY LINES – SEALING – ROUTING
- WIRING -- MI CABLE – INORGANIC INSULATION
- REDUNDANCY – MULTIPLE UNITS

E/M FLOWMETERS

- SUPPORT – PIPE OR INDEPENDENT
- BUBBLE DETECTION – VERTICAL ELECTRODES
- LEAD WIRE – TWISTED PAIRS

LEVEL

- "J" TUBE – TRANSFORMER LOCATION
- INDUCTANCE – TWISTED PAIRS

PRESSURE

- ORIENTATION – SIDE MOUNTING PREFERRED

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SODIUM TECHNOLOGY COURSE, SESSION VII

OPERATIONAL CONSIDERATIONS

R. D. Keen and R. L. Koontz

A. SODIUM FIRES AND AEROSOLS

Sodium cooled fast breeder reactors require large inventories of sodium (on the order of 1.5×10^6 lb) for a 500- to 1000-Mwe commercial plant, and about the same for the FFTF. The reactive nature of sodium, and the radioactive content of the coolant after use demands special consideration of the potential hazards (pressure rise, R/A cloud) of a sodium fire. This section, therefore is concerned with the study of fires which result from hot sodium pools and sprays reacting with oxygen, and the behavior of the resulting smoke (or aerosol).

1. Analytical Development

A sodium fire can be adequately described by the chemical reaction equations, a heat balance, and an expression for mass transfer. There is some problem with the chemical equations in that a series of oxides is formed, with the production of a specific oxide governed in a complex way by: oxygen concentration, oxygen pressure, reaction temperature, and environment.* The heat balance for a pool fire is shown schematically in Figure 1.

The pressure rise in a contained volume due to a fixed quantity of reactants is rather straightforward, based on the chemical energy release, specific heat of the reactant and dilutant gas mixture and the pVT relation.

Of greater concern is the behavior of the sodium smoke (aerosol) which, in an FBR situation, will probably contain fission products as well as the radioactive isotopes of sodium of mass number 22 and 24, and radioactive stainless steel corrosion products — cobalt-60 and manganese-54. The matter of cloud borne radioactivity from the aspects of confinement, fallout, leakage, and the resulting contamination, internal and external to the containment structure, is of primary concern. A typical inventory of radioactivity for a fast breeder reactor after an equilibrium is reached in the production of radioactive products is shown in Table 1. Notice that by far, the largest contribution is from sodium-24. Most of the gaseous products escape from the sodium.

---

*See Appendix

TABLE 1

RADIOACTIVITY LEVELS IN SODIUM AT SATURATION — 500-Mwe FBR

Primary Coolant	
Na24	50,000 μCi/cc primary sodium
Na22	2
1% Failed Fuel, 0.1% Leakage	
Cs^{137}	0.7 μCi/cc
I^{131}	0.7
Sr^{90}	0.02
$Pu^{238,239}$	0.001
Total	1.42
Corrosion Products, 1 mil/yr	
Cr^{51}	9 μCi/cc
Mn^{54}	60
Fe^{59}	2
Co^{58}	90
Co^{60}	30
Total	191

If entire fuel inventory is released to sodium: ~1 Ci/cc

The aerosol model used for computation is as follows: the source of the aerosol (burning sodium plus fission products and corrosion products) yields particles which follow a log normal size distribution. These particles spontaneously and continuously coagulate into larger particles. Particles which come together stick together (nearly 100% "sticking" efficiency). This decreases the number of particles and increases their size. As the aerodynamic radius of the aerosol becomes greater, the particles settle faster. The higher the concentrations of particles, the larger the particle sizes will be, and the settling rate will increase with respect to a fixed containment atmosphere leakage rate.

The mathematical expression for this process is the resultant work of many investigators beginning with Smoluchousky,(1) including Muller,(2) and Zebel.(3) This work was pursued further at AI,(4) yielding the following equation for aerosol concentration.

$$\frac{\partial n(r,t)}{\partial t} = \int_{o}^{r/\sqrt[3]{2}} n(R,t)n(R',t)\left[B(R,R') + G(R,R')\right]\frac{r^2}{(R')^2}\,dR$$

$$- n(r,t)\int_{o}^{\infty} n(R,t)\;\; B(r,R) + G(r,R)\;\; dR$$

$$- n(r,t)\left[\frac{v_s(r)}{h} + \frac{D_{(r)}}{\Delta}\,\frac{A_w}{V} + \frac{L}{V}\right] + S(r,t)\,.$$

The first integral represents the formation rate of particles in the size (radius) range of r, r + dr as a result of collisions between particles of radii R and R' such that $R^3 + (R')^3 = r^3$. B(R, R') is the Brownian motion function and G(R, R') is the gravitational motion function. For particles smaller than ~1/2 μ, the Brownian process of agglomeration dominates; larger particles, falling under the influence of gravity will have a velocity distribution, with the larger particles sweeping past the smaller ones, thereby causing collisions.

The second integral is a removal term and represents the disappearance rate of particles in the size interval (r, r + dr) as a consequence of collisions with all other particles. Going into the next term, $V_s(r)/h$ represents stirred settling (Stokes); $D_{(r)}/\Delta \cdot A_w/V$ represents material plated on the walls of containment and L/V is the containment leak rate. S(r, t) is the log normal distribution source term, representing particles generated by the fire. The complete aerosol equation has been programmed for the IBM/360 as HAA 3.

2. Comparison With Experimental Results

Fires resulting from sodium spray jets and free surface pools were used in simulated reactor situations to evaluate the analysis. Oxygen content (in nitrogen) and container geometry as well as sodium flow rates were varied to cover as many parameters as possible. Figures 2 and 3 show the exterior of a 40 ft^3 test chamber and the interior of a 2200 ft^3 vessel.

a. Burning Characteristics

The reaction of sodium and air at high temperatures can form a series of oxides as outlined in Appendix 1. However, as for the typical sodium fire, we are only concerned with the peroxide and monoxide. These results are shown in Table 2.

TABLE 2
THE OXIDE PRODUCTS OF SODIUM FIRES

Type	Formed	Airborne	Temperature (°F)	Environment
Spray	Peroxide	Peroxide	<1700	Oxidizing
Spray (21% O_2)	Monoxide	Monoxide	>1700	Oxidizing
Pool (2% O_2)	Monoxide	Peroxide	<1700	Reducing
Pool (21% O_2)	Monoxide	Monoxide*	>1700	Reducing

*Airborne oxide will possibly convert slowly to peroxide

(76°F) (2240°F) (76°F)

Na_2O: $\Delta F = -90$ to -42, $\Delta H = -99.4$ kcal/mole Na_2O

Na_2O_2: $\Delta F = -106$ to -35, $\Delta H = -122$ kcal/mole Na_2O_2

A significant amount of monoxide forms when the sodium fire is above 1700°F. At lower temperatures less monoxide is generated, with peroxide predominant at ~1100°F, and only trace amounts of other oxides at 952°F. This is indicated in Table 3 which shows some experimental results of spray fires. The significance is that the peroxide reaction releases less energy (per mole of oxygen) than does the sodium-monoxide reaction, so the pressure rise is less. Also notice that even with excess oxygen, only a little more than a third of the amount of sprayed sodium is converted to the aerosol; the balance falling to the floor. This is probably a matter of mass transfer with regard to oxygen, with depletion of available oxygen along the centerline of the spray cone, since the fraction consumed has little dependence on oxygen concentration.

TABLE 3
SODIUM SPRAY FIRE SUMMARY
(40-ft^3 Vessel)

Run No.	O_2 (%)	Temperature (°F)	$\frac{\text{Consumed}}{\text{Sprayed}}$	Na_2O (%)	Na_2O_2+ (%)	$\frac{\text{Pressure Rise}}{O_2 \text{ Pressure}}$	Remarks
7	21	1300	0.365	95	5	20	Excess O_2
9	2	952	0.360	0	100	11	Excess Na
10	2	827	0.350	-	-	-	

Some experimental results of pool fires are summarized in Table 4. In these tests, oxygen arrives at the reaction zone (Figure 2) by natural convection in a closed container, or is forced into the fire by controlled flow. Notice that burning rate increases with gas flow, that less aerosol is made at higher temperatures, and that there is, apparently, only a small effect in scaling up from 40 ft^3 to 2200 ft^3 and most important, only 50% or less of the oxide product becomes airborne.

TABLE 4

POOL FIRE SUMMARY

(40-ft^3 Vessel)

	Natural Convection		Forced Convection (ft^3/min) (4% O_2)					
			20		90		150	
	1000°F (4% O_2)	1300°F (21% O_2)	1000°F	1300°F	1000°F	1300°F	1000°F	1300°F
Burning Rate (lb/hr-ft^2-% O_2)	0.4	0.4	0.25	-	0.36	0.4	0.4	0.5
Aerosol (Oxide) Fraction Released	0.4	0.2		-	0.36			

	2200-ft^3 Vessel, Natural Convection	
	800°F (10% O_2)	1300°F (21% O_2)
Burning Rate (lb/hr-ft^2-% O_2)	0.4	0.5
Aerosol (Oxide) Fraction Released	-	0.5

b. Radioactivity

To simulate fission product behavior, iodine-131 was added to some of the pool fires. The specific activity of the aerosol was about twice the specific activity of the burning sodium. This indicates that the fission product activity of a sodium fire aerosol may not, at present, be completely predictable from the radioactive content of the liquid sodium. However if a reactor sodium fire occurs, and if the core is still intact, the aerosol activity will be almost entirely due to Na^{24}, and this is predictable. If the core is involved in a DBA and a fire results, then the burning sodium may have an activity of ~1 Ci/cc which is about twenty times that predicted for Na^{24}. More work needs to be done on the aerosol activity prediction based on the release of radioactive products in the liquid sodium.

c. Code Predictions

Numerous experimental checks of the code (HAA-2) with experimental data were made. One of these, particle size vs time is shown in Figure 4. The upper curve is the computed plot for a gravitational agglomeration efficiency of 1. (As larger falling particles sweep past smaller slower particles, they hit and stick.) The lower curve disregards gravitational agglomeration, and accounts for Brownian motion only. The ordinate of the plot is median particle radius for a log-normal size distribution — aerosols are not of a single-size nature. It is evident that in the experiments, gravitational agglomeration is taking place. Although good verification is obtained, the difference in shape of the curves appears to be real, showing that the analytical model still needs adjusting. Particles of greater density than sodium oxides tend to fall out of the aerosol more rapidly at a given concentration, as shown in Figure 5. In this experiment particles representative of some of the possible radioactive aerosol compounds were liberated separately and allowed to settle in the large (2200-ft^3) test vessel. Data points represent given particle densities at various initial aerosol concentrations. The "half-time" along the abscissa is defined as the time required for the initial concentration to be reduced by a factor of 2. The solid line is computed for a particle density of 4 gm/cc. Figure 5 also shows that the higher the initial aerosol concentration, the more rapid the fallout for particles of equal density. This is demonstrated again on Figure 6. If several metal oxides are released simultaneously, they will, after a short time, probably agglomerate in particles having a mixed composition representative of the pure oxide present in the aerosol, i.e., the particles seem to have no preference for agglomerating with their own kind. This is shown in Figure 7, where particles of U_3O_8 and Fe_3O_4 were generated by vaporization and oxidation of the metals, along with sodium oxide. After ~1/2 hr, the analysis of single samples showed essentially a constant ratio in the presence of the oxides, with respect to time. If single species had settled, we would expect the ratio to change because of different settling rates for different density particles of the same concentration (see Figure 6). Figure 8 compares the calculated vs experimental concentration change of a uranium dioxide aerosol.

The significance of gravitational agglomeration is again shown in Figure 9. Here, the code was run for agglomeration from Brownian motion only, and this shows a wide deviation from the experimental results, while if both Brownian and gravitational agglomeration are taken into consideration, a pretty good check is obtained.

A code, SOFIRE-I, was also developed to compute the expected pressure rise in a contained sodium fire. The results of this work are shown in Figure 10. The experimental work was done with the 2200-ft^3 vessel, using an air atmosphere. Reasonable agreement was obtained from SOFIRE-II with regard to peak pressure.

3. FFTF Application

In a hypothetical FFTF accident, 19% of the fuel and 450 lb of sodium are vaporized and oxidized. The results, using aerosol analysis techniques are shown in Figures 11 and 12. Leak rates of 10% vol/day at 30 psig for the inner containment and 1% vol/day at 15 psig for the outer containment were extrapolated. Figure 11 illustrates the reduction in airborne mass in the inner containment and the amount leaked to the outer containment which reaches an essentially constant value of ~580 gm after a few hours. The leakage from the outer containment to the atmosphere is shown in Figure 12. Again, we have a rapid decrease in the concentration of the contained aerosol, and a total leakage to the atmosphere of a little over 0.3 gm, which does not have a significant increase after 4 days.

4. Summary of Fires and Aerosols

Perhaps the most significant outcome of these studies is the rapid fallout of aerosol particles, so that for sodium-24 for example, a large contribution to airborne activity, most of the activity falls out in containment before it leaks out.

While it is easy to see how sodium radioactivity gets airborne, the situation for other isotopes is not as clear. It has been shown that iodine-131 is actually concentrated in the aerosol; this may also be the situation for materials such as cesium. It is not likely that materials having less tendency to oxidize or volatilize will have as high a relative activity in the aerosol as they do in the liquid sodium; further evaluation is needed.

B. SODIUM-WATER REACTION

1. Sodium Heated Steam Generator

Power conversion for utility fast breeder reactors is by means of Rankine cycle, which requires the production of steam to operate turbine generators. The most direct way of steam production for the FBR is to make use of a sodium heated boiler and superheater. This brings large quantities of sodium and water into close proximity, so the consequences of a reaction must be evaluated.

2. Nature of Reaction

The reaction with water is primarily $Na + H_20 \rightarrow 1/2\ H_2 + NaOH$ at ~46 kcal, a large quantity of energy. In an open pool of water, the reaction energy produces local temperatures high enough to ignite the hydrogen, or explode the local oxygen-hydrogen mixture.

An FBR steam generator-superheater is shown in Figure 13, with a typical tube-to-tube sheet weld detail shown in Figure 14. Sodium is on the shell side; the tube contains water and/or steam. The tube wall is ~1/10-in. thick, and this is all that prevents a water and sodium reaction. The outcome of a tube failure was evaluated experimentally.

3. ESADA Experiments

This work is vividly shown in the ESADA film. In this work, an experimental simulation of a boiler tube bundle and shell configuration was built and instrumented to record transient pressure. One tube was arranged to burst under a known pressure so that water and sodium near operating temperature could react under simulated tube rupture conditions. The reaction products vent to air. A typical pressure transient is shown in Figure 15; a peak pressure of 1800 psi is reached in 0.003 sec.

4. Reaction Containment

The FBR steam module shell, with a capacity to withstand ~4500 psi, will have a burst diaphragm set at 900 psi. Reaction products from a tube rupture are discharged from the burst diaphragm to a holding tank and separator (Figure 16). Hydrogen gas is vented, possibly burned at the top of a separate stack. It is expected that the quantity of reaction products will be small compared to the bulk of the sodium discharged from a burst diaphragm, so that it is possible and worthwhile to salvage and reuse the sodium. Residuals will be reacted with water and discharged as liquid NaOH-H_2O. The significant thing here is that although the sodium-water reaction is violent, the resulting damage is local and contained within the steam generator module. A failure of this type requires that the module be isolated from the system (by valves) and then be replaced.

5. Monitoring System

A tube rupture in an operating power plant will be quite evident, since pressure and flow transients will scram the reactor. Small leaks of the high-pressure water or steam into the sodium system might go unnoticed for a long time, however, without some sensitive detection device. The long-range effect would be an increase in oxide and hydride content of the sodium. (Both components can be identified with a conventional plugging meter.) But a small leak could develop into a tube rupture, so early detection is important. An adequately sensitive detector for hydrogen in sodium makes use of a metal membrane such as nickel or palladium which is permeable to hydrogen, but leak tight to sodium. Detection, for example, can then be made by analyzing the effluent gas for water after reacting the escaped hydrogen with oxygen. A reference hydrogen concentration threshold for the secondary sodium must be established however, since there will always be some hydrogen present as a consequence of water corrosion in the steam generator.

6. Summary

The sodium-water reaction must be considered in an FBR electric power plant because of the close proximity of large quantities of chemically reactive materials in the steam generator. Even though the probability of tube rupture is low, the possible reaction is violent, but should it occur, it can be controlled and contained. Means of detecting small water-sodium leaks are available, and constant monitoring provides the opportunity for corrective action before a forced shutdown takes place.

C. OPERATION AND MAINTENANCE OF SODIUM SYSTEMS

Information in this section is pertinent to non-nuclear test installations as well as power reactors.

1. Documentation

The effective and economical use of equipment and systems demands that appropriate records be kept. The scope of this effort needs to be in keeping with the work at hand, neither being an "end in itself," nor too abbreviated to be useful, so individual judgment is required. However, since the systems we are concerned with will be operated by more than one person, and over a period that may challenge the human memory, permanent documentation should at least cover the following topics:

1) A description of the equipment and/or system
2) The purpose or reasons for its existence
3) An operating procedure verified by use and kept up to date
4) A daily record (log book) of use, including data required of the test, operating conditions, descriptions of any difficulties, repairs and adjustments.

2. Initial Startup

Since no one has had operating experience on a specific, new system, careful planning of the startup procedure will be worthwhile. This is a permanent record, part of item 2 in the preceding section. Assuming we are dealing with some kind of a sodium system, it will probably include the following:

1) A checklist to be sure that all significant items, in proper sequence, are accounted for
2) A verification of cleanliness, and readiness for operation
3) A leak test, which may make use of:
   a) Pressure decay, at any required sensitivity (providing there is time)
   b) Soap bubble
   c) Halogen sensitivity of a butane gas flame
   d) Mass spectrometer for helium having a sensitivity greater than 10^{-6} cc/sec leakage
4) Evacuate, or purge with inert gas

5) Preheat, to be sure that all parts contacting sodium are well above 208°F to avoid local freezing. Usual preheat temperatures are 350 to 500°F. The higher temperature, particularly if the system is on vacuum, will assist in degassing surfaces, thus aiding sodium cleanliness.

6) Fill from sodium loading or holding tank. This may be by gas pressure differential or transfer pump. Inert gas can be displaced (vented) from the system as filling proceeds, or if inverted loops must be filled, loading will proceed under vacuum. (The vacuum line valve should be closed while admitting sodium, then sodium admission stopped while the system pumps down again.)

   a) Loading level vs operating level: An expansion space, either a gas ballast tank (near the high of the system) or a zero void bellows device is used to permit sodium expansion from the volume at loading temperature to the volume at operating temperature.

   b) A level sensor set for loading temperature volume gives the "stop fill" signal, or the sodium can be weighed in from a tank on a platform scale.

   c) System pressure is controlled from the expansion tank.

7) Establish circulation. This usually involves a pump, but may make use of thermal convection (or pressure differential for a transient or "once-through" system). Flow indicators will usually be electromagnetic.

8) Cold trap and measure oxygen concentration. Since sodium is an excellent "getter," a sodium flush may be advantageous for high-purity systems.

9) Bring the system to operating temperature, establish temperature gradients if necessary at desired flow, adjusting system absolute.

10) Check instruments, recalibrate if necessary, and proceed with test or operations.

3. Shutdown and Secure

This is also a procedure, part of item 2), paragraph 2, and requires a consistent approach. Ordinarily, the first step will involve reduction of thermal load and system temperature in a way and at such a rate that thermal stresses are minimal — this tends toward isothermal conditions, and also minimizes the possibility of inadvertently freezing some part of the system. An isothermal temperature of 350°F should be achieved before draining. It might be advisable to make another measurement of oxygen concentration at this time. The sodium in the system can then be drained to a continuously heated, holding tank, backfilling with an inert gas; or, the system may be put on "standby," circulating at a modest flow rate and uniform, low temperature, perhaps cold trapping at the same time.

4. System Repair

It is assumed here that a non-nuclear sodium experiment has been in operation for some time, and is now in need of major repair and/or modification. The general approach will be as follows:

1) Determine the condition of the system. Such matters as: whether or not it is completely drained, temperature distribution, amount of oxide or other impurities present, and the inert gas situation. These factors will all have some bearing on procedure.

2) Define the problem. Some questions to be answered are: is the work at hand the result of an accident, equipment failure, planned modification or routine maintenance?

3) Formulate an approach to achieve the objective, and write the procedure.

a. Cutting Pipe

Major work on a sodium system usually involves cutting pipe, to remove an equipment item, pipe weld, defective pipe, temperature flow and pressure instrumentation, or pipe blockage. Before any such work is started, as much sodium as possible will have been drained to the holding tank, and everything will be at room temperature and any prior spills of sodium cleaned up. If the pipe is empty, and 4 in. or less in diameter, a flow of inert gas will be established in the pipe; the pipe can then be cut using a tubing cutter, hand hack saw, portable band saw or heavy duty sabre saw. All cutting is done dry. A pan containing dry calcium carbonate is used to catch the scrap. (Plant rules may require notification of plant protection, and standby of firemen. In no case should such work be attempted alone.) After the first cut is completed, tape closes the opening to gas flow. After the second cut is completed, the pipe section is lifted out, and the open pipe is plugged or covered with tape.

The same procedure applies to small pipes filled with sodium, except that extra attention is given the scrap, to avoid ignition of the fine particles by continually covering them with calcium carbonate, and the cut ends are completely and quickly taped closed.

If the pipe is 6 in. or larger, and empty, control of inert gas flow and pipe closure is a little more difficult, and handled in the following way: two holes are drilled through the pipe wall on either side of the proposed pipe cut, as shown in Figure 17. These admit inflatable bag seals which are commercially available, and manufactured from materials compatible with cold sodium. Once the bags are inflated (with inert gas), dry cutting and removal proceed as before for smaller pipe. Usually extra care is needed for pipe support (and removal) because of the extra weight. Special cutters are available for large diameter pipe as shown in Figure 18.

b. Replacement of Pipe Section

This involves welding a cleaned (or new) pipe section into pipe containing at best, traces of sodium, at worst, solid sodium. Either situation can be handled, but it must be remembered that even small quantities of sodium can spoil the weld if present in the weld region. Cold sodium is easily cleaned back a distance of several inches from the weld, however, using scraping tools (or hammer and sharp, wood chisel). Care must be taken to limit the exposure of the sodium to air, and to quickly dispose of the chips. Final cleaning in the weld region is with clean cloth saturated with reagent grade (undiluted) ethanol. The appropriate shaping of the pipe edge for weld preparation is made, and the pipe is then TIG welded according to system specification. Pipe temperature in the region of sodium must be monitored (and controlled by chill blocks if necessary) to prevent melting the solid sodium. If bag closures were used, these are now removed, and plugs are welded into the access holes to complete the repair. Inspection may include dye check of the root pass on welding, x-ray of the completed weld, and a mass spectrometer leak test.

c. Most Likely Location of Leaks

Even with a well designed and carefully constructed system, problems can develop after long usage. The most likely location of incipient cracking and possible sodium leaks are as follows:

1) Heat affected zone of parent metal near welds
2) Weld metal
3) Machined inner pipe surfaces
4) Outer pipe surface — after long exposure to air, particularly if chlorides are present
5) Pipe penetrations
6) Inner or outer crevices where contaminants can concentrate
7) Valves — seal or seat.

d. Most Likely Causes

1) Sensitized material, stress corrosion from either side of the pipe
2) High residual weld stresses plus operating weld stress due to differential expansion of joint or due to bending and tensile loads from pipe run expansion
3) Low ductility of stainless steel under some (high temperature, low strain rate) conditions
4) Undetected foreign material in weld (slag from coated welding rods, tungsten tips, sodium, or dirt)
5) Material defect in pipe such as a slag inclusion (which sodium will slowly dissolve) or "cold shut" (which cyclic stress can open)
6) Strain relief or creep in mechanical joints and valve parts.

e. Leak Detection

In an operating system in air, leaks are fairly evident from the presence of sodium smoke. Seldom is the leak catastrophic; normal shutdown is straightforward and should be carried out immediately. Seepage leaks may be evident only after many hours of operating, by corrosion product discoloration bleeding through the insulation. In an air atmosphere, the high concentration of oxide in hot sodium can dissolve stainless steel quite rapidly from the outside; quick action in cooling and draining the system is necessary to minimize the damage and possibly prevent a catastrophic leak.

In an inert atmosphere, leak detection is more difficult since oxide smoke may not be evident. Atmospheric samples, with appropriate threshold or "blank" control on analysis are satisfactory, using a flame spectrometer, or reacting the sample with alcohol to yield hydrogen. A sodium light source and sensor may also be used to identify the absorption spectrum of sodium vapor. In general, tracing wires dependent on the electrical conductivity of leaking sodium are unreliable.

f. Cleaning for Reuse or Storage

Almost every repair or modification of a used sodium system involves cleanup of parts and pipe. Small parts intended for reuse can be effectively cleaned by soaking in ethanol or Dowanal EB. (The latter is an ethyl glycol having a moderate, but complete reaction with sodium.) Heavier alcohols (methyl, butyl) can be used for a slower reaction and with less chance of fire than with ethanol, but the butyls form a barrier film before all the sodium is used up. In any case, hydrogen gas is a reaction product, so good ventilation (or dilution with inert gas), and adequate fire protection are essential. Air drying and visual inspection completes the process. The alcohol is "spent" (loaded with oxygen) when it thickens, and must be changed.

Large rugged parts and pipe not susceptible to damage by hydrogen-oxygen explosions are often steam cleaned. This method of cleaning is rapid and effective, but messy. It is often done in an open area with adequate drainage. Commercial equipment is used with a long steam lance. Nitrogen is sometimes used to dilute the reaction gas and smoke to minimize hydrogen explosions. Protective clothing is essential, and a solid barrier is advisable. After completion, the parts are usually hot enough to air dry. Final touchup may be made using a clean cloth and Dowanal EB, or ethanol.

(1) Dangerous Materials

It is important to note here that certain solvents and cleaning fluids commonly available in the shop and laboratory are dangerous to use with sodium. These include:

1) Water
2) Carbon tetrachloride
3) Trichloroethylene
4) In general, any chlorinated hydrocarbon

(2) Special Use Materials

Liquid, anhydrous ammonia takes sodium into an ionic solution, with a change in appearance from a clear liquid to dark blue. This requires pressurization in a closed chamber, but seems safe enough from the reaction point of view.

Carbon dioxide gas at ambient temperature and a little above atmospheric pressure reacts very slowly with sodium to form sodium carbonate. This is a completely safe end product, but may require months for completion. With this in mind, pipes containing sodium have been stored under CO_2 rather than inert gas.

5. Radioactive Systems

By adding appropriate control for personnel exposure, and proper disposition of contaminated reaction products, scrap and tools, and perhaps adding temporary shielding, and remote viewing and handling equipment, the principles in this section can apply to radioactive sodium systems.

D. STORAGE AND HANDLING

1. Suppliers

In the U. S., the major suppliers of elemental sodium are: the Ethyl Corporation, duPont, and National Distillers. Current production is on the order of 3/4 billion pounds per year, the largest consumption still being the production of tetraethyl lead. Shipments can be had in the form of reagent grade 1-lb bricks in sealed cans, bricks packed in steel drums, filled 55-gal drums (440 lb net), and railway tank cars (80,000 lb). Prices range from about 10¢/lb for the commercial grade to 20¢/lb for high-purity sodium, in carload lots.

2. Handling

The most convenient form for loop use is the 55-gal drum. Equipped with strap-on-drum heaters and an inert gas supply, these may be used as melt and storage stations, using only the amount needed. Cold storage is safe, neat, and economical.

Reactor installations, such as the FFTF requiring something over a million pounds of sodium would of course be initially filled by tank car (12 to 15 carloads) although makeup amounts would probably be in 55-gal cast drum lots. Provisions would therefore be made for barrel melt stations as well as for tank car unloading.

Tank car melting requires a hot oil to be circulated through built-in heating passages. Equipment to supply the heated oil is commercially available for sale or rent. The sodium transfer line must also be heated; this is conveniently done with controlled tubular electric heaters, strapped in place. In the interest of cleanliness, austenitic stainless steel is usually used for the supply line. Leak tested flanged connections can be used for supply lines larger than 1 in., while stainless steel tubing and compression tube fittings can be used to make up connections to a drum. Tubing sizes smaller than 3/4 in. for supply connections have considerable risk of cold spots and consequent blockage. Copper and aluminum tubing should not be considered for use, even for gas supply lines connecting to a sodium vessel.

3. Maintaining Purity

Sodium purity begins with the manufacturer, who has the responsibility for the required analysis, and for proper shipping. An inert gas blanket must exclude air, since even traces of water will act as a catalyst for the chemically active sodium to react with shipping container materials even at ambient temperature (ordinarily, mild steel).

To follow through, transfer lines and holding tanks must be clean and purged of air. Even so, some oxygen contamination is bound to occur during transfer operations. A cold trap is usually provided for the sodium holding tank to compensate; this also provides the opportunity to use the first filling of the loop as a flushing or gettering operation; with the accumulated oxide then being trapped out in the holding tank.

Cover gas supplies also need some attention. At the least, the required purity is specified as a purchase requirement, and all supply lines are evacuated and purged before use, and maintained leak tight. Additional gas purification can be achieved by hot gettering with a reactive metal, or by bubbling the gas through the liquid eutectic of sodium and potassium at room temperature.

E. MAINTAINING SAFETY

It is evident that potential hazards to health and property are present in the use of sodium at high temperature and at pressures above atmospheric. However, enough is known about materials, equipment design, and operating procedures to reduce the probability of an accident to a negligible value. Safety, then, reduces to a matter of judgment in when and how to apply existing information. In a sense, this is no different from any other industrial safety program in that clean, adequate (uncrowded), well lighted work spaces are provided, that equipment controls are conveniently located, that escape routes are easily identified and accessible, that scrap is properly stored and promptly removed, that proper tools are available and correctly used, that adequate protective clothing (for eyes, head, face, hands, body, feet) is worn, and that special emergency equipment (water showers, dry powder, fire extinguishers, breakout escape panels, and air breathing devices) are available along with a crew trained in their use, and that approved procedures are followed. The next section goes into further detail in safe practices, equipment, disposal of scrap sodium, and dealing with emergencies.

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APPENDIX I*

REACTIONS OF SODIUM WITH ENVIRONMENTAL GASES

The subject of this letter is divided into two sections, the first of which deals with the thermodynamic-chemical properties of the reactants, and the products of the sodium-gas reactions. The second is a discussion of the statistically probable kinetics of sodium-oxygen reaction.

I. THERMODYNAMIC AND CHEMICAL PROPERTIES OF THE CHEMICAL SPECIES

The following definitions of† properties of Na, Na_2O, Na_2O_2, NaO_3, NaOH and Na_2CO_3 is intended to provide a guide for establishing possible limits of an equilibrium reaction.

Sodium — Na, atomic wt 22.991. This alkali metal is an extremely strong reducing agent especially where ionic mobility is possible (liquid or vapor state)

Sodium Monoxide — Na_2O, molecular wt 61.99. A white-grey material which deliquesces in the presence of moisture to form NaOH. No hydrates of this compound are known to exist. It melts at 1680°F (1193°K) with ΔH_m = 10 kcal/mol. The heat of formation at 76°F (298.15°K) is -99.400 kcal/mol Na_2O and the heat capacity is 17.43 cal/mole °K at the same temperature. It has a free energy of formation which varies from -90.13 kcal/mol at 76°F to 41.65 kcal/mol at 2240°F (1500°K). The monoxide also begins to disssociate noticeably at about 1800°K.

Sodium Peroxide — Na_2O_2: mol wt 77.99. A white or yellow white powder which is a strong oxidizer and is hygroscopic but does not deliquesce unless large amounts of moisture are available, because of the existence of multi-hydrates of the oxide (i.e., $Na_2O \cdot 8H_2O$ mol wt 222.12). The peroxide is unstable in the presence of free water and free carbon dioxide forming NaOH and

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*Letter, J.E. Granger to R. L. Koontz 2/11/70

†Handbook of Chemistry and Physics (41st Edition, Chemical Rubber Co., 1959) Cleveland, Ohio
JANAF Tables 1967, U.S. Dept. of Commerce & National Bureau of Standards, U.S. Government Printing Office
Supplement to Melbois Comprehensive Treatise on Inorganic & Theoretical Chemistry, vol II, Supplement II — The Alkali Metals, Part I (1961), John Wiley & Sons, Inc., New York

Na_2CO_3, respectively, but these reactions proceed slowly at temperatures below ~300 °F. Conflicting reports of the decomposition temperature of Na_2O_2 (780 °K vs 1200 °K) are easily understood in the light of a known crystal structure change at 783 °K which would cause the immediate disintegration of a hydrate which in turn would react with the hot oxide. This is supported by the experimental evidence* that precise decomposition temperature near 780 °K was never confirmed, only a temperature range (dehydration of compound followed by reaction). The heat of formation of peroxide at 298 °K is -122.0 kcal/mol. At this temperature it has a heat capacity of 21.361 cal/mol-°K. The free energy of formation (Δ° F) varies from -106.817 kcal/mol at 298 °K to 35.310 kcal/mol at 1500 °K. The free energy formation of Na_2O_2 becomes smaller than that of Na_2O at approximately the melting point of Na_2O (1190 °K). The peroxide melts at 948 °K.

Sodium Superoxide – (Oxide) NaO_3: mol wt 70.99. An extremely unstable yellow powder which rarely exists except as a minor product in the manufacture of Na_2O_2.

Sodium Hydroxide – NaOH: mol wt 40.01. A white deliquescent compound which melts at 591°K and boils at 1663°K· $\Delta F_f \approx 90$ kcal/g-mol.

Sodium Carbonate – Na_2CO_3: mol wt 106.0. A white hygroscopic and deliquescent powder which forms hydrates, melts at 1124°K and decomposes to Na_2O thereafter.

II. KINETICS OF SODIUM-OXYGEN REACTION

The following is a qualitative statistical approach to the oxidation of sodium metal. It is based on the fact that a good approximation for a complex reaction is a combination of binary collisions between reactants and intermediate products.

As one would expect the reaction products of the previous pages will only exist if the free energy favors that product, if enough time is allowed for the reaction to proceed, and if equilibrium can occur.

For instance, thermodynamically sodium peroxide is the favored reaction product for temperatures up to ~1200°K, after which sodium monoxide is favored. However, passing a stream of oxygen over room temperature sodium will hardly form the peroxide because the reaction rate is too small and because

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*Supplement to Melbois Comprehensive Treatise on Inorganic & Theoretical Chemistry, vol II, Supplement II – The Alkali Metals, Part I (1961), John Wiley & Sons, Inc., New York the majority of the oxide is still in an excess sodium environment which reduces any peroxide to monoxide. Thus, only in a nonreducing environment at temperatures below 1200°K can the peroxide be stable.

Binary statistics show that sodium peroxide is an intermediate in the formation of sodium monoxide by the logic in Table A-1. As can be seen, sodium peroxide is the product of two binary collisions while sodium monoxide requires three. (The only way the monoxide could be formed on the second collision is to have that one be an improbable tertiary collision between the rare free oxygen radical and two sodium metal atoms.)

TABLE A-1

SODIUM PEROXIDE AND SODIUM MONOXIDE FORMATION

Collision	Reaction	Products	Frequency of or Existence Occurrence
Zero^th (initial reactants)	None	Na and O_2	common
1 st (a)	$Na + O_2 \longrightarrow$	NaO_2	common
(b)	$O_2 \longrightarrow$	20	rare
2 nd (a)	$Na + O_2 \longrightarrow$	Na_2O_2	common
(b)	$NaO_2 + O_2 \longrightarrow$	no net reaction	-
(c)	$NaO_2 + Na_2O_2 \longrightarrow$	$Na_2O_2 + O_2$	fairly common
(d)	$NaO_2 + O \longrightarrow$	NaO_3	rare and unstable
(e)	$O + O \longrightarrow$	O_2 non-productive	rare
(f)	$O_2 + O \longrightarrow$	O_3	very rare
3 rd (a)	$Na_2O_2 + Na \longrightarrow$	$Na_2O + NaO$	common in high Na environment
(b)	$NaO_3 + Na \longrightarrow$	$Na_2O + O_2$	very rare
(c)	$Na + O_3 \longrightarrow$	NaO_3	very rare and unstable
(d)	$Na_2O_2 \xrightarrow{\Delta 1200°K}$	$Na_2O + O$	common above 1200°K
4 th (a)	$Na_2O + O_2 \longrightarrow$	$Na_2O_2 + O$	common near high Na environment
(b)	$Na_2O + O \longrightarrow$	Na_2O_2	rare
(c)	$NaO_3 + NaO \longrightarrow$	$Na_2O_2 + O_2$	extremely rare

III. CONCLUSION

Sodium peroxide will always be the product of an intimately mixed excess oxygen fire which is cooler than 1200°K. The intimate presence of moisture, CO_2, or Na will destroy this oxide yielding NaOH, Na_2CO_3, and Na_2O respectively. Sodium monoxide is only stable as an oxide above 1200°K (1700°F) although the rate of conversion to peroxide below 400°K (440°F) is almost negligible. The monoxide will also decompose to form NaOH and Na_2CO_3 in the presence of moisture and carbon dioxide.

The composition of ambient air and 2% reduced oxygen air is listed in Table A-2 and shows that the energy contribution of CO_2 to a sodium fire would be negligible while moisture would take a minor part.

TABLE A-2

COMPOSITION OF AMBIENT AIR AND 2% REDUCED OXYGEN

Species	Air	2% Oxygen
Nitrogen	787,000	978,700
Oxygen	210,000	21,000
H_2O	2,700	270
CO_2	300	30

Table A-3 lists the probable major oxide formed and released by the fires listed. Chemical analysis of experiments performed at Atomics International and elsewhere confirm these predictions.

TABLE A-3

OXIDE PRODUCTS OF SODIUM FIRES

Type	Formed	Airborne	Temperature (°F)	Environment
Spray (2% O_2)	Peroxide	Peroxide	<1700	Oxidizing
Spray (21% O_2)	Monoxide	Monoxide	>1700	Oxidizing
Pool (2% O_2)	Monoxide	Monoxide	<1700	Reducing
Pool (21% O_2)	Monoxide	Monoxide*	>1700	Reducing

*Airborne oxide will possibly convert slowly to peroxide if possible

SODIUM FIRES AND AEROSOLS

- PROGRAM OBJECTIVES
  - CHARACTERIZE FIRES BY ENERGY RELEASE AND BEHAVIOR OF REACTION PRODUCTS
  - DEVELOP ANALYTICAL MODELS, AND COMPUTER CODES FOR SAFETY ANALYSIS
  - DEVELOP SAFETY SYSTEMS
- RECENT APPLICATIONS
  - FFTF
  - FBR 500 Mwe DEMONSTRATION PLANT
  - ANL 1000 Mwe PLANT FOLLOW ON

70-MA1-48-376

FIGURE 1.

SODIUM FIRE HEAT BALANCE RELATIONSHIPS

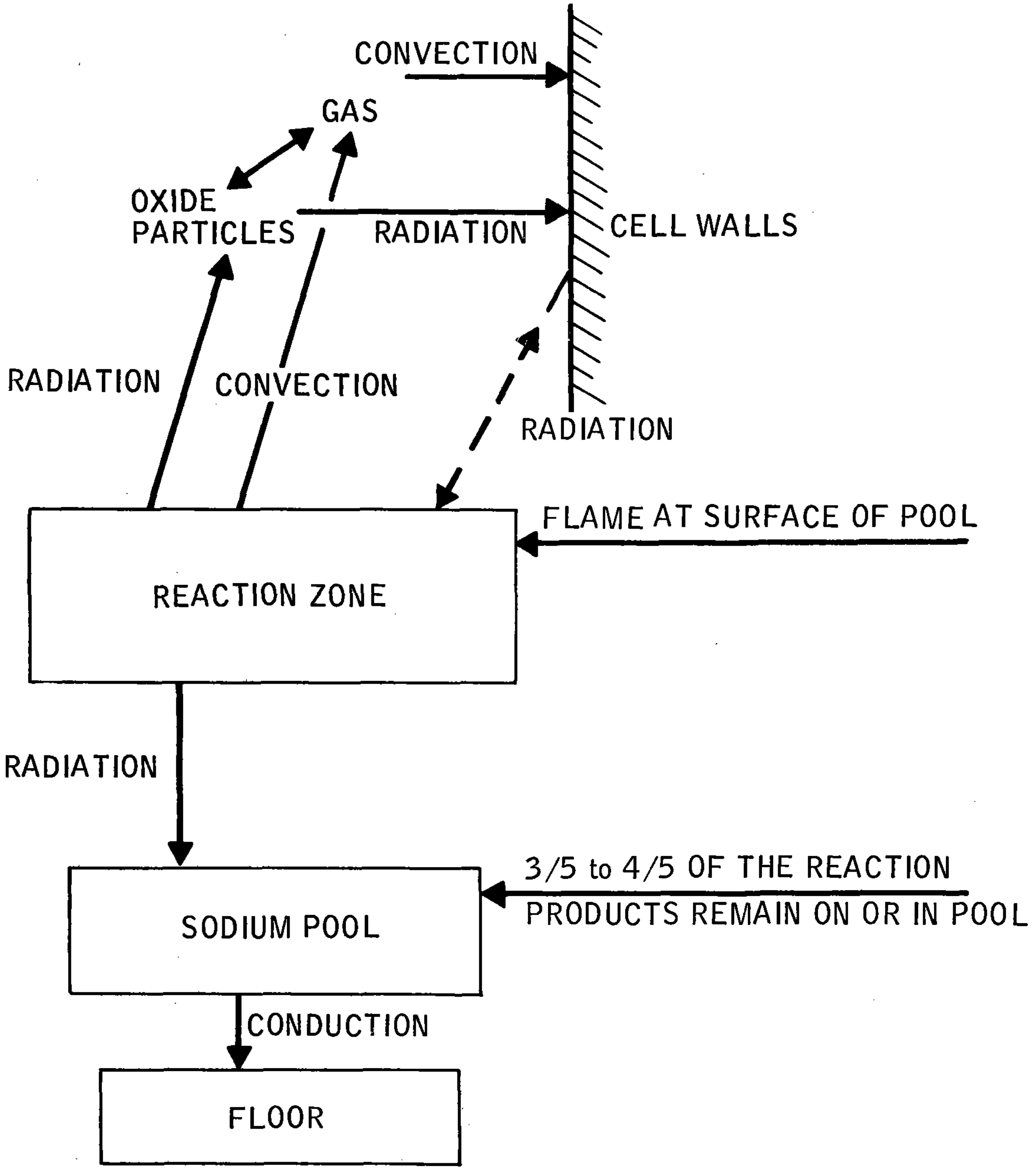
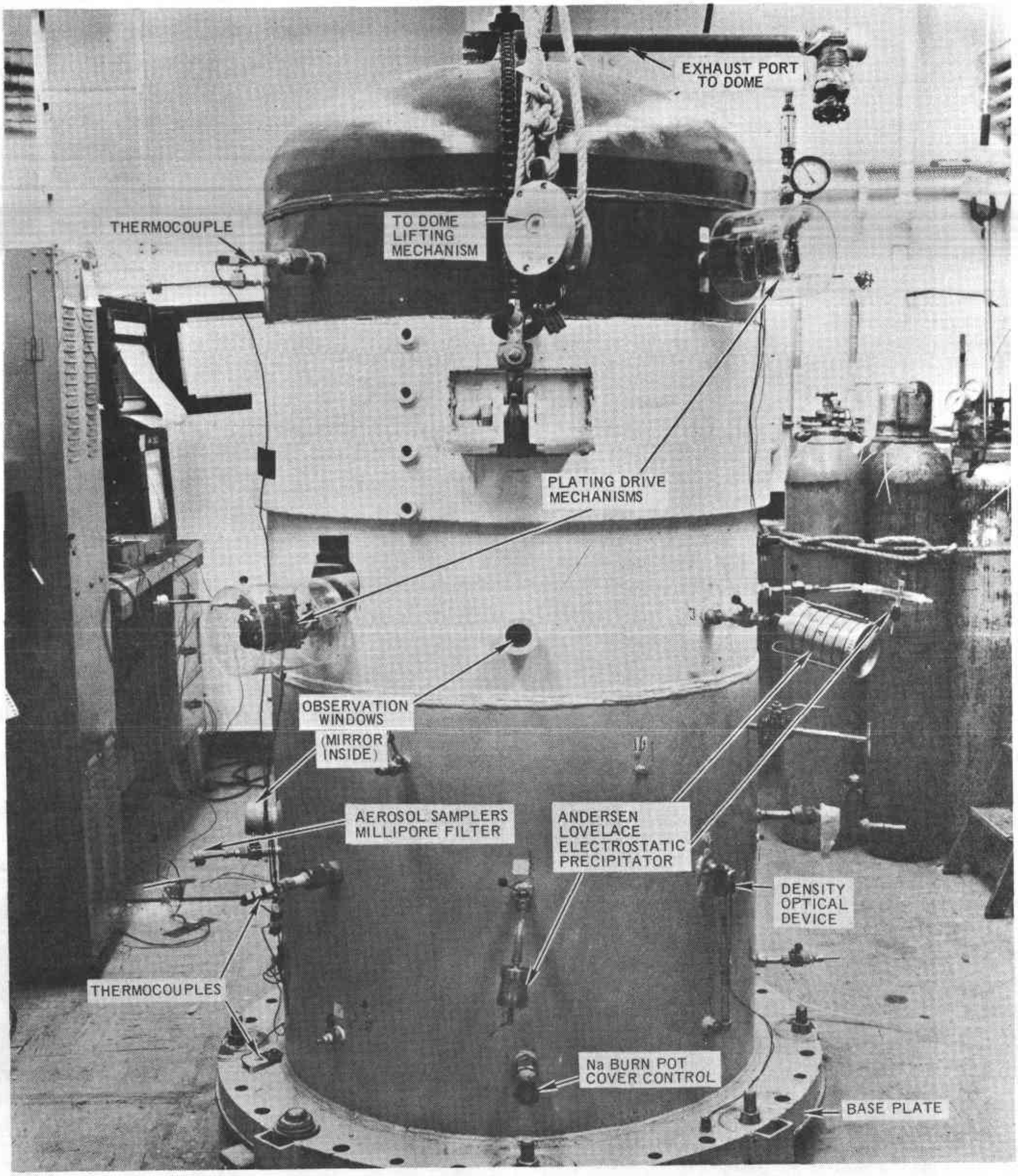
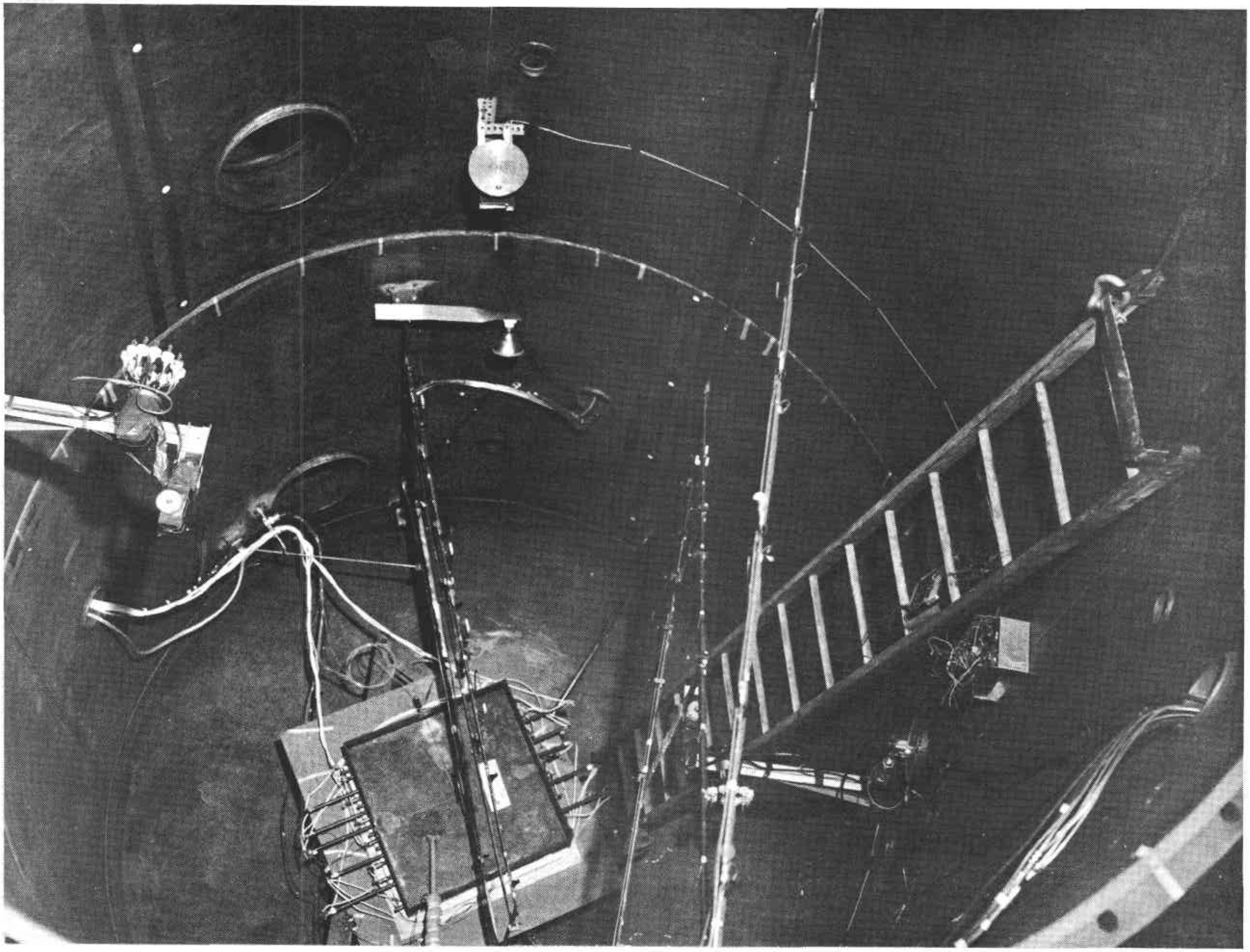


FIGURE 2. EXTERIOR VIEW OF SMALL TEST VESSEL



70-MA1-48-177

FIGURE 3. INTERIOR VIEW OF LARGE TEST VESSEL

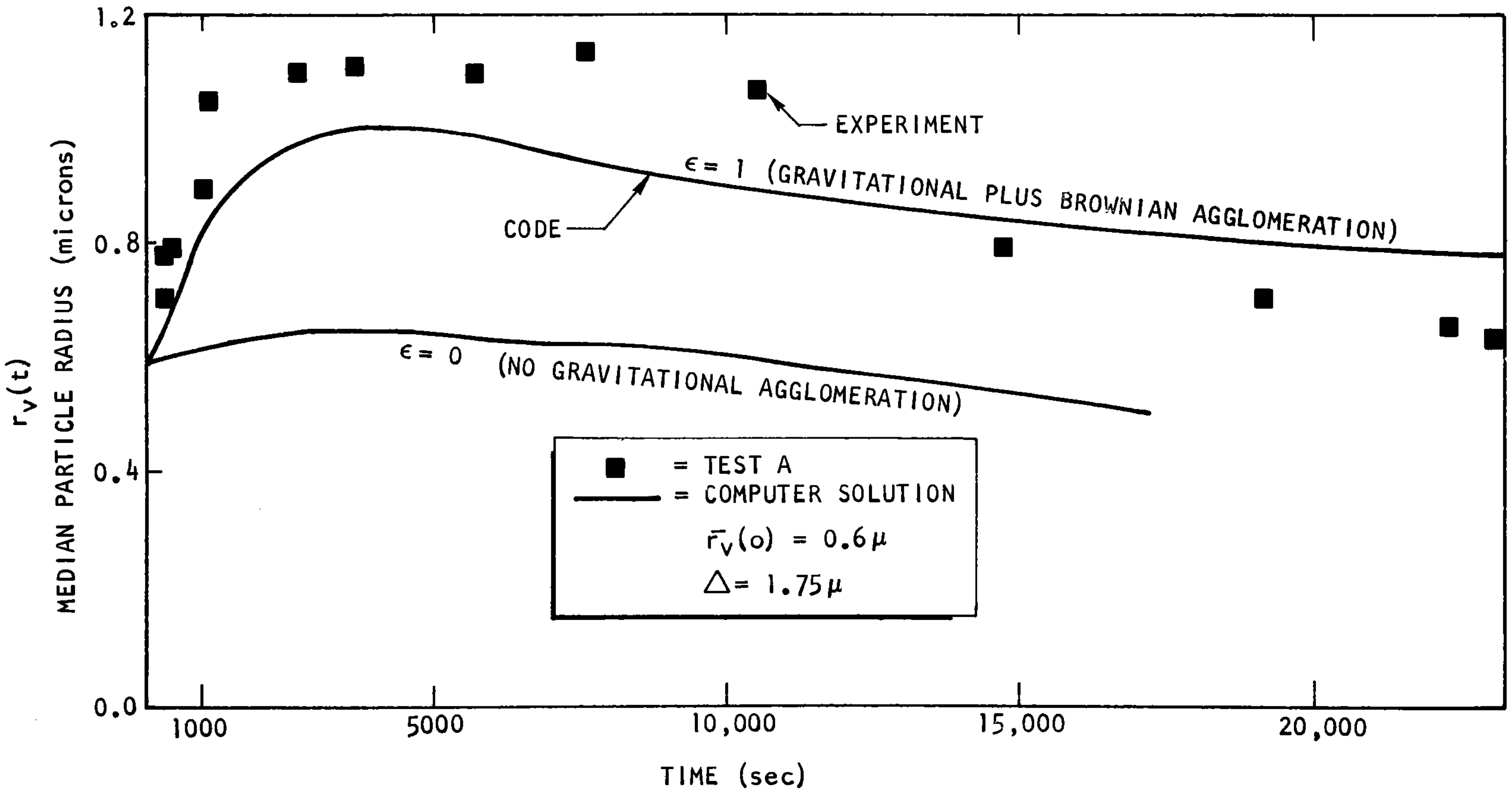


70-MA1-48-178

FIGURE 4.

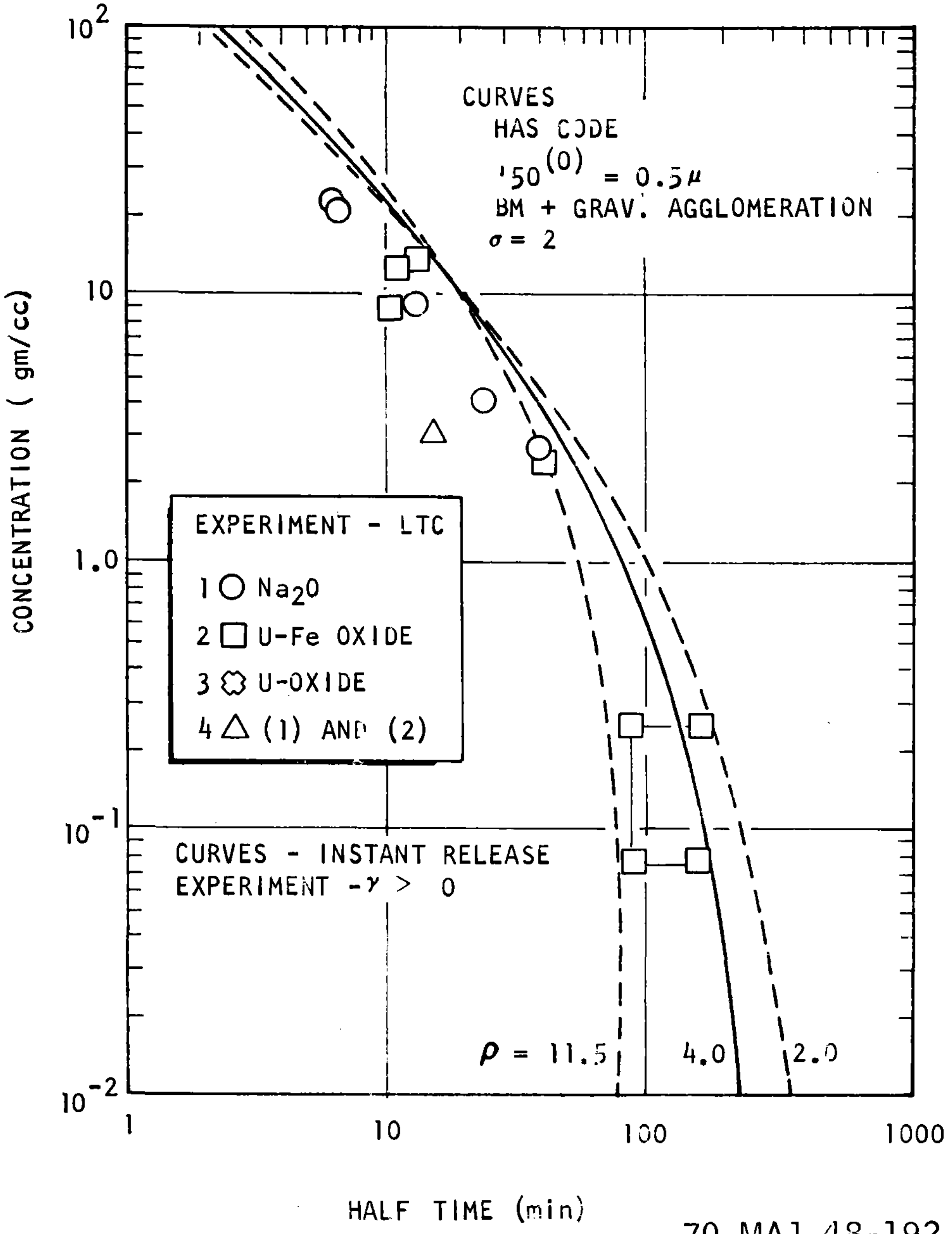
EXPERIMENTAL-CODE-COMPARISON

(MEAN RADIUS BY VOLUME)



70-MA1-48-191

FIGURE 5. EXPERIMENTAL-CODE-COMPARISON OF INITIAL CONCENTRATION AND HALF-TIME



70-MA1-48-192

FIGURE 6.

EFFECT OF INITIAL CONCENTRATION ON RATE OF FALLOUT

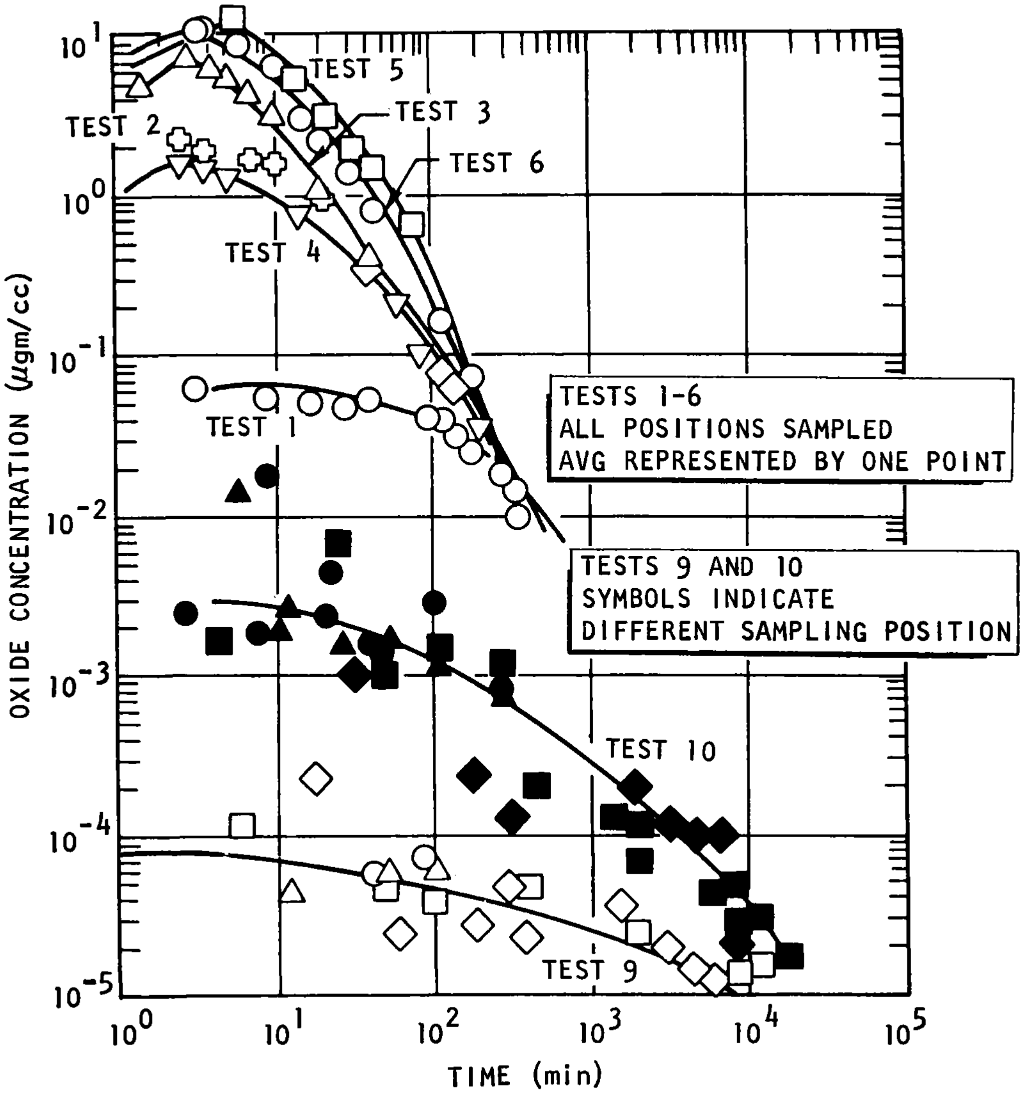


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FIGURE 7.

LTC UO_2 TEST NO. 4, AIRBORNE CONCENTRATION vs TIME FOR COMPONENTS OF AEROSOL MIXTURE

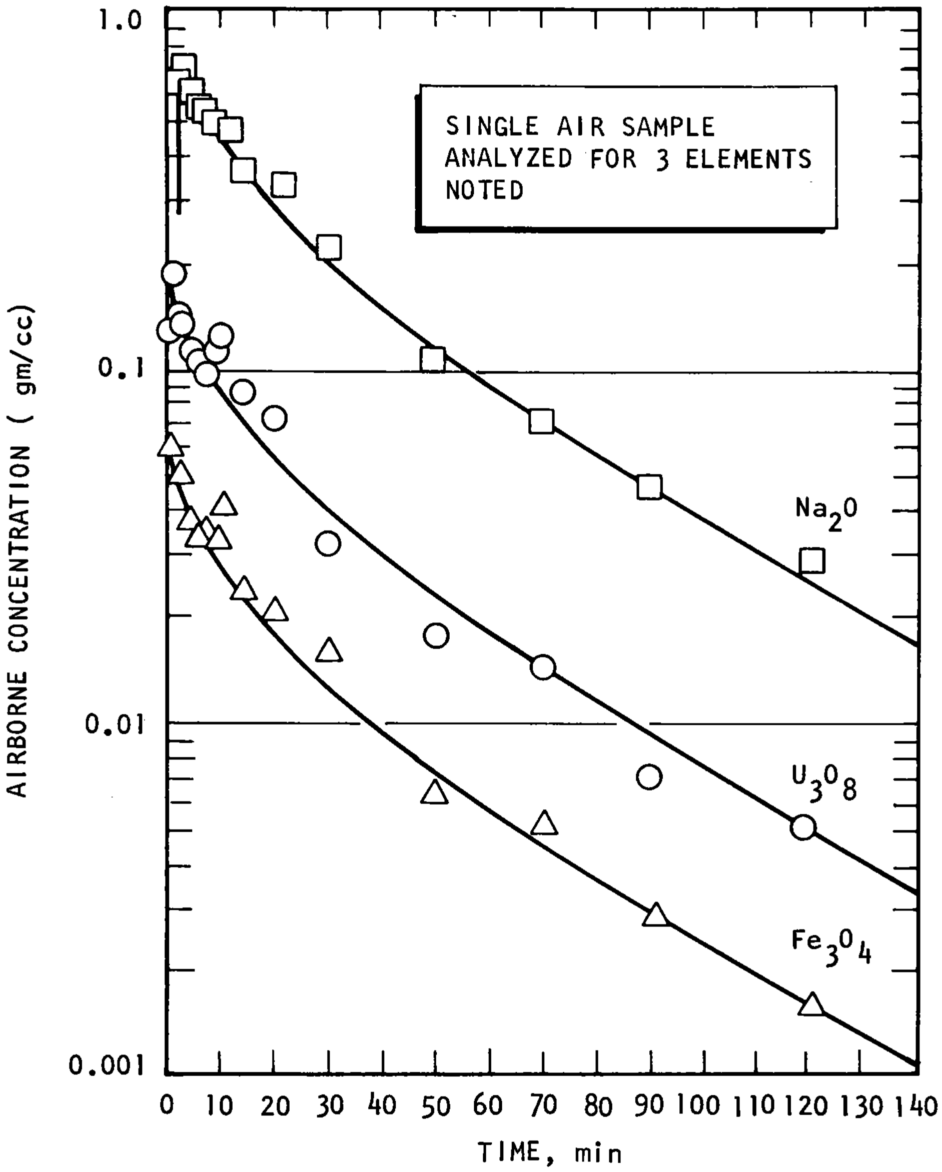

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FIGURE 8. AIRBORNE MASS CONCENTRATIONS AND SETTLED MASS VS TIME FOR LTC UO_2 NO. 6

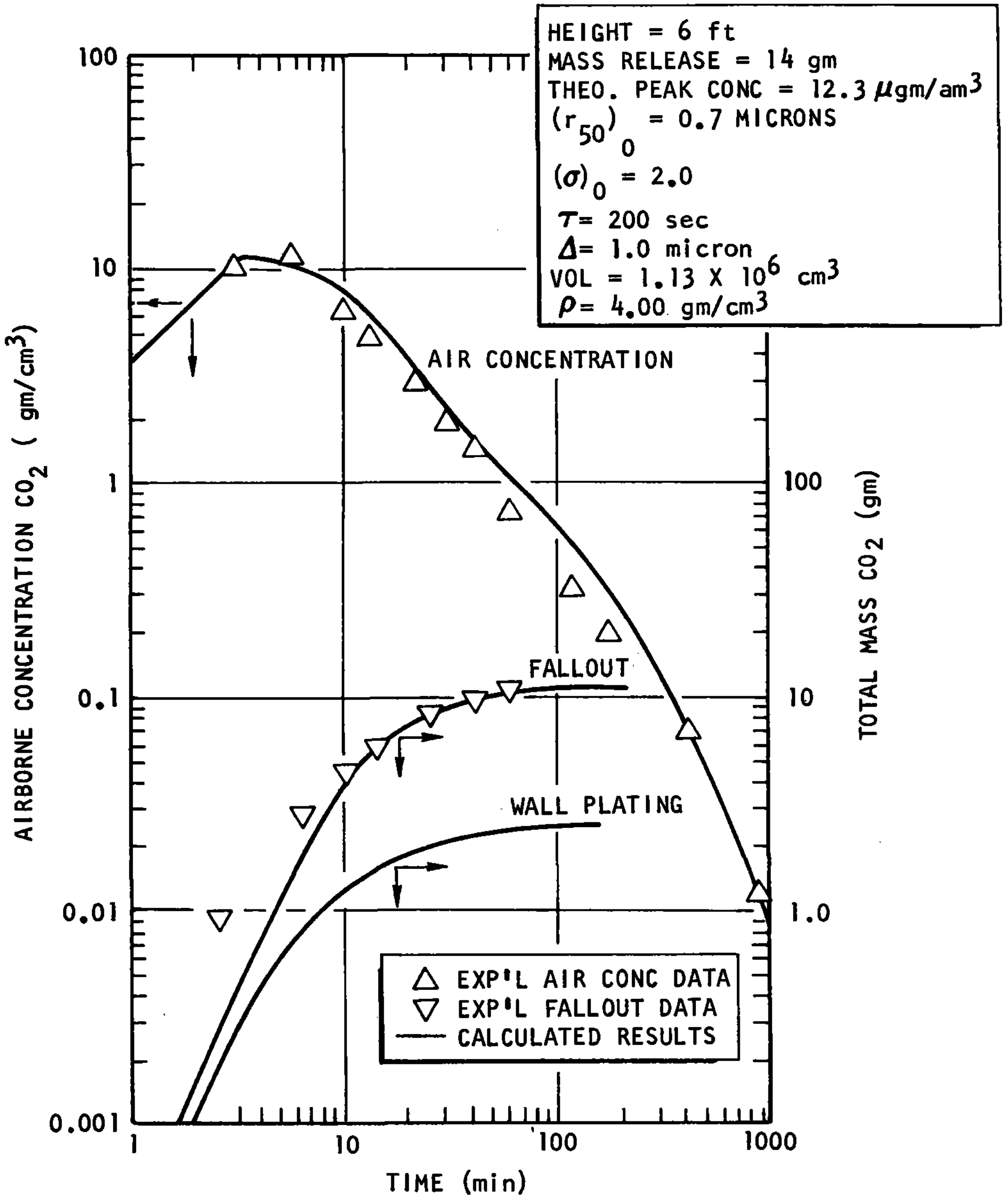

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FIGURE 9. HAA CODE vs PHASE II, TEST 2

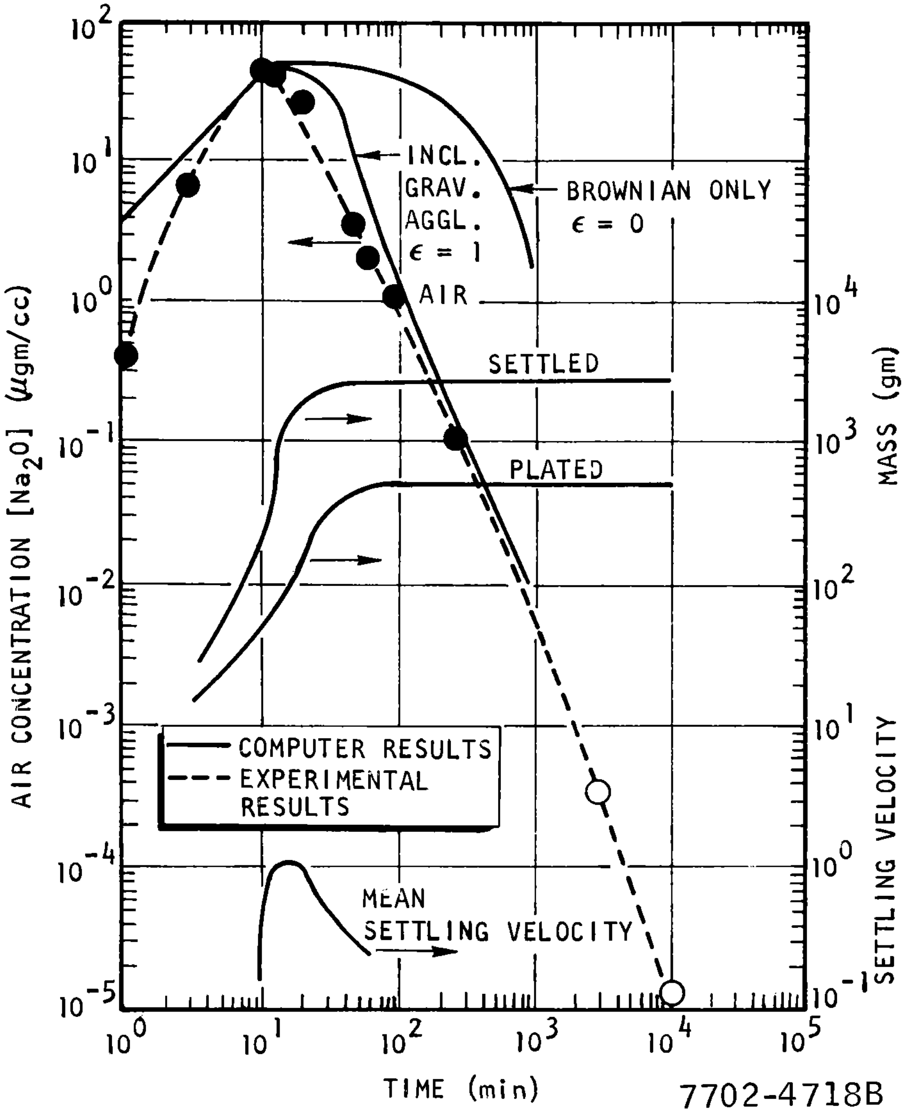

FIGURE 10.

COMPARISON OF SODIUM FIRE ANALYSES WITH SINGLE CELL EXPERIMENTAL RESULTS (SYSTEM PRESSURE)

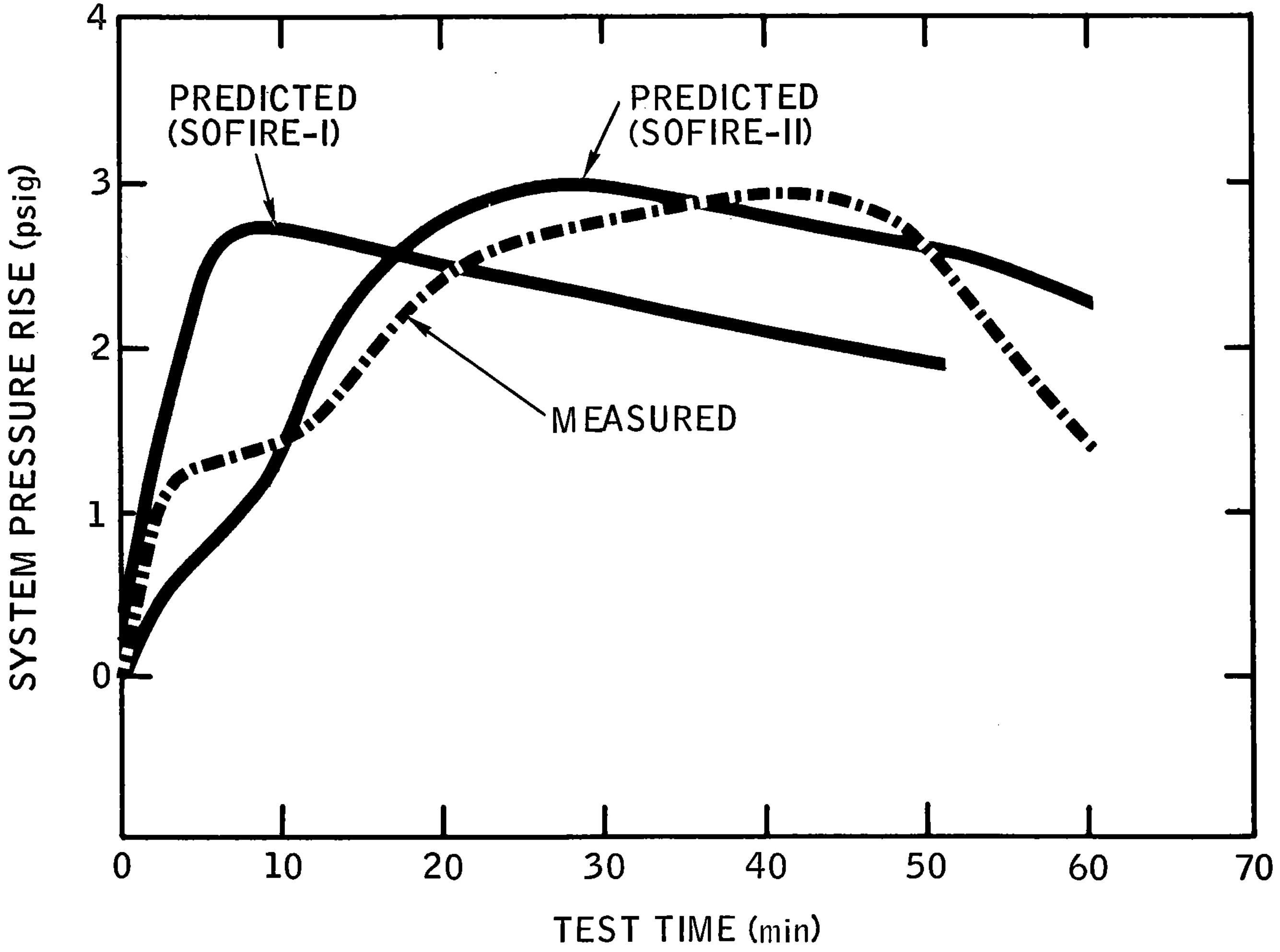

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FIGURE 11

COMPUTED AIRBORNE MASS AND LEAKAGE FOR INNER CONTAINMENT, CASE 2C

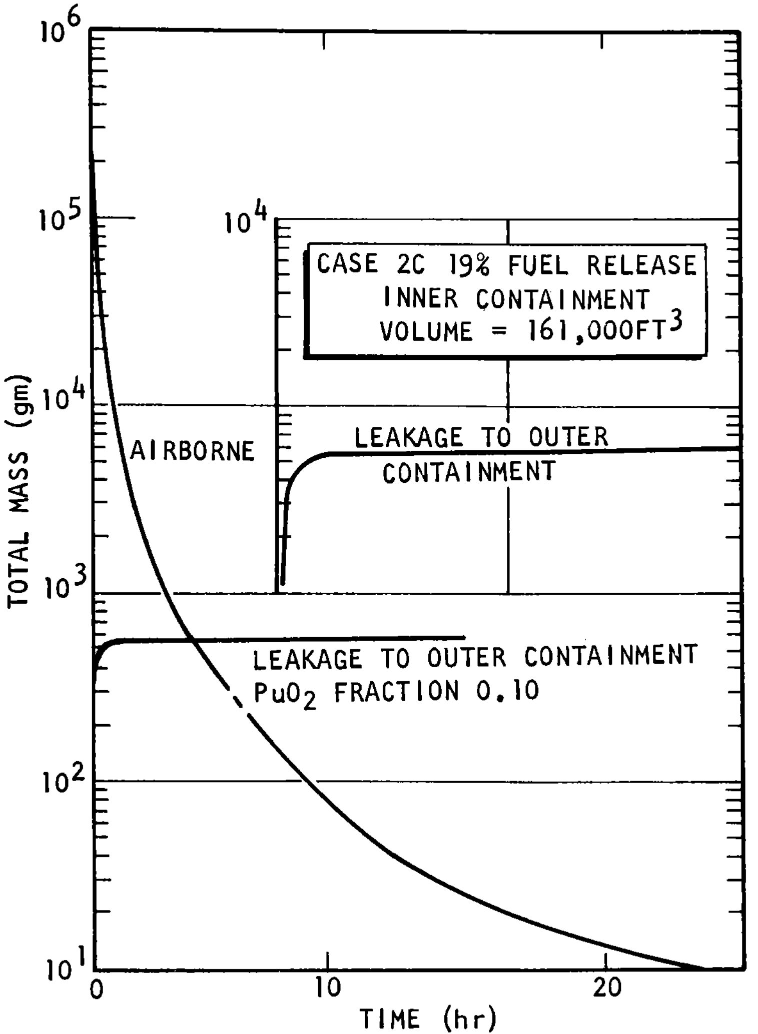

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FIGURE 12.

COMPUTED AIRBORNE MASS AND LEAKAGE FOR OUTER CONTAINMENT, CASE 2C

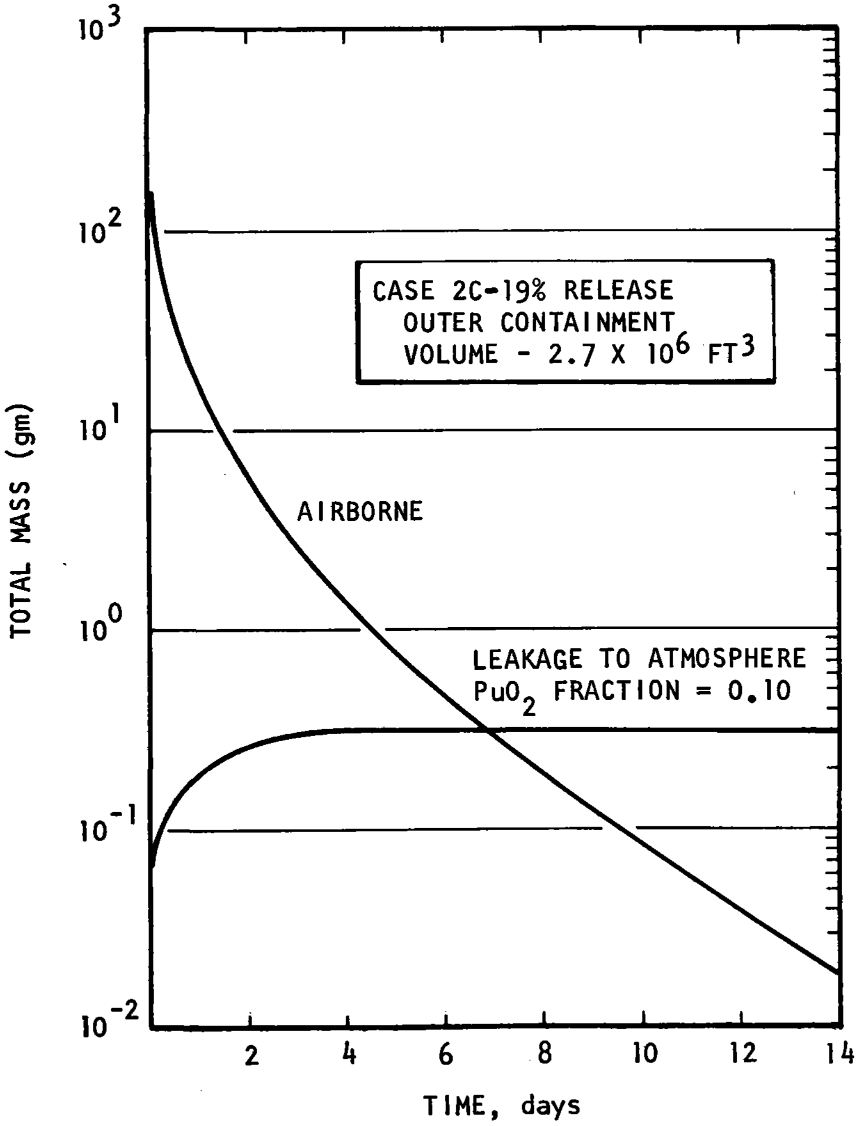
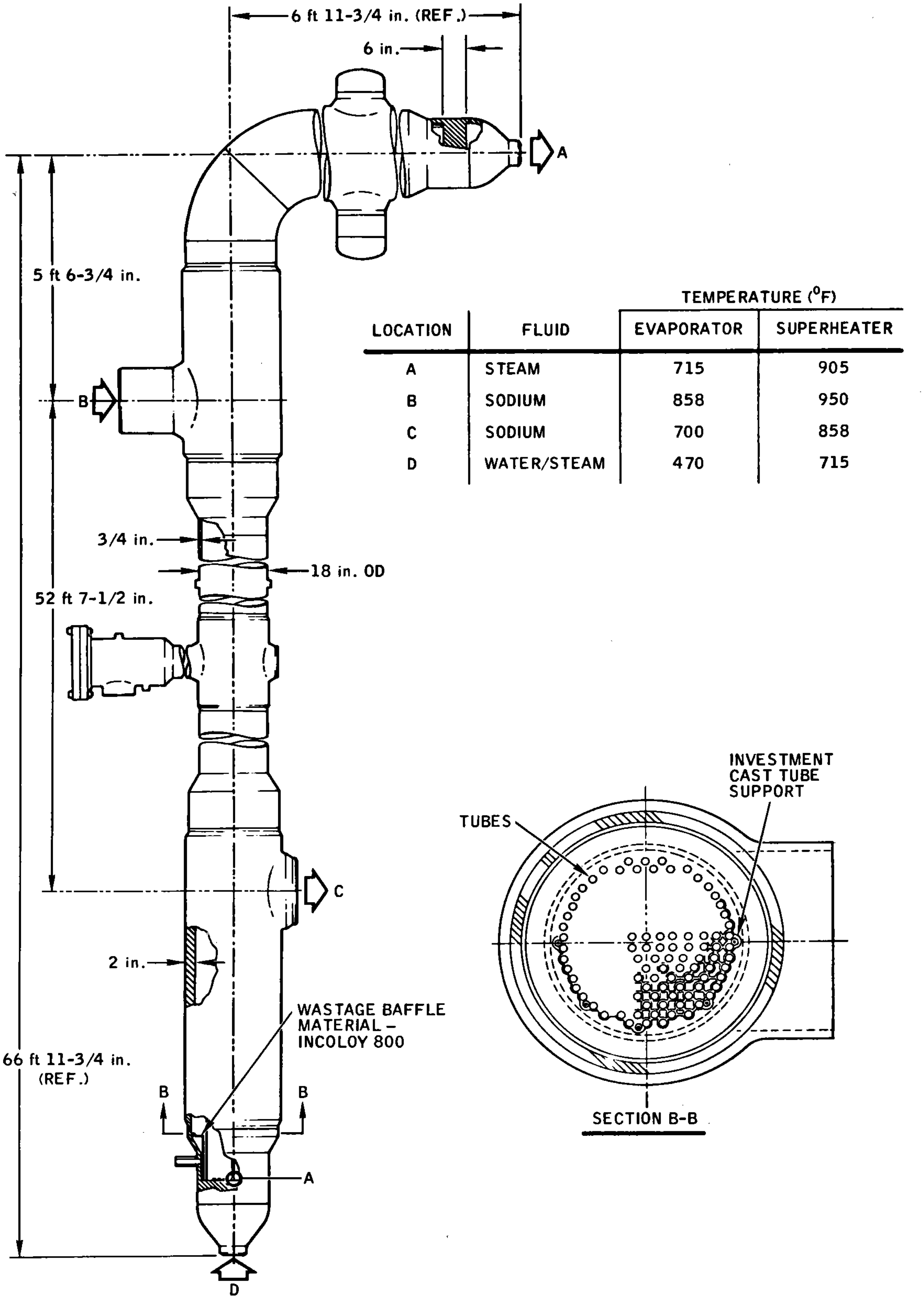


FIGURE 13. TYPICAL FBR STEAM GENERATOR



LOCATION	FLUID	TEMPERATURE (^oF) EVAPORATOR	TEMPERATURE (^oF) SUPERHEATER
A	STEAM	715	905
B	SODIUM	858	950
C	SODIUM	700	858
D	WATER/STEAM	470	715

6999-2501A

FIGURE 14.

TUBE-TO-SHEET WELD DETAIL OF FBR STEAM GENERATOR

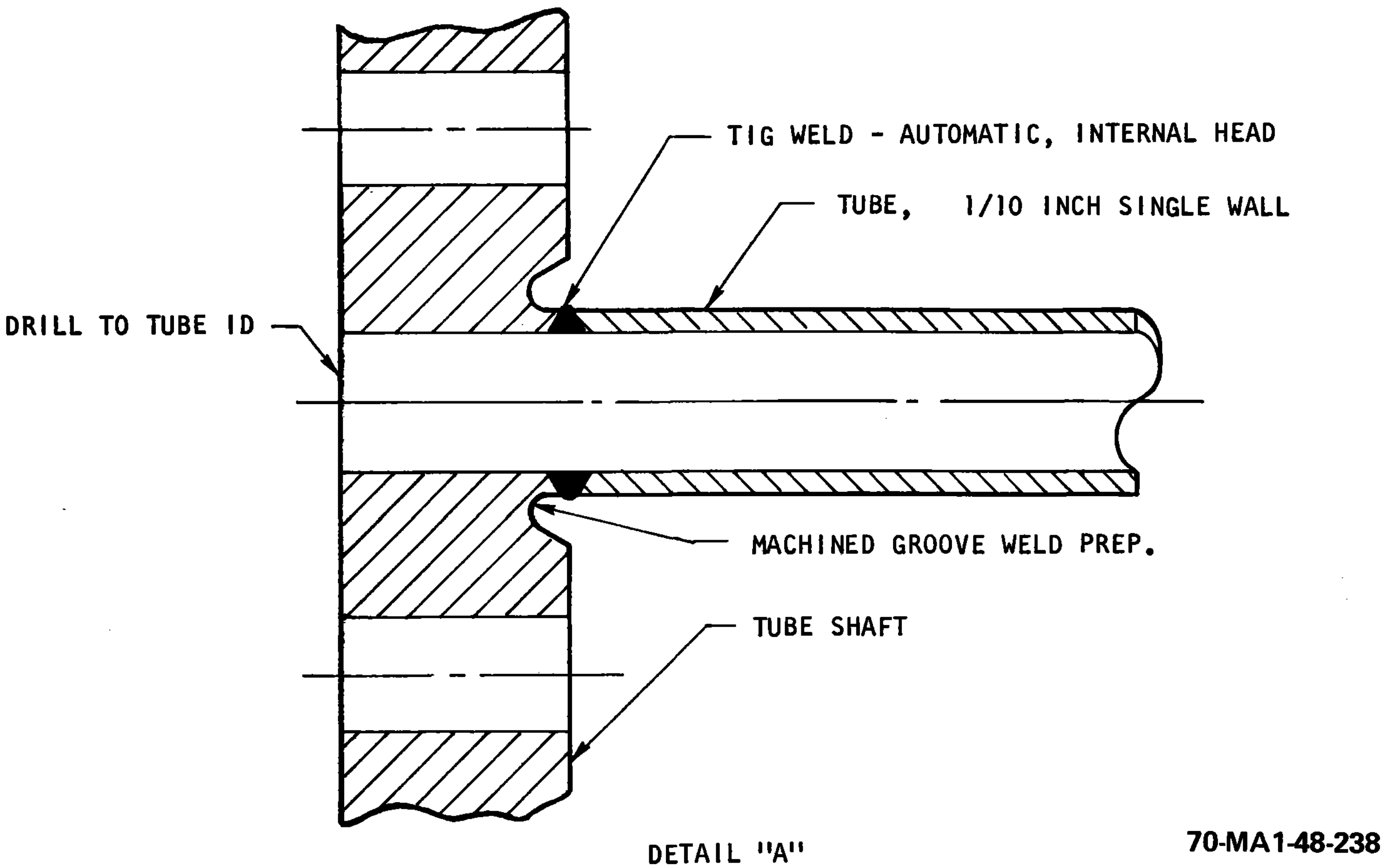


FIGURE 15. TYPICAL PRESSURE TRANSIENT

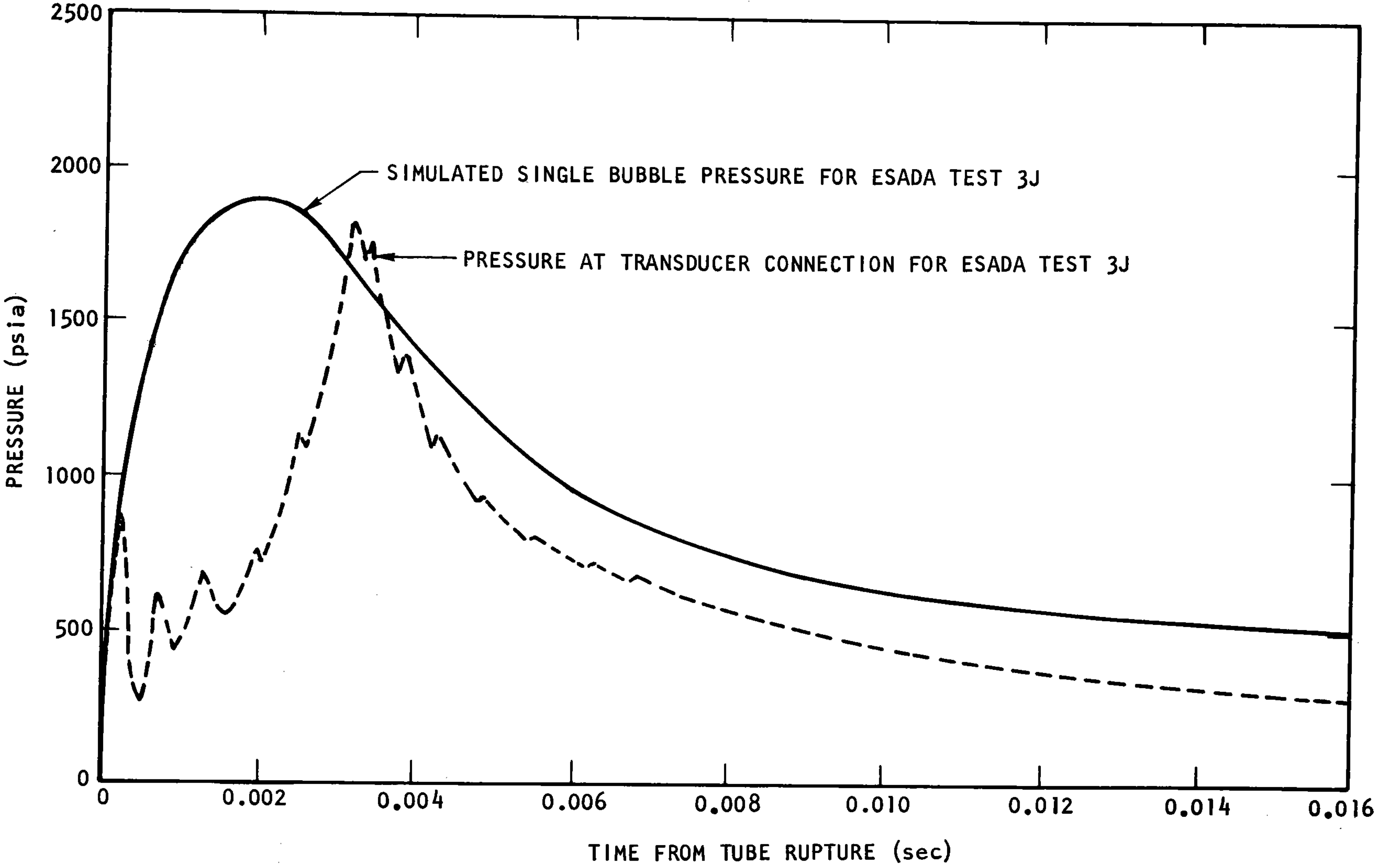


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FIGURE 16. SCHEMATIC OF HOLDING TANK AND SEPARATOR

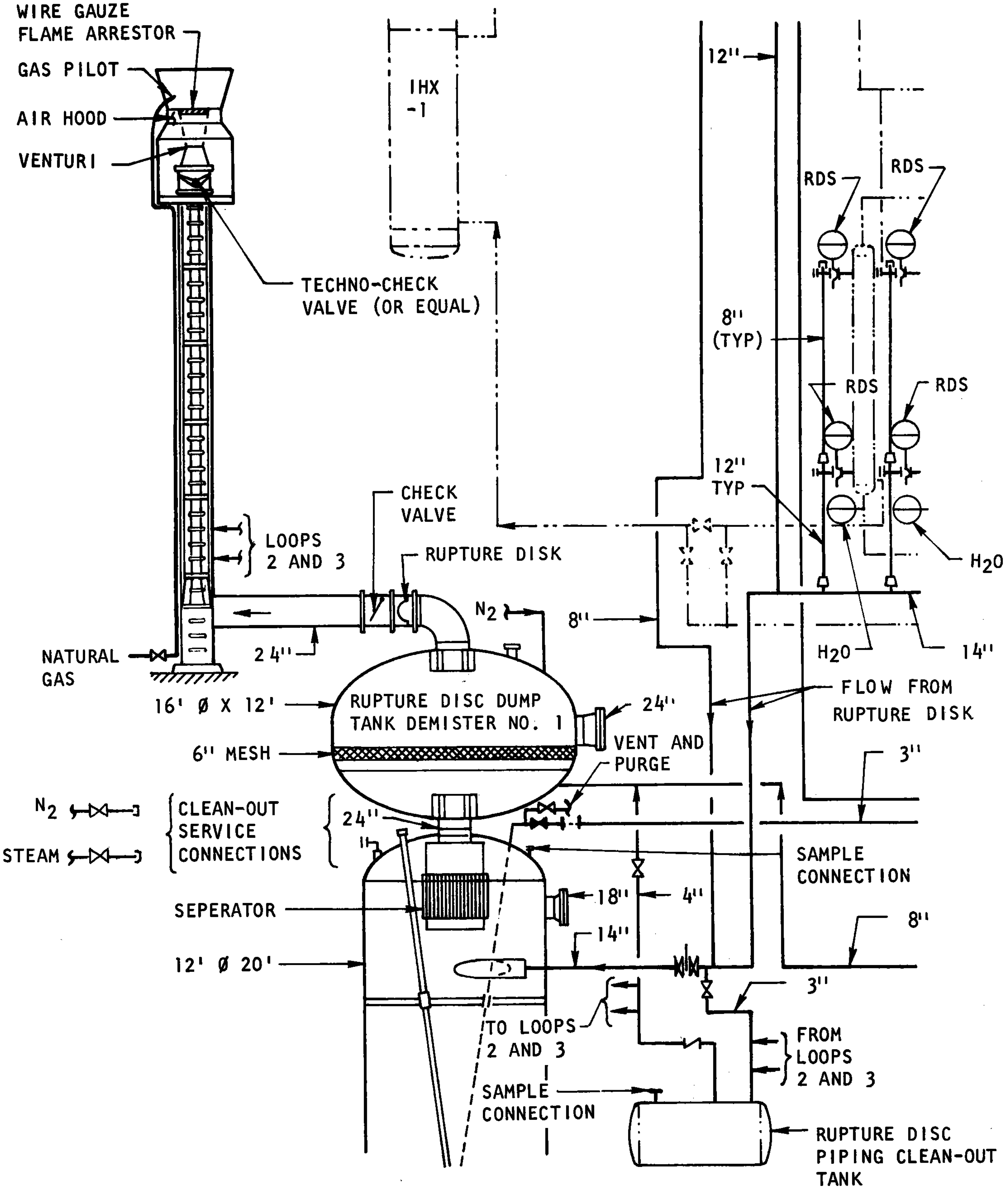


FIGURE 17. TEMPORARY PIPE CLOSURES

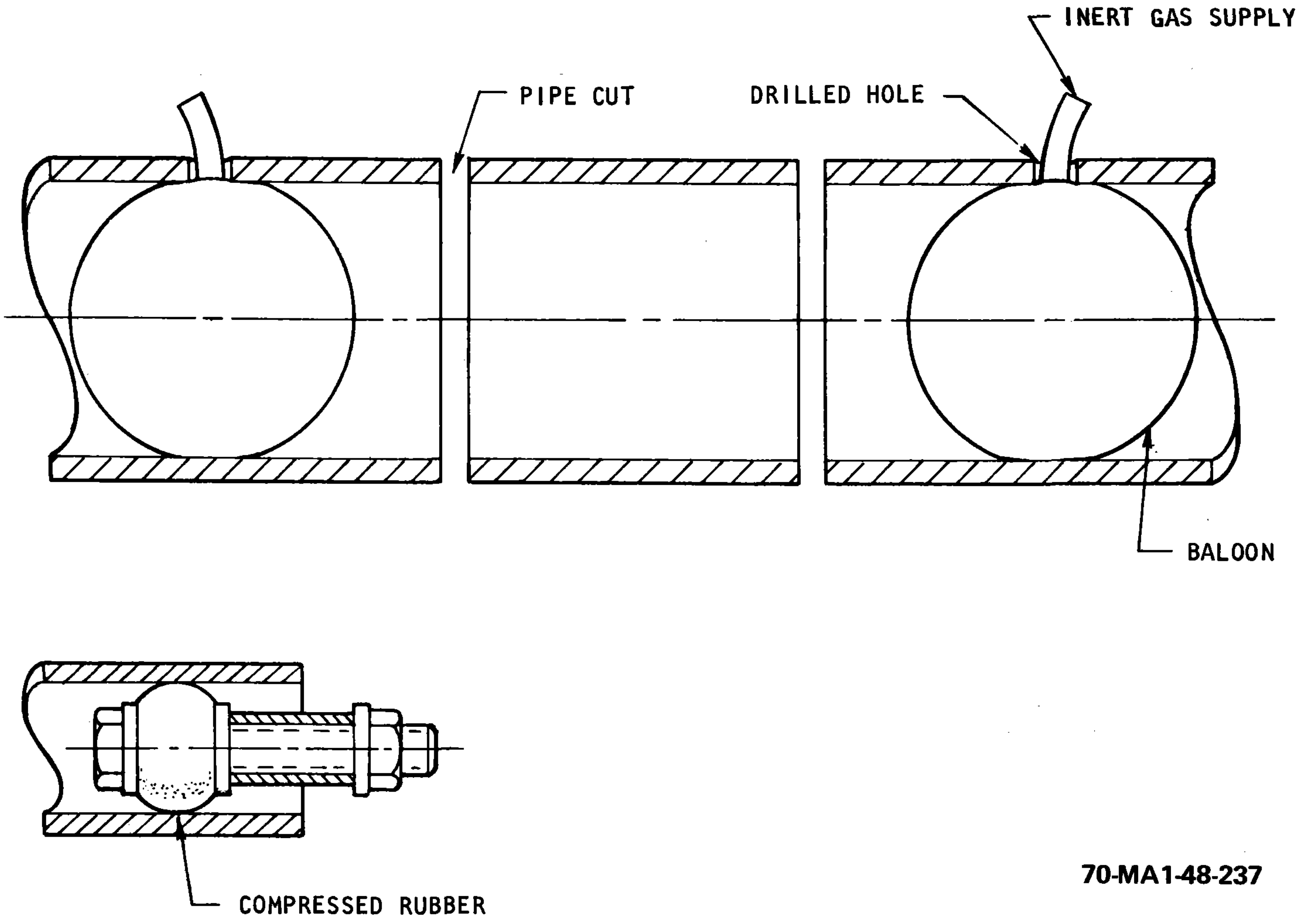
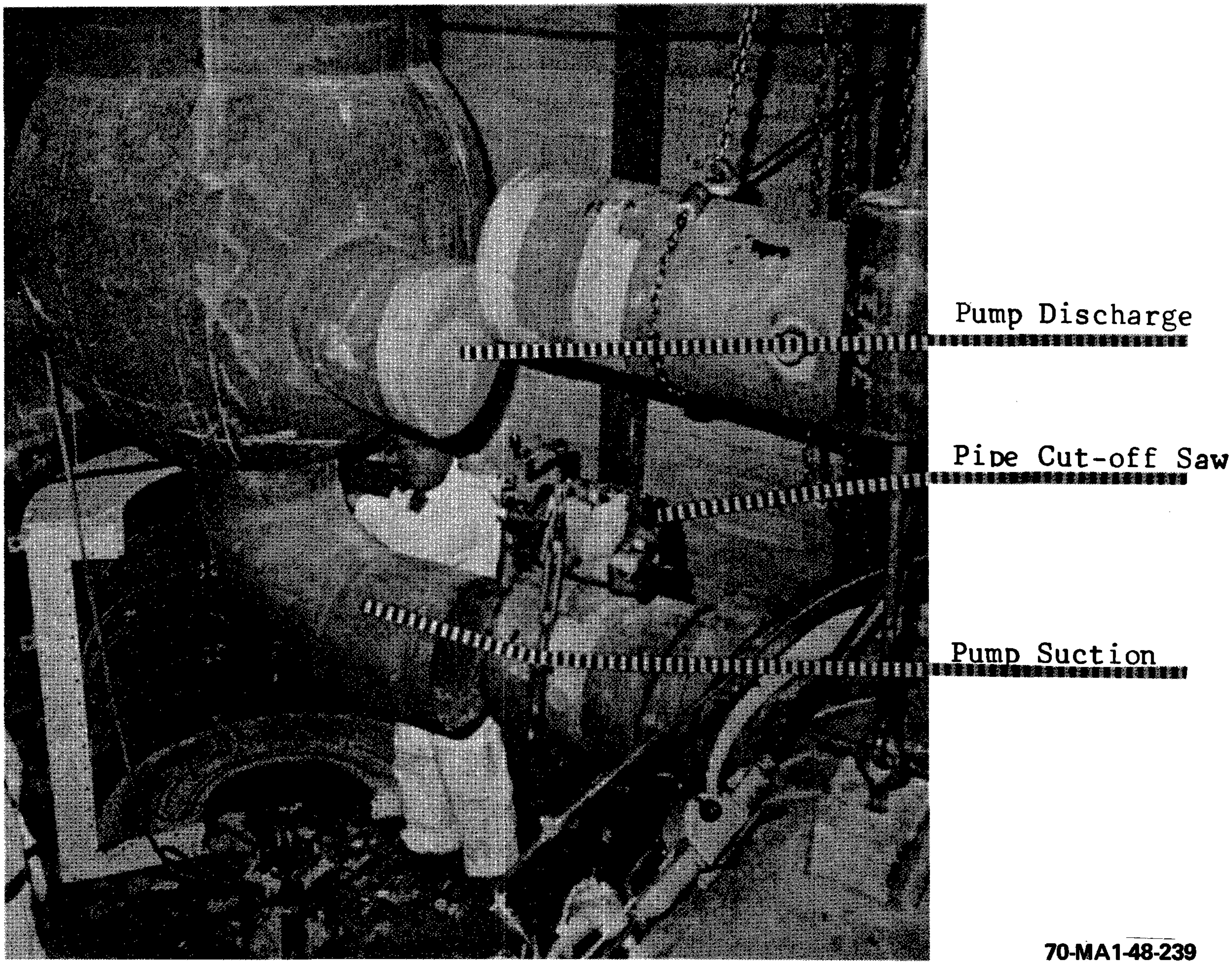


FIGURE 18. PREPARATION FOR REMOVAL OF PRIMARY PUMP



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SODIUM WATER REACTION

I. FBR STEAM GENERATOR BRINGS SODIUM AND WATER INTO CLOSE PROXIMITY

A. TUBE WALL 1/10 in.

B. $Na + H_2O \rightarrow 1/2\ H_2 + Na\ OH$, 45 kcal

C. ESADA FILM

D. DAMAGE IS LOCAL, CAN BE CONTAINED

E. REACTION PRODUCTS CAN BE SAFELY REMOVED

F. PRESSURE TRANSIENT FROM RUPTURED TUBE:

1800 psi, 0.003 sec

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SODIUM WATER REACTION (CONT'D)

I - G. BURST DIAPHRAGM 900 psi IN SODIUM SHELL SIDE

H. MODULE SHELL, 4500 psi (FEEDWATER 3000 psi TUBE SIDE,
2400 psi STEAM AT THROTTLE)

I. ISOLATE MODULE, DUMP WATER, DRAIN REACTION PRODUCTS,
SEPARATE H_2, RECLAIM SODIUM, REACT BALANCE TO
Na $OH \cdot H_2O$ AND DUMP

J. NON CATASTROPHIC LEAKS – MONITOR SODIUM FOR
HYDROGEN

K. REPLACE MODULE

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OPERATION & MAINTENANCE
REACTOR AND EXPERIMENTAL SODIUM SYSTEMS

1. DOCUMENTATION
   - A. EQUIPMENT DESCRIPTION AND PURPOSE
   - B. OPERATING PROCEDURE
   - C. LOG BOOK

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OPERATION & MAINTENANCE (CONT'D)

- II. INITIAL STARTUP
  - A. CHECK LIST
  - B. LEAK TEST
    - 1. PRESSURE DECAY
    - 2. BUBBLE
    - 3. HALOGEN
    - 4. MASS SPECTROMETER
  - C. PREHEAT
  - D. FILL FROM LOADING TANK OR "DUMP TANK"
    - 1. OPERATING LEVEL VS LOADING LEVEL
    - 2. EXPANSION SPACE
    - 3. ESTABLISH CIRCULATION
    - 4. COLD TRAP AND CHECK OXYGEN CONTENT, FLUSH IF NECESSARY
    - 5. BRING UP TO OPERATING TEMPERATURE
    - 6. ESTABLISH ΔT IF REQUIRED
    - 7. ADJUST OPERATING PRESSURE
    - 8. INSTRUMENT CHECK

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OPERATION & MAINTENANCE (CONT'D)

III. SHUTDOWN AND SECURE

1. REDUCE TEMPERATURE TO APPROX. 350°F
2. CHECK OXYGEN CONCENTRATION
3. DRAIN SODIUM – BACK FILL INERT GAS
4. REDUCE TO ROOM TEMPERATURE
5. CHECK GAS SYSTEM AND MAINTAIN SURVEILLANCE ON INERT GAS BLANKET
6. ALTERNATE: STANDBY CONDITION: MAINTAIN CIRCULATION AT 350°F AND COLD TRAP

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OPERATION & MAINTENANCE (CONT'D)

IV. SYSTEM REPAIR
  A. DETERMINE CONDITION OF SYSTEM
    1. DEFINE PROBLEM AND APPROACH
    2. QUANTITY OF SODIUM REMAINING AND LOCATION
    3. TEMPERATURE
    4. GAS BLANKET, PRESSURE & PURITY, LEAKAGE
    5. R/A LEVEL
  B. WRITE PROCEDURE, IDENTIFY OBJECTIVE
  C. HAVE FIRE CONTROL EQUIPMENT, PERSONNEL PROTECTION, FIRE DEPARTMENT STANDBY

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OPERATION & MAINTENANCE (CONT'D)

IV - D. REMOVAL OF PIPE SECTION

1. SYSTEM AT ROOM TEMPERATURE, ATMOSPHERIC PRESSURE
2. R/A CONTROL IF NEEDED
3. EMPTY PIPE, UP TO 4 in.
    - a) SET GAS REGULATOR TO MAINTAIN GAS FLOW
    - b) CUT PIPE: HAND HACK SAW, PORTABLE BAND SAW, SABRE SAW – <u>USE DRY</u>
    - c) TAPE CUT
    - d) COMPLETE SECOND CUT AND LIFT OUT SECTION
    - e) COVER OPENINGS WITH TAPE OR PLUG

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OPERATION & MAINTENANCE (CONT'D)

IV - D - 4. FILLED WITH SOLID SODIUM, UP TO 4 in.
  - a) SET PAN WITH $CaCO_3$ TO CATCH CHIPS
  - b) CUT THROUGH WITH HAND SAW OR POWER SAW
  - c) SLIP TAPE IN CUT TO COVER SODIUM
  - d) MAKE SECOND CUT, REMOVE PIPE SECTION
  - e) TAPE OR LAG EXPOSED SODIUM

5. EMPTY PIPE, LARGER THAN ABOUT 6 in.
  - a) SET GAS REGULATOR TO MAINTAIN FLOW
  - b) DRILL HOLES FOR INFLATABLE BAG SEALS
  - c) INFLATE SEALS TO ISOLATE PIPE SECTION
  - d) RIG PIPE SECTION SUPPORT AND/OR HOIST
  - e) USE ROTARY, CHAIN VISE PIPE CUTTER TO REMOVE SECTION – <u>USE DRY</u>

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OPERATION & MAINTENANCE (CONT'D)

IV - E. REPLACEMENT OF PIPE SECTION

1. FIT UP AND WELD PREPARED JOINT
2. CLEAN SODIUM WELL AWAY FROM WELD AREA
3. SUPPORT PIPE SECTION
4. RIG ARGON WELD GAS BACKFILL AND PURGE
5. FOLLOW ESTABLISHED AND APPROPRIATE WELD SPEC (PRE-HEAT, DYE CHECK, ROOT PASS, POST HEAT X-RAY, LEAK TEST)
6. IF BAGS WERE USED, REMOVE AND PLUG WELD

OPERATION & MAINTENANCE (CONT'D)

IV - F. DETECTION AND REPAIR OF SMALL LEAKS AND NON-LEAKING CRACKS – SYSTEM SHUTDOWN

1. DETECTION TECHNIQUES
    - a) VISUAL OBSERVATION
    - b) DYE CHECK
    - c) ULTRASONIC
    - d) X-RAY
    - e) LEAK TEST – MASS SPECTROMETER GENERALLY NO GOOD
2. REPAIR
    - a) GRIND OUT AND REWELD
    - b) REPLACE PIPE SECTION

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OPERATION & MAINTENANCE (CONT'D)

IV - F - 3. MOST LIKELY LOCATIONS

- a) HEAT ZONE OF PARENT METAL NEAR WELDS
- b) WELD METAL
- c) MACHINED INNER PIPE SURFACES
- d) PIPE OUTER SURFACE – AFTER LONG EXPOSURE ABOVE 800°F TO AIR ATMOSPHERE
- e) PIPE PENETRATIONS (FOR INSTRUMENTS, T, C, ETC.)

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OPERATION & MAINTENANCE (CONT'D)

IV - F - 4. MOST LIKELY CAUSES

a) HIGH RESIDUAL WELD STRESS – POOR WELD DESIGN AND POOR WELD TECHNIQUE

b) SENSITIZED MATERIAL – STRESS CORROSION FROM EITHER SIDE

c) STRAIN RELIEF OR CREEP (IN MECHANICAL JOINTS)

d) EXCESSIVE PIPE LOADS (THERMAL)

e) LOW DUCTILITY OF SOME S.S. UNDER USE CONDITIONS

f) FOREIGN MATERIAL IN WELD (SLAG FROM COATED ROD)

g) MATERIAL DEFECT – COLD SHUT OR SLAG INCLUSION

OPERATION & MAINTENANCE (CONT'D)

IV - G. LEAK DETECTION – OPERATING SYSTEM

1. IN AIR –
   - a) SODIUM OXIDE SMOKE
   - b) OXIDE OR HYDROXIDE BLEEDING THROUGH INSULATION
   - c) OXIDE SPOTS ON BASE PIPE
2. INERT ATMOSPHERE OR VACUUM
   - a) ATMOSPHERE SAMPLE – MASS SPECTROMETER, H REACTION FLAME SPECTROMETER, ETC. (REQUIRES CONTROL OR BLANK)
   - b) ATOMIC ABSORPTION – SODIUM LIGHT SOURCE
   - c) TRACING WIRES GENERALLY NO GOOD

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OPERATION & MAINTENANCE (CONT'D)

IV - H. CLEANING

1. SMALL PARTS – FOR REUSE
   - a) ALCOHOL (ETHYL, METHYL, BUTYL)
   - b) DOWANOL EB (ETHYLENE GLYCOL, n-BUTYL ETHER)
2. LARGE RUGGED PARTS (PIPE) REUSE, OR SCRAP
   - a) STEAM CLEAN
     - 1) PREHEAT AND USE N TO MINIMIZE HYDROGEN EXPLOSIONS
     - 2) REQUIRES OPEN, PROTECTED WORK AREA OR SPECIAL BUILDING
3. CONTROL LIBERATED HYDROGEN GAS
4. LIQUID NH_3 TAKES Na INTO IONIC SOLUTION
5. USE OF CO_2
6. COMMONLY AVAILABLE CLEANING MATERIALS WHICH ARE DANGEROUS
   - a) WATER
   - b) CCL_4
   - c) TRICHLOROETHYLENE
   - d) ANY CLORINATED HYDROCARBON

OPERATION & MAINTENANCE (CONT'D)

V. MAINTAINING SAFETY
  - A. WELL THOUGHT OUT, WELL UNDERSTOOD PROCEDURES
  - B. HAZARDS
    - 1.1 THERMAL BURN
    - 2. CHEMICAL BURN
    - 3. EXPLOSION
  - C. USE BARRIERS, PROTECTIVE CLOTHING, FIRE CONTROL EQUIPMENT
  - D. GET RID OF SCRAP
  - E. AN OPEN SYSTEM IS A DANGEROUS SYSTEM

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STORAGE & HANDLING

I - SHIPMENT FROM THE SUPPLIER

- A. TANK CAR
  - 1. SOLID – 80,000 lb
  - 2. REMELTED BY HOT OIL
  - 3. TRANSFER FROM CAR TOP CONNECTION, PRESSURE DIFFERENTIAL
  - 4. NITROGEN BLANKET
  - 5. SAFE STORAGE BUT HIGH DEMURRAGE COST
- B. 55 GALLON DRUMS
  - 1. 440 lb, SOLID CAST
  - 2. PREMELT WITH 6 kw BARREL HEATER, 3 hr
  - 3. TRANSFER BY PRESSURE DIFFERNTIAL (LIMIT TO 5 psid)
  - 4. CAN BE USED AS A SUPPLY STATION FOR SMALL QUANTITY
  - 5. INERT GAS BLANKET
  - 6. GOOD STORAGE

STORAGE & HANDLING (CONT'D)

I- C. DRY PACKED BRICKS
  1. 1, 2-1/2, 5, 12 & 24 lb BRICKS, 300 lb/DRUM
    a) TRANSFER IN AIR TO MELT STATION
    b) ALWAYS COATED WITH OXIDE
    c) CRUDE, POOR STORAGE, LOW COST
D. REAGENT GRADE
  1. 1 lb BARS, DOUBLE SEALED CANS
  2. OPEN AND USE IN CONTROLLED ATMOSPHERE (INERT)
  3. POOR STORAGE AFTER OPENING

II. MELT & RECEIVER STATION
  A. CAN BE PORTABLE
  B. SEVERAL BARRELS CAPACITY
  C. SAFE, FLEXIBLE

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STORAGE & HANDLING (CONT'D)

III. HOLDING OR "DUMP" TANK
   A. PERMANENTLY INSTALLED
   B. INTEGRAL PART OF USING SYSTEM
   C. PUMP OR PRESSURE TRANSFER
   D. GRAVITY "DUMP"

IV. MAINTAINING PURITY
   A. BEGINS WITH PURCHASE SPEC. & QUALITY CONTROL
   B. PICKS UP OXYGEN AND OTHER IMPURITIES DURING SHIPPING AND TRANSFER
   C. CAN BE CONTROLLED FOR MOST APPLICATIONS (10 ppm) BY COLD TRAPPING BEFORE USE
   D. CONTROL PURITY OF COVER GAS & AIR INLEAKAGE
   E. TESTS FOR PURITY

STORAGE & HANDLING (CONT'D)

V. TRANSFER OPERATION – (GRAVITY, PRESSURE DIFFERENTIAL, PUMP)

A. TEMPORARY LINES MUST BE:

1. OF SUITABLE MATERIAL – USUALLY STAINLESS STEEL
2. LEAK TIGHT UP TO 350°F
3. PURGED OF AIR (VACUUM OR INERT GAS)
4. VALVED TO PURGE, LEAK TEST, ISOLATE AND REMOVE
5. PREHEATED – USUALLY ELECTRICALLY
6. 1 in. OR LARGER

B. DETERMINATION OF QUANTITY

1. WEIGHING
2. FLOW METER
3. LEVEL INDICATORS
4. GAS PASSAGE

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STORAGE & HANDLING (CONT'D)

VI. MAINTAINING SAFETY

A. CAREFUL PLANNING AND PROCEDURES

B. SAFETY TRAINING FOR OPERATING PERSONNEL

C. PERSONAL PROTECTIVE CLOTHING

D. QUALITY EQUIPMENT OF PROPER DESIGN

E. FIREFIGHTING EQUIPMENT – EMERGENCY

F. FIRST AID – EMERGENCY WATER SHOWERS

G. KEEP SODIUM CONTAINED AIR AND WATER OUT. WATCH OUT FOR HIGH HUMIDITY, FOG AND RAIN

H. EMPTY CONTAINERS BACK-FILLED WITH DRY INERT GAS, GET RID OF EMPTIES!

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SODIUM TECHNOLOGY COURSE, SESSION VIII
SODIUM SAFETY
R. T. Johnson

A. SAFETY CONSIDERATIONS

Class D fires, in particular sodium fires, have been periodically experienced in industry. A recent survey was made compiling documented data of sodium leaks occurring in sodium-filled test loops and sodium-cooled reactors. The documented leaks occurred in valves, piping, connections, heat transfer components, pumps and other unspecified components. By far the largest number of reactor system leaks occurred in valves, approximately 48%. Leaks in lines and connections accounted for 32%, and 18% of the leaks occurred in the other components. Operations and plant protection personnel employed current fire combating technology and equipment to contain the fires resulting from these leaks. These dispensing mechanisms and techniques provide the basis of this section of Sodium Technology. Throughout the history of combating Class D fires the emphasis has been placed on obtaining an extinguishing agent that proves most effective on sodium fires. As will be shown later, the effectiveness of a sodium fire extinguishing agent is determined by (1) how well the agent seals the sodium surface from the available oxygen, (2) the compatibility of the agent and the parent sodium, and (3) the efficiency of hand or dispenser application.

1. Safety Considerations in Facility Design

Consequences resulting from a sodium leak can be mitigated by employing safety considerations in the initial facility design, and by adapting and enforcing standard operating practices throughout the lifetime of the plant. Standard facility design features used to attain these goals are discussed.

A general practice has been made to include a metal catch pan to contain sodium in the event of a large leak. These catch pans also serve as cell liners in some facilities. The purpose is to contain the leaked sodium, minimize the surface area by providing partitions within the pan, and prevent structural damage to foundation platform and concrete flooring. The catch pans are constructed of sufficient size to contain 150% of the loop or component capacity. Both test and reactor loops employ dump tanks which serve to contain the loop inventory during shutdown conditions, and provide an additional means to minimize the quantity of spilled sodium by initiating a hot drain during operation. Sodium sampling stations, which are located external to main sodium loops, are provided with sampling isolation valves. In the event of small leaks occurring in these subsystems, proper operation of these valves either isolate or minimize sodium spillage.

2. Safety Procedures

All operating sodium handling facilities conform to standard operating procedures. These procedures are prepared by test and operating personnel and are directed to the safe operation of a system, subsystem or an individual component. Operating procedures encompass three phases of operation: (1) normal operation, (2) infrequent operation, and (3) emergency operation. Operating personnel become completely familiar with these three operational phases in the course of normal work duties and through company-provided training. Contined upgrading of personnel training prevents development of poor work habits and stimulates an air of awareness.

3. Effects of Sodium and Sodium Oxide on Human Tissue

In spite of all precautions it should be recognized that personnel may be exposed to sodium as a result of accidents or firefighting activities. The most likely organs affected would be the skin, eyes and mouth or mucous membranes. Personnel should be aware of the potential reactions and effects on these tissues so that they can take prompt and proper action to prevent or minimize injury. Appropriate first aid and medical assistance should be provided to further minimize damage and treat injuries.

Sodium will destroy tissue as a result of thermal and/or chemical reaction with the moisture in tissue. Both reactions occur simultaneously as a result of (1) heat from hot or burning sodium, and (2) the formation of sodium hydroxides with body fluids.

Even if eye protection is worn, minute particles of sodium and its hydroxides may enter the eye during release. Water flushing is recommended and the services of an ophthalmologist should be obtained immediately.

Treatment of sodium eye injuries with boric acid and/or mineral oil or other types of eye medication has been discouraged. The materials are difficult to remove from the eye and interfere with evaluation of the extent of the injury.

Persons wearing contact lenses should not be allowed to work with sodium systems, regardless of the type of eye protection used. Loss of a contact lens in an emergency situation, rotation of the lens behind the eyeball, and/or the reaction of sodium with plastics used in contact lenses may result in more serious injury. A minute particle of sodium worked under a contact lens will produce a much more aggravated injury than the reaction with tears and/or water flushing.

The effects on the mouth, throat, and lungs will be mainly those of the reaction of the oxides into hydroxides and resultant caustic burn to sensitive mucous tissues.

Immediate use of the safety shower, eye wash station, drinking fountain or other sources of water is recommended. Complaint of soreness in the mouth, throat, and lungs should be noted and the services of a medical doctor, preferably an otolaryngologist, should be obtained immediately.

a. Short-Term Emergency Exposure Limit

In order to plan for accident conditions, a short-term emergency exposure limit was requested from the Atomic Energy Commission (AEC). The AEC in turn made the request to the National Academy of Sciences (NAS), National Research Council. The NAS recommendations are quoted below:

"The corrosive action of alkalies on the eye, skin and mucous membranes is well known and need not be reviewed in this report. Inhalation of mists of sodium hydroxide may produce effects varying from mild irritation to severe pneumonitis depending upon the concentration. There is a wide variability among persons in their subjective response to caustic dust but it has been observed that, in general, 6.0 mg/m^3 produces intolerable respiratory discomfort.

On the basis of the available data, the Committee on Toxicology recommends the following Emergency Exposure Limits:

10 minutes – 4.0 mg/m^3
30 minutes – 4.0 mg/m^3
60 minutes – 2.0 mg/m^3

Eye contact with mists and dust of sodium hydroxide may produce severe damage and it is therefore recommended that workers be required to wear tight fitting eye goggles when there is a potential exposure to concentrations above 2.0 mg/m^3.

In the case of sodium and sodium oxide, the Committee feels that the levels recommended for sodium hydroxide may be used since these materials are known to react with moisture to form sodium hydroxide."

B. NATURE OF SODIUM FIRES

Extensive experimental efforts have been made to characterize the nature of a sodium fire. During these experiments, the phenomena of burning sodium in normal air atmospheres and reduced oxygen atmospheres were studied. Typically, it was observed that sodium burns at the rate of 0.5 lb/hr-ft^2-% O_2 (2.11×10^{-2} kgm/hr-m^2-% O_2) or approximately 10 lb/hr-ft^2. Surface temperatures approach 1600° F.

In a normal or partially inerted air atmosphere, sodium burns directly on the exposed surface and does not have a flame front as do highly volatile compounds such as alcohol or gasoline. The surface burning can be characterized as nodular burning. Initially, upon exposure of high temperature sodium to air, burning nodules appear and slowly encompass the entire surface. Thus, the burning rate increases from zero to maximum in a finite time period, 5 to 15 minutes. Approximately 30% of the combustion products formed during burning are released as an aerosol. The unreleased combustion products, sodium monoxide or sodium peroxide, remain on the sodium surface forming a crust. The crust acts as a transfer medium through which molten sodium "wicks" to the surface. Depending on the temperature of the sodium container this oxide crust has been observed to migrate up the sides of the container.

Oxidation of sodium occurs at any temperature. Surface oxidation occurs when sodium is in the solid state. At sodium temperatures above the melting point, 207° F, combustion is generally nonsustaining until temperatures are elevated above 400° F. (High humidity environments enhance burning at low sodium temperatures and cause hydrolization during the solid state.) The availability of oxygen also has a direct effect on the burning rate of sodium. Although combustion occurs at all temperatures above 400°F and oxygen concentrations of 21%, the ability to sustain a sodium fire below oxygen concentrations of 10% diminishes due to the excellent heat transfer properties of sodium.

C. SODIUM FIRE EXTINGUISHING AGENTS

The basic elements employed in combating a sodium fire are: (1) eliminate or restrict oxygen from the sodium surface, (2) allow the sodium mass to cool to ambient temperatures to prevent further burning, and (3) minimize the sodium spill. In choosing an extinguishing agent the following requirements should be considered.

1) Does not support combustion

2) Non-toxic

3) Non-reactive to materials

4) Floats

5) Non-hydroscopic, does not dehydrate

6) Easily fluidized

7) Stores without compaction

8) Inexpensive.

Fire protection agencies have tested numerous compounds to determine their effectiveness in combating sodium fires. Most of the compounds tested did not adhere to requirements 1 and 3 above, or enhanced the sodium fire by nature of unwanted secondary reactions. One promising material, potassium carbonate ($KHCO_3$), extinguished low temperature sodium fires but at high temperatures, hydrogen was released from the compound and enhanced burning resulted. In recent studies, the formerly preferred extinguishing agent METL-X, NaCl plus a binder, was found to cause stress corrosion of stainless steel when applied to local piping leaks which had burned sufficiently to produce sodium oxides. When applied to a small sodium fire occurring in a low humidity atmosphere, CO_2 was found to increase thermal decay and prevent local burning. However, when applied in a high humidity atmosphere, water droplets were frozen and swept onto the sodium surface. Most recently, in conjunction with Atomics International and the LMEC, Ansul Corporation developed a nylon fluidizer-binder which, when combined with sodium carbonate, Na_2CO_3, permitted use in pressurized dry powder extinguishers as an extinguishant for sodium fires. This compound has been approved by the Underwriters Laboratory for use in Class D fires and appears by the trade name Na-X.

D. SUGGESTIONS FOR SODIUM HANDLING

Personnel should be made aware of the potential hazards associated with handling sodium and under what conditions maximum hazards exist. Proper orientation should deal with the reactions that occur following exposure to sodium and sodium oxides and the effects of these reactions on human tissue. A final suggestion for handling sodium includes the use of protective safety gear and familiarization with emergency equipment.

Normal handling of sodium at room temperatures require routine safety measures. The minimum requirements for protective gear include: (1) fire retardant coveralls which have no pockets or cuffs on the sleeves or legs, (2) chemical goggles, (3) hard hat provided with a full-face shield, and (4) 14-in. PVC gauntlet gloves. Minimal hazards are experienced when handling room temperature sodium, however, high humidity conditions cause hydrolization of surface sodium.

$$Na + H_2O \rightarrow NaOH + H$$

This reaction is exothermic and causes a temperature rise within the sodium. A similar reaction occurs when oxidized sodium is exposed to high humidity

$$Na + 1/2\ O_2 \rightarrow Na_2O + H_2O \rightarrow 2\ NaOH + H\ .$$

Both reactions occur when metallic sodium or its oxides contact the moisture in tissue.

The PVC gloves offer excellent protection in the prevention of sodium contacting tissue. The flame retardant coveralls also provide the same protection. The full-face shield provides protection against flaking material coming in contact with the face. The most recommended safety item is the chemical goggle, which should be used in all handling procedures.

The same protective safety gear described above is used when sodium disposal procedures are followed.

Sodium fires within a room, or building, may involve small or large quantities of sodium. In either fire, sufficient quantities of sodium oxide aerosols are released to fill the affected volume. Because of the irritating smoke, self-contained breathing apparatus is recommended for respiratory protection. To completely protect personnel entering the area, fire-retardant head covers are also recommended.

Operations which are performed with sodium at elevated temperatures such as transfer when filling a test loop or apparatus, require step-by-step procedures. Normally the system into which sodium is to be transferred is completely inerted with nitrogen or argon and preheated to transfer temperatures. The transfer is made with operators and fire personnel present. At the completion of the transfer, the sodium shipping containers are thoroughly cleaned before returning to storage or the manufacturer. In the event of minor leaks during transfer, consequences are minimized by isolating the leak through valve closure and application of extinguishing agents.

E. DISPOSAL OF SODIUM

As soon as practicable after a sodium fire , the residue, which will consist of unburned sodium, hydroxide, oxides, and Na-X extinguishing agent, should be shoveled into a dry metal container. Since disturbing the residue may cause the sodium to re-ignite, the operation should be carried out as quickly as possible and the lid placed on the container, to help exclude the oxygen from the container. While the residue is being shoveled into the container, a layer of Ansul Na-X dry powder should be applied (scoop or shovel) over the sodium, to further prevent oxygen contact with the unburned material. Containers or sodium residue should then be taken to an approved isolated area, where proper disposal can be made.

If proper personnel safeguards are available and the personnel have been trained in the disposition of sodium, the residue can be disposed of by burning in an open pan or through flushing with water. After disposing of the residue, the containers must be flushed with water. Flushing with water must be done carefully, since it is always possible that some unreacted sodium may remain after burning. Care should be taken to position oneself up-wind from the sodium smoke being emitted from burning or flushing operations.

F. FIRE FIGHTING FILM

G. EXTINGUISHERS – USE

Extinguishing agent dispensers are available from Ansul and sized in 30, 150, 350, 1000, and 3000 lb dispensers. The 30 lb units are portable and pressurized with CO_2 cartridges. The wheeled 150 and 350 lb units and the larger trailer mounted units are pressurized with nitrogen. All extinguishers containing sodium carbonate are painted yellow and identified with "Na-X" stenciled vertically in red letters. To prevent misinterpretation, those dispensers containing sodium chloride are painted yellow with a 7-in. red band painted around the bottom of the container. On the red band is stenciled "METAL-X" in white letters.

Only dry powder dispensers labeled Na-X will be found in work areas which require a noncorrosive extinguishant. Those areas not affected by the possibility of chloride stress corrosion of stainless steel are provided with either dispenser.

H. SODIUM REACTIONS

1. Sodium-Water Reaction

When liquid sodium (Na melts at about 207°F) and water are brought into contact with each other a vigorous exothermic chemical reaction takes place.

Sodium hydroxide and sodium oxides are formed and heat and hydrogen are liberated. The behavior and consequences of these reactions will depend on whether the reaction occurs in a free ambient environment or whether the system contains air or an inert atmosphere. Each condition is discussed separately below.

a. Liquid Metal-Water Reaction in Ambient Atmosphere

If the liquid metal water reaction occurs in air, ignition of the liberated hydrogen and oxygen from the air can occur. Steam and additional heat will be produced, and if sufficient water and liquid metal are present the reaction may be explosive. Damage to equipment may occur as a result of thermal stresses, shock waves, pressures, missiles, and secondary corrosive action. Unprotected personnel in the area or vicinity may be exposed to shock, blast, and missile hazards in addition to injury from thermal and caustic burns and inhalation of hazardous products. Smoke, fumes and/or steam may impair visibility and hamper escape and fire fighting activities. Dispersed material can initiate additional fires with combustibles and result in the spread and release of hazardous material to the external environment. If radioactivity is involved or toxic products are produced as a result of secondary reactions with reacting materials, the hazards and consequences are correspondingly increased.

Even small quantities of liquid sodium can be hazardous when mixed with water unless appropriate precautions are taken. For example, gram quantities dropped in a beaker or bucket containing water can cause significant injury to a person holding or standing next to the container (burns, glass splinters, etc.). Initial reactions between pound quantities of reactants can result in significant local damage to equipment and potential injury to personnel located several meters or more from the event. An uncontrolled reaction between multigallon quantities of reactants in a room or vault can completely disrupt the area and severely damage an entire conventional building. Due to the erratic nature of the reaction (violent mixing and splattering) the reaction is difficult to prevent or control if the reactants are free to contact each other.

Because of the potential hazards from liquid metal-water reactions it is common practice to completely exclude water from areas where these materials are handled in an air environment. If the use of water is necessary, specially designed provisions and procedures must be employed to prevent possible contact (e.g., during equipment failure or accidents) or to limit and control the interaction (e.g., during cleaning or waste disposal operations).

b. Reaction in Controlled Environment

Liquid metal-water reactions in a rigid container or controlled atmosphere (e.g., closed vessel or inert atmosphere vault) generate heat and free hydrogen. The reaction rate is very rapid and if the free volume in the system is limited, a correspondingly rapid rise in pressure will occur. If sufficient water and liquid metal are involved to result in pressure exceeding system limitations, the system will rupture. The initial event may be sufficiently violent to result in additional damage to surrounding equipment or unprotected personnel in the vicinity. If the rupture occurs in, or vents to, an air environment, secondary reactions between the liberated hydrogen and oxygen will occur, resulting in additional hazards to equipment, facilities, and personnel.

2. Other Reactions

Liquid sodium may affect or react chemically with many other common materials and may result in physical damage to equipment, fire, and injury to people. Some of the materials and characteristics which designers and operating personnel should be particularly aware of are discussed below.

a. Structural Materials

1) Metals — Most irons and steels are relatively inert and resistant to attack by liquid sodium and present no immediate safety hazards due to chemical reactions. However, not all are suitable for system use at high temperature and for long system lifetimes. For example, excessive corrosion or solubility can degrade the system integrity and lead to hazardous conditions (plugging, fouling, leaks, rupture).

   Aluminum melts at about 1200°F and should thus not be expected to provide isolation or containment for Na at high temperatures or under accident conditions where temperatures approaching or in excess of 1200°F will prevail. In general, many metals including tin, zinc, magnesium, copper, aluminum, etc., should not be used in a system which will be in contact with liquid sodium for prolonged periods of time.

2) Concrete — Liquid sodium spilled onto concrete may react with water or chemicals in the concrete and damage or destroy the surface (particularly if the metals are released at high temperature). This should be expected. For example, sodium is molten at 207°F and has been known to ignite in air at temperatures as low as 230°F. It the fire is not extinguished, a rapid rise in temperature will occur. Temperatures in the order of 1300°F have been measured in burning sodium. If the material is in contact with concrete, the temperature of the concrete will soon increase above the boiling point of water (212°F). Spalling of the concrete will occur as a result of heat, steam, and additional chemical reactions between the metal and constituents of the concrete. Splattering and dispersal of hot sodium, caustics, and concrete particles will occur and can result in additional fires and injury to personnel in the immediate vicinity. NaK is molten at about 12°F, may ignite spontaneously when exposed to moist air, and results in the evolution of hydrogen, which may result in even more vigorous reactions. Thus, exposed concrete is not suitable if liquid Na or NaK spills are possible. In practice, drip pans or steel liners over concrete are used to prevent reactions and protect the surface.

3) Insulating Materials — Significant quantities of insulating materials will be required and used in any plant handling liquid metals. The largest quantities will be used for thermal insulation for systems, components, and the facility. However, significant quantities may be used for electrical insulation and this may have significant safety implications, as well.

In general, if the materials are dry or do not contain chemically-bound water (e.g., calcium-silicate or magnesia), the reactions do not present a direct hazard. However, the materials may be consumed as a result of contact with hot Na or NaK and thus their function is destroyed. The temperature of the liquid metal and system will determine the most suitable material.

3. Cleaning Agents

Most common cleaning agents (especially those containing water) will react chemically with sodium. Liquid ammonia, a notable exception, does not react chemically with sodium and may be safely used to clean contaminated equipment or systems. Water, steam, methyl alcohol and ethyl alcohol, butyl alcohol, and butyl cellosolve (in order of decreasing reactivity) will react chemically with alkali metals and are frequently utilized for cleaning systems or in disposal operations. The most frequently used alcohol used for cleaning is Dowanol EB, ethylene glycol monobutyl ether. Cleaning or disposal operations must be well planned and conditions must be controlled to limit the rate of reaction. Accumulation and secondary reactions from evolved hydrogen must be prevented and/or controlled. Alcohol in containers open to the air will accumulate moisture, which in turn increases the reaction rate. The heat of reaction also increases the reaction rate.

I. FIRST AID

In the event sodium comes in contact with tissue, three basic first aid measures are to be performed:

1) Remove clothing if covered with sodium, brush any particles off the skin and hair.

2) Get into a safety shower; continue flushing for 10 minutes.

3. Obtain medical help immediately.

If sodium contacts the eyes, flush thoroughly in an eye wash shower for at least 10 minutes and obtain medical help.

LEAK DOCUMENTATION

NUMBER OF LEAKS IN:

TEST LOOPS	124
REACTORS	109
	233

COMPONENT	PERCENTAGE OF LEAKS
VALVES (MOSTLY BELLOWS)	48%
LINES	17
CONNECTIONS	15
HEAT TRANSFER	8
PUMPS	3
OTHERS	7

PAST REACTOR EXPERIENCE

REACTOR TYPE	LEAKS				DETECTION			
	TOTAL	SMALL <10 lb	LARGE >10 lb	LARGEST LEAK (lb)	LDS	VISUAL	INDIRECT	UNSTATED
1957 SRE	26	26	0	10	0	26	0	0
1959 BR-5	14	11	–	2	5	2	7	0
1962 HNPF	13	13	0	10	3	5	0	5
1963 DFR	7	1	2	4000	2	1	0	4
1965 EBR II	23	16	1	600	4	17	0	2
1966 FERMI	11	9	–	–	9	1	0	1
1967 RAPSODIE	3	–	1	4000	1	0	0	2
1969 SEFOR	2	2	0	2	0	2	0	0
1970 KNK	10	7	3	1100	–	–	–	–
	109	85	7		24	54	7	14

SAFETY CONSIDERATIONS AND FACILITIES SYSTEM FEATURES

- SHUT OFF ISOLATION VALVES IN SYSTEM
- METAL LINED CATCH BASIN 150% CAPACITY
- MINIMIZE EXPOSURE TO CONCRETE
- CATCH OR DUMP TANKS IN SYSTEM
- MASTER ELECTRICAL SWITCH
    - CUT OFF HEATERS AND PUMPS
- INSTRUCTION FORM ON TESTS OR EQUIPMENT WHEN UNATTENDED – HOW TO SHUT DOWN
- RAISED FOUNDATION PLATFORMS
- KEEP WATER AWAY

SAFETY PROCEDURES

- OPERATING PROCEDURES
    - FREQUENT
    - INFREQUENT
    - EMERGENCY
- USE OF EQUIPMENT TAGGING PROCEDURES
- TRAINING

EFFECTS OF SODIUM ON HUMAN TISSUE

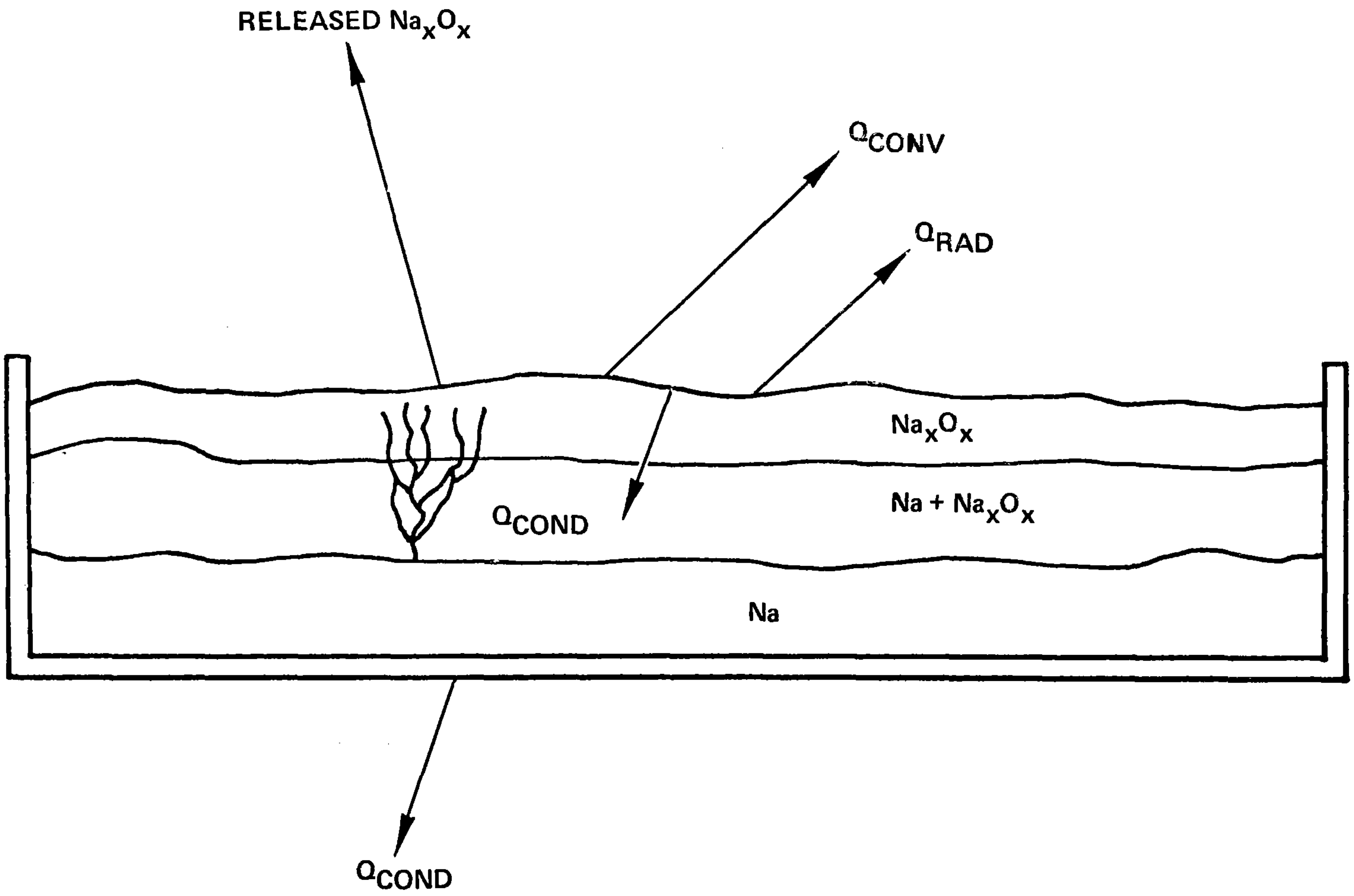
- AMBIENT TEMPERATURES
  - Na + MOISTURE ON TISSUE → NaOH (CHEMICAL BURN)
- ELEVATED TEMPERATURES (ABOVE 207°F)
  - Na + MOISTURE ON TISSUE → NaOH (CHEMICAL + THERMAL BURN)
  - $\mathrm{Na_xO_x}$ + MOISTURE ON TISSUE → NaOH (CHEMICAL BURN)

COMPARATIVE HEAT RELEASE

MATERIAL	HEAT RELEASE (Btu/hr-ft^2)
GASOLINE	600,000
WOOD PALLETS IN PILE 8 ft HIGH	2,100,000
SIMULATED PACKED STOCK, PILED TO PROVIDE AN 8-in. CHIMNEY EFFECT BETWEEN PILES 8 ft HIGH	960,000
ADULT, HEAVY EXERTION	3 to 4000
SEDENTARY ADULT	400
SODIUM BURNING	40,000

REF. NFPA GUIDE FOR SMOKE AND HEAT VENTILATION,
INDUSTRIAL VENTILATION, AGCIH

CHARACTERIZATION OF Na FIRE



METHODS OF COMBATING A SODIUM FIRE

- REMOVE FUEL
- REMOVE HEAT
- REMOVE OXYGEN

EXTINGUISHING AGENT REQUIREMENTS

- DOES NOT SUPPORT COMBUSTION
- NONTOXIC
- NONREACTIVE TO MATERIALS
- FLOATS
- NON HYDROSCOPIC, DOES NOT DEHYDRATE
- EASILY FLUIDIZED
- STORES WITHOUT COMPACTION
- INEXPENSIVE

SODIUM FIRE EXTINGUISHING MATERIALS

COMPOUND	REACTION SEVERITY	DESCRIPTION OF APPLICATION
Na_2CO_3	0	COMPLETE EXTINGUISHMENT OF FIRE
$CaCO_3$	0	COMPLETE EXTINGUISHMENT OF FIRE
NaCl	0	COMPLETE EXTINGUISHMENT OF FIRE
KCl	0	COMPLETE EXTINGUISHMENT OF FIRE
CaF_2	0	COMPLETE EXTINGUISHMENT OF FIRE
SiC_2	0	COMPLETE EXTINGUISHMENT OF FIRE
C	0	COMPLETE EXTINGUISHMENT OF FIRE
$Na_2C_2O_4$	1	WEAK FLAME UP
LiCl	1	MELTS, WILL FLAME UP DURING APPLICATION
NaF	1	MELTS, MILD FLAME UP DURING APPLICATION
Na_2SO_4	1	PARTIALLY MELTS
CaO	1	MELTS, FLAME UP DURING APPLICATION
NaI	1	MELTS, RELEASES SMALL QUANTITY OF I_2
KI	1	MELTS, RELEASES SMALL QUANTITY OF I_2
	DO NOT USE FOLLOWING MATERIALS	
K_2SO_4	4	SEVERE SPATTERING DURING APPLICATION
Al_2O_3	4	SPARKING AND INCREASED SMOKE DURING APPLICATION
CO_2	8	INCREASED BURNING DUE TO CONDENSED HUMIDITY
$KHCO_3$(+50)	5	INCREASED BURNING DUE TO RELEASED HYDROGEN
WATER	10	EXPLOSIVE REACTION

CLOTHING REQUIREMENTS FOR HANDLING METALLIC SODIUM

- FIRE RETARDANT COVERALLS
- CHEMICAL GOGGLES
- HARD HAT WITH FULL-FACE SHIELD
- 14-in. PVC GAUNTLET GLOVES

SUGGESTIONS FOR SODIUM HANDLING

TRANSFER

- COVER GAS PROVIDED TO SODIUM CONTAINER, TRANSFER LINER AND SYSTEM
- LINES AND SYSTEM PREHEATED
- LOW TRANSFER PRESSURE – 7 TO 10 psi
- OPERATOR PRESENT
- FIRE PERSONNEL PRESENT
- SODIUM CONTAINERS CLEANED (CHECK ICC APPROVED)

SODIUM DISPOSAL

- PROPER PROTECTIVE CLOTHES (COVERALLS, HARD HAT, GOGGLES, GLOVES, LEATHER SHOES)
- RESPIRATORY EQUIPMENT AVAILABLE
- SHOVEL RESIDUE INTO CONTAINER
- SEPARATE RESIDUE LAYERS WITH Na-X or $CaCO_3$
- DISPOSE IN OPEN PAN OR THOROUGH FLUSHING WITH WATER

FIRST AID

- BRUSH SODIUM OFF
- SAFETY SHOWER – WITH CLOTHES STRIPPED
- SEE A DOCTOR FOR TREATMENT

PROTECTIVE MEASURES WITH SODIUM

- THE PRINCIPLE OF EXTINGUISHING A SODIUM FIRE IS BASICALLY THE SAME AS FOR ANY OTHER BURNING MATERIAL
  - SODIUM FIRES
    - EXCLUDE AIR AND COOL BURNING MATERIAL WITH INERT MATERIAL
    - SMOTHER BY COVERING BURNING SODIUM WITH SOLID INERT MATERIAL, SODIUM CARBONATE OR SODIUM CHLORIDE
    - ANOTHER TYPE OF INERT MATERIAL IS Na-X PRESSURIZED FIRE EXTINGUISHER
  - RECOMMENDED PROTECTIVE CLOTHING
    - FACE SHIELD, JONES GOGGLES OR CHEMICAL GOGGLES AND DRY PVC GLOVES
    - FLAMEPROOF COVERALLS WITH SUBSTANTIAL SHOES (NO SNEAKERS)
    - CLOTHING SHOULD BE FREE OF CUFFS TO AVOID CATCHING LOOSE PIECES OF SODIUM
- THERE ARE FOUR STEPS TO BE FOLLOWED IN COMBATTING A SODIUM FIRE
  - PROTECT YOURSELF
  - CONTAIN THE COMBUSTIBLES
  - EXTINGUISH THE FIRE
  - CLEAN UP

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