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NUCLEAR METALLURGY LECTURES
Chapter I

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AUTHOR

S. H. BUSH

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NUCLEAR METALLURGY LECTURES CHAPTER I

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NUCLEAR METALLURGY LECTURES

Chapter I

Introduction and Course Summary

INTRODUCTION

The purpose of this course is two-fold. It should serve as a review for the metallurgist of the classical metallurgical concepts applied to such metals as uranium, thorium, plutonium, and zirconium. These metals are relatively unfamiliar to the metallurgist, but the concepts are still the same ones applied to familiar metals. The second purpose is to acquaint the non-metallurgist with the reasons for selection, advantages, and disadvantages of the various fuels and structural materials used in a reactor. Thus, there are two purposes: the first is conceptual, and the second is explanatory. A blending of the two must inevitably result in an oversimplification of the metallurgical concepts and an assumption of certain background material which, actually, may not be available to the non-metallurgist.

It is not the purpose of this course to convert you to metallurgists, but a greater familiarity with the reactions metals undergo in a Hanford pile, the reasons for selecting these metals, and the problems faced in producing and fabricating these metals should be valuable to all technical personnel connected with HAPO. It is hoped that the information presented will familiarize you with the overall program so that you can orient your own work with this program.

Survey of Present Outlines

The present lecture is an introduction to the material to be covered. This lecture will have two purposes. The material to be presented in the remaining lectures will be outlined briefly, and the various concepts to be covered in this course will be discussed.

The next two lectures will deal with what we call pile physics. In these lectures, the relevant physics will be described for the metallurgists rather than the physicist. The fundamental reaction upon which pile operation is based, the fission process, will be described. The two important facets dealing with neutrons in a thermal reactor such as the graphite moderated, water-cooled HAPO piles, will also be discussed. These two facets are the slowing down theory and the diffusion theory of neutrons. Familiarity with these concepts is essential if we are to understand why we are so limited in the selection of structural materials in a thermal reactor.

Two other concepts will be dealt with in the lectures on pile physics. The first is concerned with the distribution of neutrons in a unit cell of a Hanford-type pile. Metallurgically, we are concerned with the microscopic picture. The integration of the reactions occurring in all unit cells is not significant, metallurgically speaking. The behavior of the fuel and structural components within the unit cell is adequate for our purpose. The second concept deals with the processes by which the total fission energy is transferred to the materials composing the pile. When we consider that a fission event releases approximately 200 million electron volts from the fission fragments, prompt neutrons, prompt gammas, radioactive series,

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and absorbed neutrons, it is obvious that the transfer of this energy is of extreme importance. The power developed is a function of the average neutron flux and the total number of ^{235}U nuclei present. Some 3×10^{10} fissions per second are necessary to produce one watt of power. Since we are concerned with the removal of several hundreds of megawatts as heat, it is obvious that an understanding of the transfer of this energy to the metal, water, or graphite is of primary importance.

The pile engineering aspects of the reactors must also be understood if we are to comprehend the part the various pile components play in the overall reactions. Since graphite is the principal constituent of the pile on a volume basis, its behavior must be discussed. Obviously, the fuel is an essential constituent so the various types used will be described. This includes natural and enriched uranium plus the C and J slugs used for "spike" enrichment. The third major component is the process tube. The basis for the selection of the metal in the process tube will be covered extensively. Such miscellaneous components as shields, both thermal and biologic, operational instrumentation, and control systems will also be described.

One of the principal constituents in any reactor is the coolant. In the case of HAPU piles, water is used, and it is essential that cooling be continuous since the loss of coolant at high power levels could be catastrophic. The important factors are water treatment to minimize corrosion or solids deposition so as to minimize film buildup with resultant loss of heat transfer, delivery of the water to the pile by adequate pumping facilities, and water holdup after discharge so as to prevent the discharge of water with unduly high radioactivity into the river. As the pile power levels are raised, the exit water temperature increases. This finally becomes the controlling factor so that rear face pressurization is necessary if we are to increase power levels. This will also be discussed.

The actual operation of the pile will be described to familiarize you with the factors controlling such operation. For example, the factors affecting pile start-up will be discussed. Excess reactivity is essential during such a start-up so the methods of enrichment as well as the factors resulting in loss of reactivity will be described. The rate of power increase until the pile comes to equilibrium will also be discussed.

Pile shut-down will be covered. Such shut-downs can be normal, or very rapid; the latter being known as the "scram" shut-down. The physical processes of these shutdowns as well as the reasons for shutdowns will be covered.

Metallurgically, we are more concerned with the operation of the fuel element. The composition of this fuel element and the conditions under which it operates will determine the power of the pile and the properties of the element. The surface and core temperatures will vary with the type and size of fuel elements, whether alloy or natural uranium. These temperatures in turn will establish the tube power and, ultimately, the pile power. In turn, the power is limited by the available coolant and the excess reactivity, as well as by certain restrictions on core temperature.

Unfortunately, the operation of a pile does not consist of charging in fuel, irradiating for some prescribed time, then discharging. Under existing operating conditions, there is a finite chance of slug rupture. The types and mechanisms of failure, as

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well as the factors relating to such failures, will be described.

Finally, the importance of increasing power levels and exposures will be covered. These factors control the quantity of plutonium manufactured if not the quality. As power levels are increased, temperatures must be increased. This means a more satisfactory fuel element must be developed.

The sixth chapter will deal with the preparation of uranium metal from the ore. This will include a description of the ores, the source of these ores, and their abundance. Beneficiation processes will be described as will the intermediate steps preceding reduction to the metal. The melting and casting processes and the specialized process producing "dingots" will be described, together with the potential advantages of this direct casting system which eliminates remelting.

Now that we have covered the preparation of the metal, we can discuss its properties. We use natural uranium containing some fissionable isotope, uranium 235 in this instance. This isotope during its fissioning produces the necessary excess of neutrons which can be captured by the uranium 238, forming uranium 239, which decays by beta emission to neptunium and thence to plutonium, our end product. An alternate path used to a limited extent is thorium which yields uranium 233 as an end product. The latter has not been used extensively to date.

In a heterogeneous reactor, such as the graphite moderated, water cooled HAPU piles, we are faced with the use of alpha uranium in a relatively massive form as slugs. The relatively poor thermal conductivity of uranium means there will be a marked thermal gradient from center to surface of the slug, and this, combined with the anisotropic properties inherent in an orthorhombic structure, leads to pronounced stresses which can be markedly affected by the relative orientation of the anisotropic crystals or grains as they are called. The seventh chapter will deal with the allotropic modifications of uranium, and the slip and twinning systems in the metal. Preferred orientation will be discussed as will thermal cycling, instability, and transformation mechanisms.

We realize we are forced to use an anisotropic metal, and this anisotropy can profoundly influence mechanical and physical properties. The change in mechanical properties can be particularly important since it will influence the methods of fabrication. Chapter eight deals with the properties of uranium. The tensile properties are discussed as functions of previous fabrication or heat treatment history and as a function of testing temperature. Fatigue, creep, impact, and hardness are also dealt with as functions of these variables. In the case of physical properties, the significant ones to be discussed are thermal conductivity, electrical resistivity, and thermal expansion. Here, again, prior history plays an important part.

The lectures on the structure and properties of uranium serve as a basis for the discussion of the fabrication of the metal into slugs. Such operations as forging, rolling, and extrusion of ingots and dingots will be covered. The various heat treating techniques such as salt bath and induction, as well as the principles of uranium heat treating will also be described. Finally, such finishing operations as machining, drawing, and swaging will be explained. It is hoped that the lecture will acquaint you with present techniques, reasons for their selection, and probable

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future techniques of fabrication.

Once we charge the uranium in the pile, we are faced with yet another problem. This is the dimensional instability of the uranium which is intimately related to the anisotropic properties of the metal. Such gross effects as the elongation of uranium in amounts varying from less than one to almost one hundred percent, or a comparable decrease in length accompanied by an increase in diameter are obviously significant since these changes will influence the operations of the piles. This dimensional instability, fortunately, is related to macroscopic anisotropy rather than that existing within each grain so the overall orientation is extremely important. The tenth chapter deals with the various damage mechanisms occurring in a reactor. Damage by beta or gamma radiation, fast neutrons, and fission fragments will be described as will the dimensional behavior of uranium. The various theories advanced to explain the dimensional instability will be discussed so as to clarify this phenomenon.

Dimensional instability is but one effect occurring within a reactor. We are also concerned with the damage to the mechanical and physical properties of fuels and structural materials. At present, there is a great deal we do not know about the damage mechanisms. As reactors are operated at higher temperatures, fuel burn-outs are increased and the gross flux is raised. It is essential that the fundamental knowledge of irradiation damage be increased. If this is not done, we will be faced with making a multimillion dollar investment with insufficient information on the behavioral characteristics of the various reactor components. This is difficult to sell to private enterprise.

One of the best tools used in the evaluation of irradiation damage in both fissionable and non-fissionable materials is the x-ray diffraction unit. The eleventh chapter will deal with the use of such equipment. The theory of x-ray diffraction will be reviewed as a precursor, then the various methods of determining changes in crystal structure in metals such as peak shift, intensity changes, and line broadening, and change in line shape will be discussed. With this information as background, the damage in such non-fissionable materials as aluminum, molybdenum, zirconium, and graphite together with that in fissionable materials such as uranium, uranium dioxide, and thorium will be described.

Of equal importance in interpreting the damage in irradiated fissionable and non-fissionable materials is the determination of the mechanical and physical properties of these materials after irradiation. The properties of those metals of significance in in-pile operation, such as aluminum, zirconium, thorium, and uranium, will be discussed as functions of pre-irradiation history, exposure, and testing conditions. One fact is quite obvious from this review. There is a great deal of information still to be obtained. The present information is admittedly sketchy and often contradictory. If we are to understand and interpret radiation damage, we will need a great deal more data.

We realize that fuel element failures are an item of major importance in HAP0 pile operation since excessive down time is extremely expensive. Fuel element failures have been discussed to some extent in previous lectures; in lecture thirteen, the failures in the various types of slugs used in HAP0 piles will be reviewed, and

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various failure mechanisms will be described. These can be divided into failures induced by the buildup of corrosion product formed by penetration of the jacket by water, or into cleavage failures.

One of the problems facing the designer of a new type fuel element for the HAPO piles is the feasibility of alloying the uranium. Certain rather severe restrictions exist due to the nature of HAPO operation. We are plutonium producers and the addition of any alloy dilutes the uranium and reduces the amount of product, ignoring the loss in reactivity due to the capture of neutrons by the alloy addition. These limitations severely restrict the quantity of alloying element we can add so we still have an alpha uranium structure which may have enhanced corrosion resistance and some change in physical and mechanical properties. Primarily, the problem is one of economics. Do we gain sufficiently by the addition of these alloys to balance the cost of lost product, lost reactivity, and alloys. In the case of a power reactor, these restrictions decrease in importance and the problem must be re-evaluated. The effect of such alloy additions on the properties of irradiated uranium has not been determined, but there is no reason to believe that much will be gained. When we consider that the proposed additions are molybdenum, silicon, zirconium, and niobium, we see we have but one material, silicon, which is relatively inexpensive and has a low capture cross section.

In any water cooled reactor we are faced with the problem of aqueous corrosion. As we increase exit water temperatures toward the proposed goal of 150 - 170 C, the rate of corrosion will probably be the limiting factor establishing the material to be used for jackets and tubes. For this reason, an understanding of the theory of corrosion and HAPO corrosion practice is desirable. This information to be given in chapter fifteen will consider aluminum, zirconium, iron, and their respective alloys in terms of costs, corrosion control techniques, and corrosion limits.

One of the fundamental components in a reactor is the jacket encasing the slug. We are concerned with the methods of fabrication for present and proposed jackets, and with the costs of such jackets as aluminum, zirconium, or stainless steel. These details will be covered in chapter sixteen.

Another important component in the HAPO piles is the process tube. We demand certain things from such tubes. They must not absorb too many neutrons; their mechanical and physical properties must be adequate for the conditions of operation; the materials must not suffer excessive irradiation damage; fabrication must pose no insuperable problems; and the cost must not be unrealistic. With these as bases, aluminum, zirconium, stainless steel, and other materials are discussed as tube materials.

Next, we must consider our product. We are plutonium producers and this plutonium at the time is used as bomb material. A possible use in the future is as a reactor fuel. In dealing with the metallurgy of plutonium we must consider physics and health considerations which limit the operations we can do on the metal. The separation and reduction to the metal will be reviewed, and the various allotropic forms described. Of interest are the physical and mechanical properties, and the alloys will be described, as will the fabrication and irradiation behavior of the metal.

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The final chapter will deal with the design of fuel elements. As reactor operating conditions are changed, such as increases in temperature and exposure level, or as we consider fuel elements for power purposes, the philosophy of fuel element design must also change. Such a program must be long range in scope and consist of a series of in-pile tests to evaluate the effects of fuel element geometry and composition on the life of the element. Such factors as heat transfer, dimensional stability, corrosion resistance, and manufacturing feasibility must be factored in to any such study. These details will be covered in chapter nineteen.

Physical Metallurgical Concepts

Certain physical metallurgical properties play an important part in the selection of metals to be used in reactors. Such factors as physical properties, mechanical properties, structural properties, corrosion, alloying, and heat treatment, are of importance. For example, we will not use a material for tubes no matter how desirable its other properties are if its creep strength is 10^{-2} in/in/hr under conditions of pile operation. This factor can be very real when we examine the creep strength of aluminum alloys at 600 F. At this temperature the various aluminum alloys flow plastically under nominal loads.

While we cannot select fuel or structural metals on the basis of physical metallurgical properties alone, we should realize their importance. Adequate pre- and post-irradiation data covering such properties as thermal conductivity, thermal expansion, room and elevated temperature tensile strength, creep strength, toughness, corrosion resistance, and dimensional stability, will permit the optimum material to be selected for such structural components as tubes or jackets.

An investigation of fundamental alloying concepts for both fuel and structural metals is desirable. The behavior of as yet uninvestigated alloys can be calculated as a first approximation by the application of such tools as thermodynamics, the Hume-Rothery rules, and the phase rule. As new systems are considered such an approach becomes more desirable.

The application of certain fundamental heat treating concepts can also prove valuable. At present, there is a great deal not known about the heat treatment of uranium. The application of theory to existing information may disclose certain anomalies and lend to the establishment of a definite program for determining the behavior of uranium during various heat treatments.

Mechanical Metallurgical Concepts

Such mechanical metallurgical operations as melting, casting, forging, press forging, rolling, drawing, extruding, or swaging may be common to all metals. The fact that a material is fissionable or anisotropic should not affect the evaluation of the fabrication behavior of such a material from a conceptual point of view. The unit operation can be evaluated from the pertinent mechanical property data if such are available. If these data are available, then the selection of the proper equipment to perform the necessary fabrication operation need not be completely empirical. The principal problem is not that we are working with a relatively rare fissionable matter if we are considering uranium, or a relatively rare anisotropic material, if we are considering zirconium, but that we have insufficient data to permit us to intelligently select the optimum fabrication conditions.

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Process Metallurgy

The same reasoning applied in the discussion of physical and mechanical metallurgy is applicable to process metallurgy. Those operations common to this branch of metallurgy such as concentration, extraction, electrometallurgy, or reduction are not unique to these materials. We simply adopt existing techniques to obtain the metal in a purity commensurate with overall cost. Therefore, when we analyze the production of such materials as uranium or zirconium, we should not do so in terms of the specific metal, but rather in terms of the particular operation which will be one common to many metals.

Basis for Selection of Materials

Two categories of materials are of importance in the HAPO piles. These are the fuels and the structural materials. Both categories will be covered extensively so we will only review briefly certain properties at this time.

Fuel Materials

Of the three fuel materials of concern at present, uranium, thorium, and plutonium, we are primarily concerned with uranium at HAPO since natural uranium is the principal fuel charged into the piles.

The basic reactions of concern to us are of two types. The first is a neutron capture followed by fissioning. The second consists of neutron capture followed by radioactive decay. Fissioning can be caused by the capture of either fast or thermal neutrons. For example $^{92}\text{U-238}$ will not normally fission after capturing a thermal neutron, but will when it captures a fast neutron due to the higher excitation energy of these neutrons. Fission in $^{92}\text{U-238}$ requires neutrons containing about 1 Mev of kinetic energy.

Fission Reactions of Importance

Significant capture reactions are usually limited to $^{92}\text{U-238}$ and $^{90}\text{Th-232}$. The so-called natural uranium is most common, but thorium has applications, particularly in breeder reactors. The significant reactions in these instances are tabulated below.

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Important Capture Reactions

On the basis of availability thorium is quite desirable. It is estimated that there is 3 times as much thorium as there is uranium. Therefore, there is a definite possibility that we will see an increased use of thorium relative to uranium.

It is obvious that we are concerned with the reactions in a pile for two reasons. The first is to produce a material used in weapons. This means ${}_{92}\text{U-233}$ or ${}_{94}\text{Pu-239}$. The second reaction is to produce power from the heat developed during the fission reactions. When we consider that existing Hanford reactors could produce large quantities of power without too extensive adaptation, it is apparent that a reactor built with the purpose of developing power in mind could be much more efficient.

Structural Materials

Obviously the selection of metals to serve as structural components in a reactor poses several problems. In the case of the Hanford piles we are primarily concerned with the materials used for tubes and jackets. For such applications we are concerned with certain physical metallurgical properties. Such mechanical properties as tensile strength, creep strength, and toughness are important; thermal conductivity is probably the most significant physical property. We are also concerned with the corrosion resistance of these materials. If the reaction rate at the operating temperature is too rapid in either the aqueous medium or in the gaseous medium, a material exposed to either media is unsatisfactory.

Certain mechanical metallurgical considerations are also important. A material requiring specialized and expensive equipment for melting is not as desirable as one not requiring such procedures. The same thing is true for fabrication techniques. If all other factors are equal, we will select the process which requires the least time and with the lowest unit costs.

We make the final selection on the basis of three factors. These are: (1) satisfactory physical metallurgical properties, (2) desirable mechanical metallurgical techniques, and (3) economic considerations. The three factors are interdependent, and economics are closely allied to the mechanical metallurgy aspects.

In the economical analysis we are concerned with availability of the material. If we cannot get it, or if it is extremely rare, it should not be considered. A second factor is cost. The ore can be relatively abundant, but a very expensive reduction technique can be as significant a factor discouraging its use as would be the case if the material were quite scarce. Fabrication cost is an important factor, intimately related to the mechanical metallurgical techniques. A relatively common material may

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find limited application because it is so difficult to fabricate. These factors are common to any problem where a metal is to be used, but there is a further and severely limiting factor in a thermal reactor. If the neutron absorption cross section is too high, the material cannot be considered. Obviously the problem is one of deciding when a cross section is too high. This depends on what one is willing to pay in enrichment and loss of product.

A capture cross section is defined somewhat arbitrarily in terms of a beam of neutrons incident on a nucleus represented in Figure 1.

Figure 1 - Schematic Representation of a Neutron Beam Incident on Nucleus.

The fraction of neutrons contained in 1 cm² of the beam, that is intercepted by a single nucleus is called the total cross section σ of the particular material for such neutrons. We are primarily concerned with absorption of neutrons by the nuclei. Most cross sections are about 10⁻²⁴ cm²/nucleus in size, and we define this as a "barn". 1 barn is equal to 10⁻²⁴ cm²/nucleus. Nuclear cross sections are obtained experimentally since existing theory will not permit us to calculate them.

From the metallurgists point-of-view the significant cross section is the macroscopic rather than the microscopic. He is concerned with gross quantities of metal and must know what this represents in loss of product.

A macroscopic cross section is defined in terms of reciprocal centimeters.

$$\Sigma = N\sigma \text{ where } N = \text{No. of atoms per cc.}$$

$$N = \text{Avogadros No.} \times \text{density/atomic weight.}$$

$$N = 0.602 \times 10^{24} \text{ d/A.W.}$$

$$\sigma = 10^{-24} \text{ cm}^2/\text{nuclei}$$

$$\text{Avogadros No.} = 0.602 \times 10^{24} \text{ nuclei/gram atoms}$$

$$\text{Density} = \text{gram/cm}^3$$

$$\text{Atomic weight} = \text{gram/gram atoms}$$

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Since the microscopic cross section is measured in barns, where a barn equals 10^{-24} cm², the exponents of 10 cancel each other. If $\Sigma = N\sigma$, it follows that

$$\frac{-dI}{I} = \Sigma dx \text{ where } \frac{-dI}{I} \text{ represents the number of neutrons absorbed in a path } dx;$$

therefore, Σdx represents the probability that neutrons will be absorbed in the path dx .

We can calculate the gross cross section of an alloy quite easily by a formula

$$\Sigma = N_1 \sigma_1 + N_2 \sigma_2 + N_3 \sigma_3 + \dots + N_i \sigma_i$$

where N_i is the number of nuclei per cm² of the i th kind present and σ_i is the microscopic cross section for the given material and energy levels. Essentially we are considering

$$N_i = \frac{\text{density}}{\text{atomic wt.}} \times \text{Avogadro's No.} \times \text{atomic fraction of particular element}$$

With the macroscopic capture cross section in mind let us compare the metals in the periodic table.

TABLE I

MACROSCOPIC THERMAL-NEUTRON ABSORPTION
CROSS SECTIONS OF RELATIVELY COMMON METALS

<u>Low Cross Section</u> <u>< 0.020</u>		<u>Medium Cross Section</u> <u>> 0.020 < 0.20</u>		<u>High Cross Section</u> <u>> 0.20</u>	
Beryllium	0.0011	Potassium	0.028	Lithium	2.9
Sodium	0.012	Iron	0.19	Titanium	0.29
Magnesium	0.015 0.0040	Zinc	0.077	Vanadium	0.35
Aluminum	0.012	Niobium	0.078	Chromium	0.25
Calcium	0.010			Manganese	1.01
Zirconium	0.0080			Cobalt	3.0
Tin	0.020			Nickel	0.40
Lead	0.006			Copper	0.31
Bismuth	0.0005			Molybdenum	0.25
				Cadmium	115.0
				Antimony	0.1555
				Hafnium	4.6
				Tantalum	1.1
				Tungsten	1.01

Obviously a large number of these metals have no structural applications so if we limit our comparison to those metals having low or medium cross sections and structural applications, our choice is limited to those in Table II, with some alloying permissible in the high cross section group.

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TABLE II

MACROSCOPIC THERMAL-NEUTRON ABSORPTION
CROSS SECTION OF ACTUAL OR POTENTIAL STRUCTURAL METALS

<u>Low Cross Section</u> <u>≤ 0.020 cm⁻¹</u>		<u>Medium Cross Section</u> <u>≥ 0.020 to 0.20 cm⁻¹</u>	
Beryllium	0.0011	Iron	0.19
Magnesium	0.016 0.640	Zinc	0.077
Aluminum	0.012		
Zirconium	0.0077		
Tin	0.020		

If we limit ourselves to these metals, we should compare them to determine their limitations. On the basis of cross section beryllium is very desirable, but its advantages end there. Beryllium is relatively rare, expensive, extremely susceptible to minor impurity contents insofar as mechanical properties are concerned, and difficult to fabricate; after fabrication the properties are only fair. Corrosion resistance is good. Magnesium is abundant, inexpensive, and relatively easy to fabricate. The corrosion resistance in water is poor, and mechanical properties at even nominal temperatures are poor. Aluminum is abundant, inexpensive, and easy to fabricate. Corrosion resistance is good to excellent in water to 100-150 C. Above this temperature the resistance decreases sharply, being dependent to a marked degree on the impurities in the water. Mechanical properties of the common alloys are adequate to about 200 C. At higher temperatures and pressures the creep rate is excessive so the material is unsatisfactory for tubes. Zirconium is relatively rare and expensive to produce and fabricate. Its aqueous corrosion resistance is excellent to above 300 C and gaseous corrosion is no problem to about 400 C. Fabrication is rather difficult. The mechanical properties are excellent in the range of a water cooled power reactor. Tin as such is relatively expensive and not usable unless alloyed heavily with a material such as copper. Iron has a much higher cross section than is desirable in a thermal reactor, however, it is inexpensive, easy to fabricate, and has very good mechanical properties. It would be best to alloy with chromium and/or nickel which will increase the cross section substantially resulting in excessive reactivity loss in a conventional thermal reactor. Corrosion resistance, when alloyed, is excellent. Zinc as such is not satisfactory as a structural material. Addition of alloy improves the properties, but changes the cross section.

On these bases the logical materials are aluminum, zirconium, and stainless steels. The properties of these alloys are compared in Figures 2 and 3, indicating the temperature ranges over which these materials can be used.

The aqueous corrosion resistance of the significant structural materials will be covered in detail in a later lecture.

Figure 2

ELEVATED TEMPERATURE YIELD STRENGTH OF SELECTED MATERIALS
Compiled from references 1, 2, 3, 4, 5, 6

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Figure 3

ELEVATED TEMPERATURE TENSILE STRENGTH OF SELECTED MATERIALS
Compiled from references 1, 2, 3, 4, 5, 6

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A comparison of these materials based on the criteria established can be made from these data. The material you select will depend on the application you have in mind. The important thing to realize is the interrelationship of the physical, metallurgical, mechanical metallurgical and economic factors. These factors will be covered extensively for both fuel and structural materials in succeeding lectures.

REFERENCES

- (1) The Reactor Handbook, Vol. 3, Materials, April 1953, Secret.
- (2) Irrmann, R., "Sintered Aluminum with High Strength at Elevated Temperatures," Metallurgia, September 1952, p. 109.
- (3) Lyle, John P., Jr., "Excellent Products of Aluminum Powder Metallurgy," Metals Progress, December 1952, p. 109.
- (4) Grube, K., and Eastwood, L. W., The Development of Aluminum - 6 per cent Magnesium Wrought Alloys for Elevated Temperature Service and Their Resistance to Corrosion in Water at Temperatures up to 600 F, BMI-T-38, July 15, 1950.
- (5) Schwope, A. D., and Chubb, W., Mechanical Properties of Zirconium-Tin Alloys, BMI-798, December 22, 1952, Secret.
- (6) Technical Progress Report - Naval Reactor Program, November 15, 1952 to January 1, 1953, WAPD-MR-35, Secret.

Sign. H. Bush
Head, Physical Metallurgy
Pile Technology Section
ENGINEERING DEPARTMENT

SH Bush:rd

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