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FAST AND MODERATED LOW-POWER, LIGHTWEIGHT REACTORS FOR NUCLEAR ROCKET PROPULSION

by Frank E. Rom
Lewis Research Center
Cleveland, Ohio

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INTRODUCTION

The current U.S. program to develop a nuclear rocket engine is centered around the application of nuclear rockets to large-scale manned interplanetary missions. Conventional mission studies indicate that reactor power levels of 10,000 megawatts and higher (500,000 lb thrust) are desirable for this application (refs. 1 to 5). Inasmuch as the payload for these missions is of the order of several hundred thousand pounds, minimizing the weight of the powerplant (as long as it is measured in tens of thousands of pounds) is not as important in improving performance as is increasing specific impulse. Consequently, there has been little emphasis placed on the selection of reactors based on minimum weight. Certain applications of nuclear rockets, as discussed in references 6 to 9, would require the minimization of reactor weight. In particular, missions where the payload weight is of the order of the powerplant weight, would show major performance gains if lightweight reactors were available. Such missions are typical of unmanned high-energy (high-velocity increment) instrument probes. In addition, if perigee propulsion (successive small bursts of thrust near the perigee) is used at Earth departure in place of the conventional technique of applying a continuous single high-thrust period, the required power levels are reduced by an order of magnitude even for manned missions (ref. 10).

The possibility of providing low-power lightweight reactors for nuclear-rocket application is examined herein. The nuclear propulsion scheme considered is the direct heating system where hydrogen, the propellant, is heated by passing it through a reactor core made of high-temperature materials. Figure 1 illustrates a typical nuclear rocket. Hydrogen is pumped from the propellant storage tank and fed to the nuclear rocket engine. It is used to cool the nozzle, reflector, pressure shell, or any other parts that require cooling before it passes through the reactor core. The core is composed of an array of fissionable fuel-bearing heat-transfer passages that permit removal of the fission energy generated within the core materials. Thrust is produced by expanding the heated hydrogen through a convergent-divergent nozzle. A control system is provided to startup, operate, and shutdown the reactor.

It is the purpose of this lecture to describe the fundamental reactor types, to present the properties of the high-temperature materials available for nuclear-rocket-reactor application and to present various reactor con-

cepts that may have the potential for achieving the goal of low-power lightweight nuclear-rocket powerplants.

REACTOR TYPES

Reactors are usually classified according to the energy range of the neutron spectrum that produces fissions with the fuel. Reactors in which the majority of the neutrons cause fissions while they are near their birth energy are called fast reactors (fig. 2). If the neutrons are slowed down by collisions with the materials of the reactor so that the majority of neutrons are in thermal equilibrium with the reactor materials before they cause fissions then they are called thermal reactors. In between, there are the epithermal and intermediate reactors where the neutrons cause fission while at energies between thermal and birth energy. The use of a moderator material to slow neutrons to thermal energy results in the neutrons having greater probability for fission when they do collide with fissionable fuel nuclei because of the higher cross section at lower energies (fig. 2). Less fuel atoms are therefore required in the thermal reactor that will be shown to be important from the standpoint of less complicated reactor-fuel-element-materials development. Fast reactors require large concentrations of fuel atoms for two reasons. First of all, if an abundance of other materials were present, an excessive number of thermalizing collisions would occur from neutron birth to fission capture thus shifting the spectrum downward tending to make the reactor intermediate or thermal. Secondly, since the probability of fission absorption at high energies is very much less than at thermal energies, more fuel is required to maintain a sufficient number of fissions for criticality. As will be discussed later, the large fuel concentrations required constitutes an important problem of the fast reactor.

Reactors can also be classified according to the arrangement of the materials contained within them (ref. 11). If all the materials are relatively uniformly dispersed throughout the core the reactor is said to be homogeneous. If significant portions of the core materials are physically separated from other portions the reactor is said to be heterogeneous. Illustrations of homogeneous and heterogeneous reactors are shown in figure 3. In the homogeneous fast reactor the fissionable fuel, such as a uranium compound, is dispersed in, dissolved in, or mixed with a suitable refractory structural material, such as tungsten or zirconium carbide. The heat that is generated by the fissioning fuel is transferred to the refractory structural material by conduction since it is intimately mixed with the fuel. The heat is removed from the fuel-refractory mixture by hydrogen flowing through appropriate heat-transfer passages. In this illustrative case, the heat-transfer surfaces are supplied by small circular flow passages uniformly distributed across the face of the core. Inasmuch as the fast reactor requires relatively large amounts of fissionable fuel for criticality, it is necessary to maintain high concentrations of fuel within the refractory material. Typically, about 50 percent of the core material volume may be occupied by fuel atoms or molecules. This may be expected to lead to large adverse effects on the properties of the re-

fractory material that contains the fuel. The chief advantage of the fast reactor is that it can be made small in size if the fuel concentration can be kept high.

The homogeneous thermal reactor is identical in arrangement of materials to a fast reactor except that the fuel bearing material is replaced with material that is also a good moderator. In the case of the nuclear rocket the moderating material must therefore be a refractory material since the fission heat is generated within it. Since it must supply the heat-transfer surfaces necessary to transfer the heat to hydrogen, the moderator must also be resistant to hydrogen attack. If the core material is not resistant to hydrogen, the exposed surfaces must be protected by a coating of a material that is. The amount of fissionable material required for this reactor is relatively low. The effect on the properties of the refractory moderator should be relatively low.

In summary, to make a good thermal homogeneous nuclear-rocket reactor the moderator must (1) be a good refractory material, (2) be compatible with a fuel material, and (3) be compatible with hydrogen propellant. The chief disadvantage of the thermal homogeneous reactor is that the range of materials that satisfy the preceding requirements is very limited.

The thermal heterogeneous reactor separates the moderator from the fuel-bearing material as shown in figure 3. This separation permits the use of the best refractory materials for the high-temperature heat-generating portions of the reactor without regard to its moderating capability. Inasmuch as the moderator need no longer operate at the fuel-element temperature levels, it may be independently cooled and maintained at any desired temperature level, limited only by the ability to remove the moderator heat with available coolants. In the case of the nuclear rocket, the incoming hydrogen represents a more than adequate heat sink at low temperature levels. Many moderators can, therefore, be considered. The penalty for the privilege of being able to use the best refractory material together with having a choice of moderators, is that a cooling system is required for the moderator. In addition, insulation must be provided between the hot fuel-element zones and cool moderator zones. Inasmuch as the reactor is thermal, the fuel loadings tend to be low thus minimizing fuel-material-development problems. The fuel-bearing refractory materials must be low in neutron absorption cross section to take advantage of the low fuel-loading requirement of this reactor type.

REFRACTORY MATERIALS

The primary purpose of the nuclear rocket is to heat hydrogen to as high a temperature as possible to achieve the maximum specific impulse. In the case of the solid-core or heat-transfer-type nuclear rocket that is being considered in the present lecture, the fissionable material is contained within solid materials. Refractory materials are, therefore, the key to the achievement of the best nuclear rockets. More specifically, the properties desired of the nuclear-rocket reactor fuel-element material are as follows:

(1) High operating temperatures (~5000° F)

(2) Compatibility with fissionable material it contains

(3) Compatibility with hydrogen up to about 5000° F

(4) Low evaporation rate for long life (~10 to 100 hr)

(5) Adequate tensile and creep strengths at all temperatures for long life and reliability

(6) Good thermal stress and shock resistance for recyclability (~100 cycles) and operation at high power density (high thermal conductivity, low expansion coefficient, low elastic modulus, high strength)

(7) Low neutron absorption cross section particularly for thermal reactors

(8) Fabricability

The following discussion progressively goes through the various properties of refractory materials that might be considered for fuel-bearing materials in an attempt to indicate their potential.

Melting Points

The melting points of refractory materials (metals and ceramics) are listed in table I to indicate the maximum temperature potential that is available for fuel-bearing materials. Of the refractory metals tungsten has the highest melting point of 6120° F (ref. 12) followed by rhenium at 5740° F (unpublished data from J. A. McGurty, General Electric Co., Cincinnati, Ohio), tantalum at 5430° F (ref. 12), osmium at 4890° F (ref. 13), molybdenum at 4710° F (ref. 14) and niobium at 4530° F (unpublished data from J. A. McGurty). Inasmuch as tungsten 184 is an isotope of tungsten, it has the same melting point as natural tungsten. The melting point of the alloys 0.74 W - 0.26 Re and 0.90 Ta - 0.10 W (ref. 15) are shown in the table to indicate that it is possible to combine refractory elements with the hope of improving some desirable property at the expense of another. For example, rhenium is added to tungsten to increase its ductility at room temperature; a loss in melting point of 470° F results, however. The reactor designer must use his judgement in determining whether such trade-offs in properties are worthwhile.

The melting point of the nonmetallic refractories are shown in the right hand column of table I. The data were obtained from reference 16. Hafnium carbide (m.p., 7030° F) and tantalum carbide (m.p., 7020° F) have the highest melting points of any known compounds. They are followed by carbon, which sublimes at 6700° F. Niobium carbide (m.p., 6330° F) is one

of the four known materials that has a higher melting point than tungsten. All the other ceramic materials listed have melting points lower than tungsten.

From the melting-point data alone, it would appear that tungsten, hafnium carbide, tantalum carbide, carbon (graphite), and niobium carbide have the greatest potential for achieving the highest nuclear rocket hydrogen temperature.

Nuclear Properties of Refractory Materials

Nuclear properties are of major concern to thermal reactors and only of minor concern for fast reactors. In general, the thermal absorption cross section for fuel-element materials for thermal reactors should be less than 10 barns. If this value is exceeded the fuel-loading requirements tend to approach those required for fast reactors. The thermal cross section is irrelevant to the fast reactor. The resonance integral, however, is of some concern inasmuch as the low-energy tail of a fast reactor neutron spectrum frequently dips down into the resonance range, as in the case where a moderating reflector is used with the fast reactor. An additional source of low-energy neutrons may arise from inelastic collisions of neutrons with core materials.

Some nuclear properties of refractory materials are listed in table II. The data were obtained from reference 17. The properties listed are the thermal microscopic absorption cross section and infinitely dilute resonance integral. For easy reference the material density and atomic density are also shown. Carbon has the lowest cross section of all the materials considered. Tungsten, which has the highest melting point of all metals, has a thermal absorption cross section of 19.2 barns, which is rather high for thermal reactors. It also has a relatively high resonance integral. The most abundant isotope of tungsten, W^{184}, has a low absorption cross section (2 barns) and a low resonance integral (10 barns). The desirability of enriching natural tungsten in the W^{184} isotope for thermal reactors is apparent. Tantalum and rhenium have unacceptably high cross sections. These elements have no isotopes with low cross sections and are therefore poor candidates for thermal reactors. Of the carbides, NbC and ZrC would be suitable for use in thermal reactors. HfC and TaC are satisfactory for fast reactors only.

This table indicates that the materials with attractive melting points only C, W^{184}, Mo, ZrC, and NbC would be satisfactory for thermal reactors. The remaining materials have relatively high neutron absorption cross sections that make them applicable only for fast reactors. It should be emphasized that tungsten must be enriched in the W^{184} isotope to reduce the thermal cross section to less than about 10 barns, which should be acceptable for a thermal system.

Vaporization Rate of Refractory Materials

It is important to consider the vaporization rate of the refractory
materials, since it determines at a given temperature the lifetime of the
material to be used for fuel elements. Figure 4 shows the vaporization
rates in vacuum of the most refractory materials known. The rate of
evaporation in the presence of a flowing hydrogen atmosphere may be less
than that which occurs in a vacuum. The actual rate under such conditions
would depend on the hydrogen density, hydrogen velocity, and rate of dif-
fusion of the refractory material atoms or molecules in hydrogen. As can
be seen from figure 4, tungsten has the lowest vaporization rate of any of
the materials known. The vaporization rate of tungsten is almost an order
of magnitude lower than any other refractory material. At a temperature
of about 5000° F the vaporization rate of tungsten is about 0.10 mil per
hour. In 10 hours, therefore, 1 mil of material would be evaporated; in
100 hours 10 mils would be evaporated. It is doubtful whether vaporization
rates greater than 0.10 mil per hour would be desirable for a nuclear-
rocket application. At this evaporation rate tantalum would have a maximum
operating temperature of about 4700° F. Tantalum carbide, niobium carbide,
hafnium carbide, and rhenium would have maximum operating temperatures of
about 4500° to 4600° F. There is a discrepancy in the data available for
hafnium carbide. The second set of data for hafnium carbide shown to the
right would indicate an operating temperature of about 4300° F. Carbon,
molybdenum, and zirconium carbide would have operating temperatures con-
siderably less than 4000° F for a vaporization rate of 0.10 mil per hour.
At 4000° F the vaporization rates for Mo, C, and ZrC are about 0.5, 1.0,
and 5.0 mils per hour, respectively. In order to be used at or above
4000° F, these materials must be coated with a material that has a lower
evaporation rate. In order to achieve operating temperatures beyond
4000° F then, the only materials to consider without coatings are tungsten,
tantalum, rhenium, tantalum carbide, niobium carbide, and hafnium carbide.
The alternative is to design a reactor that can tolerate large losses of
material. This, of course, would require fuel elements with rather thick
sections so that the amount lost could be tolerated. Whether such a scheme
can produce a fruitful reactor will depend greatly on the ingenuity of the
designer. The data for the vaporization rates were obtained from the fol-
lowing references: TaC and ZrC, reference 18; NbC, reference 18; W, refer-
ence 19; HfC, reference 20; Mo, unpublished data from J. A. McGurty; C,
reference 21; Re, reference 22, unpublished data from J. H. Port, Chase
Brass & Copper Co., Cleveland, Ohio, and unpublished data from J. A. McGurty;
and Ta, reference 23 and unpublished data from J. A. McGurty.

Additional Properties of Refractory Materials

Table III shows some additional properties of refractory materials that
are of importance for nuclear rockets. The table lists the thermal conduc-
tivity, linear expansion coefficient, modulus of elasticity, ultimate ten-
sile strength, and thermal stress parameter. The thermal stress parameter
is the product of the thermal conductivity and ultimate tensile stress
divided by the product of the linear expansion coefficient and modulus of
elasticity. The data are for a temperature of 5000° F, unless otherwise

noted. The thermal stress parameter is of great significance in indicating the ability of the material to withstand the thermal stresses involved with the high heat fluxes that occur in a nuclear-rocket reactor. The ideal fuel-element material would have a high thermal conductivity, a low linear thermal expansion coefficient, low modulus of elasticity, and high strength. It would, therefore, have a high value for the thermal stress parameter. The data for table III were obtained from the following references: W, references 12, 15, and 24; Ta, reference 25; Mo, reference 26; C, references 27 to 31; HfC and TaC, reference 32; NbC and ZrC, references 13, 16, and 33 to 41.

The properties in table III are given at the highest temperature for which data could be found. High-temperature property data is virtually nonexistent and in several cases room-temperature values or estimates are given. The data should not be accepted as the last word in properties. The data shown are merely indicative to give a rough idea of the relative merits of the various refractory materials shown. Tungsten has the highest thermal conductivity of all the materials shown. Its value is about 3 to 3.5 times that for the carbides or graphite.

The linear expansion coefficient is very nearly the same for all the materials considered, varying from about 3 to 5×10^{-6} inch per inch per $^\circ$F. The modulus of elasticity is shown to be quite high for the carbides, due chiefly to the lower temperature at which the data were obtained. Tantalum has the lowest value shown, being about one-tenth that for tungsten. Graphite has a value about one-fourth that of tungsten.

Depending on the rate of application of load, tungsten has an ultimate tensile strength at 5000° F of 2000 to 7000 psi. The only other data at 5000° F is that for graphite. Graphite at 5000° F has a tensile strength of about 1600 to 6000 psi depending on its grade and density. The highest temperature for which strengths of the carbides have been measured is 4000° F. The tensile strength was assumed to be one-half of the measured bend strength for these materials.

The corresponding values for thermal stress parameter indicate that tungsten at 5000° F and tantalum at 4500° F have the greatest thermal stress resistance of all the materials considered. Molybdenum and graphite have a thermal stress parameter about one-half to one-sixth that of tungsten. The carbides show a thermal stress parameter of less than one-tenth that of tungsten.

Melting Points of Refractory Uranium Compounds

The melting points of the refractory uranium compounds and uranium

metal are shown in table IV. The data for the compounds were obtained
from reference 42 while the data for the metal was obtained from refer-
ence 43. The highest melting point shown is 5230° F for uranium nitride.
Unless the nitride has an overpressure of nitrogen, it is unstable and de-
composes into nitrogen gas and uranium metal (ref. 44). Its use would,
therefore, be limited to situations where nitrogen overpressure could be
maintained. Uranium dioxide and uranium carbide are the commonly used
uranium compounds. Uranium dioxide has a melting point of 5075° F, while
the carbides of uranium have a melting point of 4350° F. Uranium boride
(m.p., 4625° F) would not be attractive especially for thermal reactors.
In addition, the lower uranium atom density of UB_4 makes it less attractive
particularly for fast reactors where high uranium loadings are required.
Uranium sulfide (m.p., 4465° F) although possessing a higher uranium atom
concentration than UO_2 has an appreciably lower melting point and would be
less attractive for this reason. The melting point of uranium metal is
shown for comparison purposes. Uranium dioxide stands out as the most re-
fractory stable uranium compound.

Vaporization Rate of Uranium Compounds

The vaporization rate of the refractory uranium compounds in vacuum
is shown as a function of temperature in figure 5. The vaporization-rate
data for UN were obtained from reference 45, for UO_2 from references 12,
46 and 47, for US from reference 48, and for UC from references 46, 47,
and 49. The vaporization rates of uranium nitride, uranium dioxide, and
uranium sulfide are all about the same. Uranium carbide has the lowest
vaporization rate of all the uranium compounds shown. If the criterion
that was applied earlier for refractory materials is used, note that uranium
carbide would operate at a temperature of only about 4000° F without exceed-
ing the 10^{-1} mil per hour vaporization rate. Uranium nitride, uranium
dioxide, and uranium sulfide must operate at a temperature of less than
3200° F so as not to exceed this evaporation rate. It is clear that, in
order to achieve a temperature approaching 5000° F, the uranium compounds
cannot be used alone as fuel because of their high vaporization rates.
This indicates the necessity for complete containment of fissionable com-
pounds by refractory materials for operation at high temperature to pre-
vent exposure at surfaces where the fissionable compounds would evaporate.

Compatibility of Refractory Materials and Fuels

In order to provide a satisfactory fuel element the refractory mate-
rial that constitutes the matrix or container for fissionable material must
be compatible with the fissionable material and hydrogen. Compatibility
means that no reactions take place during operation of the fuel element
that affects the properties of the fuel element significantly.

Data on the compatibility of refractory fuel-element materials with
uranium dioxide, uranium carbide, and hydrogen is shown in table V. Tung-
sten shows no reaction with UO_2 up to the melting point of UO_2 (ref. 50),

a reaction with UC at 4540° F (ref. 29), and no reaction with hydrogen. A composite of tungsten and UO_2 should be of great interest for fuel elements because tungsten is the most refractory metal, UO_2 is the most refractory stable uranium compound, and tungsten is inert to hydrogen.

No data were found for the compatibility of rhenium with UO_2. It forms a ternary phase at 3270° F after 24 hours (ref. 51). There is no reaction with hydrogen at least to 4000° F (ref. 13).

Tantalum shows no reaction with UO_2 (ref. 50). There is no reaction with UC up to at least 3270° F (refs. 52 and 53). Tantalum shows negligible reaction with hydrogen at 2370° F and higher (ref. 71); however, it reacts with hydrogen at temperatures below 2000° F to form the hydride. If tantalum is to be used for fuel-element material in a hydrogen-cooled reactor, the reactor temperature must pass through the low-temperature range quickly to avoid hydride formation.

Molybdenum does not react with UO_2 at least up to the melting point of molybdenum (ref. 50). Molybdenum reacts with UC at 1835° F (ref. 52). There is no reaction with hydrogen up to the melting point of molybdenum (ref. 12). Molybdenum-UO_2 composites would make a satisfactory basic fuel-element material if operating temperatures are limited to less than the melting point of molybdenum.

Graphite is not compatible with UO_2 in that it forms UC at a temperature of 3500° F (ref. 50). Uranium carbide and graphite have a eutectic temperature of 4260° F (ref. 53) and at 4350° F UC and UC_2 melt (ref. 42). There is a strong reaction between hydrogen and graphite above 2800° F (ref. 29). As discussed in reference 54, graphite-based fuel elements must be protected from hydrogen reaction by a technique such as the use of a coating that is compatible with hydrogen. The metallic carbides are obvious candidates for such use. The development of techniques for coating graphite with the carbides of zirconium, niobium, and tantalum was reported in reference 55.

Hafnium carbide shows no reaction with UO_2 up to 5000° F (ref. 50), forms a continuous solid solution with UC, and reacts with hydrogen above 4840° F (ref. 56). Although HfC is one of the highest melting refractory materials it has a limited potential in its application as a fuel-element material inasmuch as it reacts with hydrogen far below its melting point. In addition, if it is used as a solid solution with uranium carbide, its melting point would be depressed.

Tantalum carbide behaves in a manner similar to hafnium carbide. It reacts with UO_2 at 4900° F to form UC (ref. 50). It forms a solid solution with UC and reacts with hydrogen above 4630° F (ref. 56). NbC and ZrC also react with UO_2 above 4000° F and 4500° F, respectively (ref. 50). They form solid solutions with UC and react with hydrogen above 4680° F and 4780° F, respectively (ref. 56). The limitations of these carbides for fuel-element application are similar to those for hafnium carbide.

Tungsten

It has been shown by the previous figures and tables that tungsten appears to have very attractive properties especially with regard to vaporization rate, compatibility with one of the most refractory fuel compounds, uranium dioxide, and compatibility with hydrogen. Tungsten has also been shown to have excellent resistance to thermal stress at 5000° F because of its relatively high thermal conductivity and strength. Although tungsten can be used in its natural state for fast reactors it must be enriched in the tungsten 184 isotope if it is to be used for thermal reactors. On the basis of data such as this, tungsten may be expected to have the greatest potential for producing the highest specific impulse obtainable by solid core nuclear rockets.

Inasmuch as tungsten seems to have the greatest promise of all the refractory materials considered for nuclear-rocket fuel elements, additional data are presented for tungsten. The data that follow and the data that precede apply for tungsten without fissionable material additives such as would be required for fuel elements. Very few data are available on the effect of fuel additives. It would be anticipated, however, that most properties would be adversely affected.

Strength properties. - In figure 6 the tensile strength of tungsten is plotted as a function of temperature for both recrystallized and wrought tungsten /ref. 15). At temperatures above 4000° F, the properties of wrought and recrystallized tungsten are essentially identical. Below this temperature range recrystallized tungsten has somewhat lower tensile strength than wrought tungsten. In general, at temperatures below 2000° or 3000° F the tensile strength of tungsten is greater than 10,000 psi and at room temperature the values exceed 100,000 psi. At 5000° F tungsten has a tensile strength of at least 2000 psi.

Figure 7 shows the elongation of tungsten plotted as a function of temperature, while figure 8 shows the reduction in area from reference 15. These data show that tungsten exhibits ductile behavior over the entire temperature range above about 400° to 500° F. At this temperature or below, the tungsten exhibits a brittle behavior. Minimum elongations vary from 5 to 10 percent for temperatures of 600° F to almost the melting point. At 5000° F the elongation is approximately 10 percent, indicating that the material is ductile at this temperature whether recrystallized or wrought.

The yield strength of tungsten is shown in figure 9. As in the case of the tensile strength, no difference in the properties of wrought or recrystallized tungsten is indicated at temperatures above 4000° F. The yield strength at 5000° F is, at least, 1000 psi. Stress-rupture data for tungsten (ref. 15) is shown in figure 10. At a temperature of 5000° F, the time to rupture for a stress of 1000 psi is about 30 hours. By further extrapolation, the stress anticipated to produce rupture in 100 hours is about 800 psi. The creep stress of tungsten as a function of linear creep rate for several temperatures is shown in figure 11. At a

temperature of about 5000° F the allowable creep stress is about 800 psi for a linear creep rate of 10^{-4} inch per inch per minute. This creep rate is consistent with producing an elongation of about one-half percent in 10 hours. At 4000° F the allowable creep stress is about 1800 psi for a creep rate of 10^{-4} inch per inch per minute.

It should be noted that the properties of tungsten that have been discussed do not include the properties of tungsten containing a fissionable material additive. Much work needs to be done to determine the properties of fueled tungsten for a range of fuel loadings required for thermal and fast reactors.

Tungsten 184 production. - As discussed earlier, in order to use tungsten for a thermal reactor it must be enriched in the tungsten 184 isotope because it has a relatively low thermal and resonance absorption cross section. The total cross section of tungsten as a function of neutron energy is shown in figure 12. It is readily observed that the isotopes 182, 183, and 186 have several high resonance peaks in the lower resonance range indicating a high resonance absorption integral. On the other hand, tungsten has only a relatively small resonance at the higher end of the neutron energy range. It is quite apparent that it is desirable to enrich the tungsten in the 184 isotope. The Oak Ridge gaseous diffusion plant has made a study indicating the feasibility of enriching the tungsten in the 184 isotope (ref. 57). The conclusion reached was that it is feasible to enrich tungsten in the 184 isotope in existing gaseous diffusion plant equipment with essentially no modification. Quantities of the order of 8950 pounds per year could be produced in existing equipment at a cost of about $1450 per pound. The tungsten 184 would be enriched to a value of 78.4 percent in this case. Estimates have also been made for the cost of producing enriched tungsten in a new plant. Figure 13 indicates the results obtained in reference 57. The cost of the tungsten product in dollars per pound is shown as a function of production rate in pounds per year for two enrichments (93 and 65 percent W^{184}). For production rates of 60,000 pounds per year the cost is about $1600 per pound for 93-percent enrichment and $1000 per pound for 65-percent enrichment. When the fissionable material saving created by the use of tungsten 184 and the cost of a mission are taken into account, the cost of the tungsten is quite reasonable.

Typical compositions of isotopically enriched tungsten are shown in table VI. For reference purposes the composition of the natural tungsten is also shown. Notice that the tungsten 184 isotope is the most abundant of the tungsten isotopes although the 182, 183, and 186 isotopes are also quite abundant. In mixture 1 the tungsten 184 has been enriched to 57.9 percent with the corresponding values for tungsten 182, 183, and 186 as shown. The total thermal cross section has been reduced from 17.4 barns for natural tungsten to 7.2 barns for the enriched tungsten. The dilute resonance integral has been reduced from 325 to 177 barns. Composition 2 has been enriched to 78.4 percent in tungsten 184. In this case the thermal cross section has been reduced to 4.5 barns and the resonance integral to 88 barns. Enriching to 93.0 percent reduces the thermal cross

section to 3.0 barns and reduces the resonance integral to 32 barns.

FUEL ELEMENT PROBLEMS

The preceding discussion has indicated the basic materials and their properties that are available for producing fuel elements for high-temperature high-power-density reactors. These data provide a basis for the choice of a basic fuel-element material. The basic fuel-element material is defined as a suitable combination of a refractory fuel material and a refractory material to support and/or contain it. For example, one concept of a basic fuel-element material discussed in reference 58 is "plates in which a high melting uranium compound (e.g., UO_2) has been dispersed in a matrix of a suitable high temperature material."

In order to be of use in a reactor the basic material must be formed or fabricated into a geometry that permits fission heat removal by hydrogen. Heat-transfer surface and supporting structure to withstand aerodynamic loads, to maintain the fuel element geometry, and to withstand loads imposed by high power density and pressure drop must be provided by the fuel-element design.

The problems associated with basic fuel-element materials and fuel-element design for high-temperature high-power-density operation is discussed subsequently.

Basic Fuel-Element Materials

The requirements for the basic fuel-element material for a nuclear rocket are "that the uranium compound should not react with the matrix material, that they should have adequate strength and resistance to failure by repeated thermal cycling, that they should not be attacked or eroded rapidly by the flowing hydrogen, that fission product damage be minimized, and that they can be reliably fabricated into required shapes" (ref. 58). The statement that "the uranium compound should not react with the matrix material" applies in particular with basic fuel-element materials that are composed of a dispersion of a refractory uranium compound within a matrix of a refractory material. Dispersed fuel-type fuel plates using refractory materials have been made. In general, such plates are made by powder metallurgy. Figure 14 (ref. 58) shows the specimen after three steps in the fabrication process. As-pressed, as-sintered, and as-rolled photos are shown. The rolling step provides a high density nonporous plate that is important in reducing the evaporation of the fuel compound. Even with the high densities achieved in the rolling process the loss of fuel is still quite rapid. Metal cladding of these specimens greatly reduce the loss. Figure 15 (ref. 58) indicates the gains obtained by the use of cladding. The specimens were about 1 inch by 1 inch by 0.030 inch thick and were clad only on the flat surfaces leaving the edges unclad. Reference 58 points out that preliminary studies are sufficiently encouraging to indicate that the refractory

metals are promising candidates for the matrix material for the fuel of nuclear rockets. A great deal of research is required to determine all the properties of these refractory dispersion-type fuel elements for the range of fuel loadings required for thermal and fast reactors.

Another type of basic fuel material is the solid solution. This applies particularly to the solution of uranium carbide in the refractory carbides such as HfC, TaC, NbC, and ZrC. Because of the low vaporization rate of UC and the high melting point of the refractory carbide, solid-solution-type fuel-element materials appear quite attractive. The chief problems associated with them are the poorer mechanical and strength properties typical of ceramic materials and the reduction in melting point caused by the addition of UC. The poorer mechanical properties were pointed out in the discussion of table III. In particular, the thermal stress resistance even at temperatures considerably lower than that desired for operation of nuclear rockets was shown to be about an order of magnitude less than that for the refractory metals. The reduction of melting point by the addition of UC in solid solution with zirconium carbide typifies this particular problem. Figure 16 gives the melting point for the continuous series of solid solutions of UC-ZrC varying from pure ZrC to pure UC. The addition of 10 percent of UC reduces the melting point by about 380° F; 20 percent addition by about 600° F. Concentrations of 10 or 20 percent UC would correspond to loadings typical of those for thermal reactors. Fast reactors require loadings of the order of 50 percent. At 50 percent, the reduction in melting point is 1320° F. Data for the other carbides, which have higher melting points, would be expected to show large effects roughly in proportion to the difference in melting points of the refractory carbide and uranium carbide. For hafnium carbide and tantalum carbide the reduction in melting point would be about 1800° F for a loading of 50 volume percent.

A third type of basic fuel-element material is achieved by the use of a refractory-material can containing a refractory fuel-compound. For example, a tube of a refractory metal could be filled with UO_2 and sealed. These tubes would then be assembled in some arrangement to form proper heat-transfer surfaces. The virtue of this scheme is its simplicity. One difficulty is associated with the difference in expansion rates between the UO_2 and the refractory tube, particularly if the fuel becomes molten. Another source of difficulty for high-power-density reactors is the steep temperature gradients that will be found in the fuel. If the cans are too large in diameter melting will occur. Recycling of such an element where the fuel melts will certainly lead to difficulties due to the volume changes occurring on freezing and melting.

Typical Fuel-Element Geometries

Several typical but ideal fuel element geometries are shown in figure 17. They have been used or may be used in many reactors of all types using both liquid and gaseous coolants. The plate-type fuel element fabricated from fuel-bearing material consists of a spaced stack between which

coolant may flow to remove heat. Elements such as these are used in many water-cooled reactors in the United States. The flat plates may be formed into cylinders to obtain a concentric-ring-type geometry. Such elements were used in the HTRE-1 reactor (ref. 59). Further discussion of elements utilizing flat plates can be found in reference 60. Other possibilities for typical fuel elements are the tube bundles where the basic fuel-bearing material is formed into tubes of the proper hydraulic diameter and spaced as desired so that the coolant may flow both inside and outside the tube bundle. Many other geometries are possible (see refs. 60 and 61). The only limitation is the ability to fabricate them. For example, one could consider a hexagonal honeycomb fabricated with fueled material. Also shown is a hole matrix element design where the fuel material is essentially a block of fueled material that has been drilled for flow passages. Square honeycomb is another type that would be similar to the hexagonal honeycomb element, but may be more suitable for different manufacturing techniques. The typical fuel-element geometries shown are merely for the purpose of illustrating the dreams of the heat-transfer expert. The problem of developing any of these elements is a difficult and tedious operation particularly when dealing with refractory materials that are quite difficult to handle, especially when they are fueled.

Design Considerations

The primary function of the fuel element in addition to locating the fuel physically is to provide heat-transfer surfaces and flow passages for heating the reactor coolant. The flow area required to pass the hydrogen propellant through a nuclear-rocket reactor core for a given power level is determined by the pressure and velocity of the propellant. The power removed from each unit of flow area within the core is determined by the flow rate per unit area and temperature rise of the hydrogen. Figure 18 plots the reactor power per unit flow area (Mw/sq ft) as a function of reactor exit pressure in psi. These curves are shown for three different values of reactor-exit dynamic head ($\rho v^2/2g$). High dynamic head means high flow rates, high pressure drops, and large aerodynamic forces. High flow rates are desirable to minimize reactor size. The figure shows that if the reactor operates with reactor exit pressure of 600 psi and with a dynamic head of 20 psi approximately 1200 megawatts of reactor power could be removed for every square foot of flow area available in the core. The dynamic head used in this curve is important in determining the effect of aerodynamic loads on the fuel elements. As was found in the case of the HTRE-1 and HTRE-3 reactors (refs. 60 and 61), it was difficult to operate fuel elements at high dynamic heads (greater than 10 psi, for instance,) particularly those elements that were made from flat or curved sheets typified by the flat-plate and concentric-ring geometries indicated in figure 17. As the flow rate is increased over these elements a dynamic head is reached where the element collapses. This is illustrated in figures 19 and 20. Figure 19 shows a flow test of a HTRE-1 element (ref. 61). The four photographs indicate the condition of the element after testing at a series of increasing dynamic heads. For the lowest dynamic head, which is the case for picture on the left, there is no distortion. As the dynamic

head is increased toward the right more and more distortion can be seen which, of course, would lead to a fuel-element failure. Another illustration from the HTRE-1 program is shown in figure 20, which shows the effect of airflow on a curved plate element (ref. 61). Here hot air flowing from right to left was passed through an array of curved plates simulating a fuel element. The failure that occurred as the dynamic head was increased beyond that which the fuel element could take is shown quite clearly. Aerodynamic loads are, quite apparently, important considerations in fuel-element design. The choice of dynamic head for a reactor design must await extensive design and test work on a large variety of fuel-element designs. A range of values is therefore shown.

In addition to aerodynamic loads, the fuel element is subjected to thermal stress due to thermal cycling and to the high rates of internal heat generation and heat transfer from the elements. High thermal stresses can lead to distortion of the elements with subsequent failure due to starving or excess flow of coolant in some passages leading to excess temperatures and possible meltdowns.

Pressure drop is of concern to the fuel element, since the pressure drop exerts a load that must be transferred from the element to a structure that holds the individual pieces of the element. Proper structural designs must minimize distortion and utilize a minimum amount of material. High heat fluxes can also lead to internal stresses that lead, in turn, to cracking of the elements thus allowing the fissionable material to escape, since fissionable material has a relatively high vapor pressure compared with most refractory materials. In addition to causing a loss of fuel, cracking could cause complete destruction of the element.

Power generation in reactors is generally not uniform either in the radial or the axial direction because of the falling off of the neutron flux from the center to the edges of the reactor. This means that across any particular element there will be a variation of power that will lead to nonuniform temperature in the element. It is desirable, of course, to run the entire element at the maximum possible temperature to achieve the greatest heat-transfer efficiency. This means that either the fuel concentration must be varied across the element or the hydraulic diameter of the flow passages must be varied so as to lead to uniform temperatures by tailoring of the flow distribution. Nonuniform flow distribution can also occur in an undesirable manner due to the variations in hydraulic diameter caused by allowable tolerances in the fuel-element manufacture. Poor tolerances will lead to poor uniformity of hydraulic diameter, which, in turn, will cause nonuniform flow distribution and unwanted hot spots. Tolerances in the fuel element must be carefully controlled in the manufacturing of the element to minimize this problem and produce the most efficient element.

Fuel-Element Evaluation

After a satisfactory basic fuel-bearing material is fabricated, experi-

mental testing will determine how good this composite material is. An
example of one such test is the determination of the ability of the fuel
material to retain the fissionable material at high temperature in the
presence of hydrogen. The test specimen is subjected to high temperature
in a furnace and the rate of loss of UO_2 is measured as a function of
operating time and number of temperature cycles. In addition, in-pile
testing can determine the effect of radiation and fission product damage.
One such test is shown in figure 21. A uranium bearing specimen about 1
inch square is suspended in a capsule that is evacuated and placed in a
materials-testing reactor so that neutrons will cause fission within the
specimen. The capsule is evacuated and provided with irradiation shields
surrounding the specimen so that the specimen can operate at temperatures
desired for nuclear rockets. This is a relatively inexpensive and rapid
test and permits a rapid evaluation of the variables that may be encountered
in fabricating fuel materials of this type.

As confidence is gained in a particular material combination or fabri-
cation techniques, fuel-element designs can be fabricated. These designs
can be tested in an out-of-pile flow test facility to determine their suit-
ability for withstanding the dynamic head loads that might be encountered
at the high hydrogen flow rates desired in a high-power-density nuclear
rocket. The flow test facility would supply hot hydrogen in sufficient
quantities to test experimental fuel-element designs at design flow rates
and temperature, simulating high-temperature operation in the reactor.
These would be isothermal tests in that there is no internal heat generation
within the fuel element and since the gas heats the element, the element
attains the temperature of the gas. The effect of aerodynamic loads on any
configuration can be studied in this kind of test. Following an out-of-
pile test such as this, in-pile testing, where samples of fuel-element con-
figurations are exposed to neutrons in a test reactor and cooled by a gas
coolant, can be carried out. This type of test can be used to check the
operation of experimental fuel elements at the high dynamic heads while
operating at full temperature. A typical in-pile flow test loop is shown
in figure 22. The photograph shows a model of an in-pile test apparatus
designed for the NASA Plum Brook Reactor at Sandusky, Ohio. The fuel speci-
men is contained at the end of the long snout that is inserted into the
proximity of the test reactor core. The tank to which the snout is attached
contains the necessary heat-transfer and pumping equipment necessary to
cool the test specimen.

Other tests that can be performed on fuel elements are mechanical tests
simulating the loads that might be encountered in flight or during the
boost phase of the operation of a nuclear rocket. For example, the fuel
element might be subjected to extreme vibrations during the boost. In
addition, large side loads may occur due to gimbaling of the engine to
change the thrust vector.

Following preliminary testing of this nature, reactor-core testing is
the next logical step. Such tests would be similar to the GCRE testing
prior to the ML-1 development and Kiwi testing prior to the NERVA develop-
ment. Figure 23 illustrates a Kiwi test. It includes an experimental

nuclear-rocket reactor contained with a system that has a nozzle and associated pumping and control systems. The purpose of testing, of course, is to find those difficulties that are not made apparent by testing individual components of the reactor core. Very frequently, problems arise that cannot be anticipated by design or by preliminary testing of the components thus providing the main purpose of testing a whole reactor.

MODERATORS

The following properties are desirable for nuclear-rocket reactor-moderating materials:

(1) Low molecular weight

(2) Low neutron absorption

(3) High moderating atom density

(4) High operating temperature

(5) Good thermal stress resistance

(6) Low overall density for light weight

The properties of the common moderating materials are shown in table VII. The data for this table were obtained from references 12, 13, 16, 27, 28, 61, and 62. They are listed in order of decreasing operating temperature. Lithium hydride is listed as a moderating material with the assumption that the lithium used is the isotope lithium 7 (Li^6 which constitutes 7.42 percent of natural lithium, has a prohibitively high thermal neutron absorption cross section). The maximum operating temperatures indicated are thought to be reasonable based on previous experience with these materials. In the case of the hydrides, decomposition or reduced ability to retain hydrogen limits the operating temperature. For light and heavy water the maximum operating temperature is chosen to be about 50° F less than the saturation temperature at 1500 psi, which is expected to be beyond the highest operating pressure desired for nuclear-rocket applications.

To minimize reactor size and hence weight, it is highly desirable to select a moderator with the smallest age. With the exception of D_2O the moderators are listed in order of decreasing age. It can be seen that the moderators which contain hydrogen are the best from this point of view. Graphite, of course, has the largest age because of its relatively high atomic weight.

An additional desirable property for nuclear-rocket moderators is that they have a low overall density, while possessing a high concentration of moderating atoms. Lithium hydride and water fulfill this dual requirement. Zirconium hydride, although possessing a high hydrogen density

has a high overall density, being about 6 times as heavy as either water or lithium hydride.

Another concern for moderators to be used for high-power-density reactors is that large amounts of energy due to gamma and neutron attenuation is deposited within them. Removal of this heat sets up thermal stresses. A measure of the ability of a material to withstand thermal stress is a parameter that is proportional to the product of the strength of the material and its thermal conductivity and inversely proportional to the product of its elastic modulus and its expansion coefficient. This figure of merit labeled thermal stress resistance is also shown in the table. Water, being a liquid, does not have this problem and is so indicated by the sign ∞ for its thermal stress resistance. Lithium hydride has the poorest thermal stress resistance of all the materials considered. Graphite, with the exception of the liquid moderators, is most resistant to thermal stress.

In summary, if high-temperature operation is desired, and reactor size is no objection, graphite is the best moderator for large high-power-density reactors. If minimum size, minimum weight, and high power density are desired, water appears to be the most attractive moderator. Inasmuch as water must operate at a relatively low temperature, provisions must be made for circulating and cooling the water. In the case of the nuclear rocket, more than adequate cooling capacity is available in the hydrogen propellant before it passes through the high-temperature core. An additional concern for water or any other moderator that operates at a lower temperature than the fuel elements is that insulation must be provided between them. As will be shown later, this problem although appearing difficult at first glance is really quite straightforward in its solution.

FAST REACTORS

Fast reactors offer the potential of minimum size cores that would tend to make them lightweight and therefore be of direct interest to low-power applications. Criticality studies have been made (ref. 63) of fast reactors for application to nuclear rockets. This study provides the basis for a discussion on fast-reactor weight, size, fuel-loading requirements, and fuel investment. Design problems of fast reactors, in general, are discussed keeping in mind the implication of these problems for nuclear-rocket fast-reactor cores.

It has been indicated that tungsten offers the greatest potential as a fuel-element material for fast reactors. The high potential operating temperatures, low evaporation rate, superior ability to withstand thermal stress, compatibility with UO_2 (the most refractory stable uranium compound) make tungsten the obvious choice for further evaluation. Accordingly, the discussion of fast reactors will be centered around tungsten - uranium-dioxide systems. The fuel material is considered to be a uniform dispersion of uranium dioxide particles in a tungsten matrix.

Criticality

Criticality studies include the determination of reactor weight, size, fuel loadings, and fuel investments as determined by criticality requirements.

Reactor weight. - The weight of fast tungsten UO_2 reactors as a function of void cross-sectional area, core void fraction, and volume fraction of UO_2 in the fuel element composite is shown in figure 24. (The ratio of UO_2 volume to the sum of UO_2 volume plus tungsten matrix volume is herein referred to as volume fraction of UO_2 in the fuel element or as fuel loading. Thus, a 40-percent fuel loading implies that of the tungsten and UO_2 in the core, 40 percent is UO_2 and 60 percent is tungsten.) The void area is a measure of the reactor power. For any given value of hydrogen flow per unit area, the reactor power would vary directly with flow area. In the case of the fast reactor, all void cross-sectional area was assumed to be available for flow. In other words, the void area is equal to the flow area. A typical value of reactor power per unit flow area might be 1000 megawatts per square foot (see fig. 18). This corresponds to about 50,000 pounds of thrust per square foot of flow area. It will be convenient to recall these values to add significance to later curves plotted as a function of flow or void area.

It is readily apparent that increasing the void area increases the reactor weight. For example, increasing the reactor void area from 0 to 2 square feet at a fuel loading of 50 percent increases the reactor core weight from 1300 to 4200 pounds. Decreasing the fuel loading from 50 percent increases the reactor weight at an increasing rate. For example, at 1 square foot of void area the reactor weight increases from 2800 to 4200 to 5500 pounds, while decreasing fuel loading from 50 to 40 to 35 percent, respectively. The minimum reactor weight shown in this figure is about 1300 pounds and occurs at zero void area with a fuel loading of 50 percent. The importance of high fuel loading in minimizing fast reactor weight is clearly indicated.

Reactor diameter. - The reactor diameters that correspond to the weights given in figure 24 are shown in figure 25. The minimum reactor core diameter shown is 1.3 feet. Including the beryllium side reflector yields a reactor overall diameter of 2.1 feet. The reactor core diameter is not nearly so sensitive to fuel loading as reactor weight. A void area of 1 square foot decreasing the fuel loading from 50 to 35 percent increases the core diameter from about 1.7 to 2.1 feet.

Fuel-plate thickness. - The corresponding fuel-plate thickness (assuming that all of the UO_2 and W is in the form of plates that are spaced so as to produce a flow passage length to diameter ratio of 300) is shown in figure 26, as a function of void area and fuel loading. (A flow-passage-length to hydraulic-diameter ratio of 300 is considered an adequate minimum value to provide a reasonably low difference between the maximum wall temperature and outlet gas temperature.) The plate thickness is determined by setting the flow-passage length to diameter ratio. This is due to

the fact that, for each fuel loading, there is only one void fraction for each flow area desired that makes the reactor critical. There is, therefore, only one reactor length for a given ratio of reactor length to diameter ratio. Only one plate spacing will then satisfy the condition that flow passage length to diameter ratio is fixed. Since the void fraction is fixed there is only one plate thickness for each plate spacing.

Reducing the flow area below 1 square foot causes the plate thickness to increase rapidly. For a fuel loading of 50 percent, the required plate thickness is 0.050 inch at 1 square foot of flow area. For a flow area of 0.3 square foot the required plate thickness has increased to about 0.100 inch. Decreasing the fuel loading makes this effect more pronounced. For a fuel loading of 40 percent, for example, the required plate thickness for a reactor with a flow area of 0.3 square foot is 0.200 inch.

The difficulty encountered with large plate thickness is thermal stress. The thermal stress problem can be alleviated in the case of fast reactors by increasing the flow passage length to hydraulic-diameter ratio. For example, if the length to diameter ratio is doubled so that it is 600 instead of 300, the plate thickness would be reduced by a factor of 2. The plate thickness is inversely proportional to the flow passage length to hydraulic-diameter ratio. It should be noted that changing the length to hydraulic-diameter ratio does not in any way affect criticality. It merely causes a rearrangement of the same core material.

Fuel investment. - Another consideration in evaluation of reactors is the fuel investment. Figure 27 indicates the fuel investment as a function of void area and fuel loading for the tungsten UO_2 fast reactor. As can be seen from the figure, fuel investment for fast reactors tends to be large, particularly for large void areas. For small reactors in low power range, however, the fuel investments are not quite as severe. For example, for the case of 50-volume-percent fuel loading, fuel investments of about 500 pounds would yield a reactor with a void area of about 0.3 square foot, whereas the fuel investment for a reactor with 3 square feet of void area would be in the neighborhood of 1600 pounds for a 50-percent fuel loading. Decreasing the fuel loading to 35 volume percent increases the fuel investment by about 30 percent. As in the case of the reactor diameter the fuel investment is not quite so sensitive to fuel loading as is the reactor weight, because the fuel becomes a smaller fraction of the total reactor weight.

Reactor Design Problems

Fast-reactor design problems for the fast tungsten UO_2 system can be divided into fuel-element problems and core-design problems both of which will be discussed in the following sections. A typical fast-reactor-core design is discussed to illustrate the features of a particular fast reactor.

Fuel element. - As was shown earlier the fuel-loading requirements for

the fast-tungsten reactor tend to be large. The reactor weight is quite sensitive to fuel loading and the highest possible fuel loadings are desirable. The higher loadings tend to produce materials problems because high loadings imply large volume fractions of fissionable material within the refractory materials of which the fuel elements are made. It may be necessary to use 50 volume percent of the UO_2 within the fuel-element matrix. In the case of the tungsten-UO_2 fast reactor, it could hardly be expected that the properties of tungsten would not be affected by such large additions. The strength of the tungsten would be expected to be affected adversely inasmuch as the properties of UO_2 are much inferior to those for tungsten. In reference 58 it is pointed out that there is difficulty in retaining UO_2 within a refractory metal matrix at high operating temperatures. It would be anticipated that the larger the volume fraction of UO_2, the worse the problem of retention of UO_2 would be. Reference 58 points out that it is necessary to clad the refractory metal UO_2 matrix in order to prevent the loss of UO_2. Inasmuch as the cladding would be pure refractory metal while the matrix is a mixture of UO_2 and refractory metal, difficulties might be anticipated due to the difference in properties of the matrix and the cladding. In addition, the use of the cladding leaves less refractory material available for the matrix inasmuch as the ratio of UO_2 and refractory metal in the entire core is fixed at 50 percent. The volume fraction of UO_2 in the matrix would be increased to a greater or lesser extent depending on the cladding thickness, thus aggravating the materials problem. In addition to cladding, it may be necessary to use refractory-metal support structures within the core. This also would reduce the amount of refractory matrix material available for the core of the fuel element thus aggravating the problem even further.

The high power densities and the thick fuel plate required for fast reactors that will be used for nuclear rockets will lead to thermal stress problems particularly for small size minimum weight reactors. Thermal stress could lead to fuel cracking with subsequent high UO_2 loss rates and thermal distortion of the fuel elements. Thermal distortion, in turn, depending on the fuel-element design, could lead to nonuniform flow passage hydraulic diameter. Nonuniform hydraulic diameter would produce nonuniform flow distributions with consequent hotspotting.

In addition to these sources of difficulty, the loads imposed by flight is of considerable importance. The reactor must be boosted by conventional chemical rockets in which case large vibration and acceleration loads will be imposed by the booster. In addition to the vibration and large accelerations, there will be side forces experienced by the core due to the attitude control movements of the booster rocket.

The fuel element must be capable of restarting, particularly, as pointed out earlier, for the development phase of the nuclear-rocket development program. In order to assure no difficulty in restarting the material should not exceed elastic limits during temperature cycling so that distortion due to cooling and reheating does not occur. The development of satisfactory fuel elements for the fast tungsten-UO_2 system will require a great deal of laboratory experiments, fueled-materials research, and extensive evaluation testing under simulated operating conditions.

Core design. - The reactor core is an assembly of a sufficient number of fuel elements to provide nuclear criticality conditions. The core must support the elements so that they withstand all the loads placed on them such as those due to pressure drop and flight loads. The core must also accommodate large changes in dimension due to thermal expansion. It is particularly interesting to note the thermal expansion problem. A tungsten fuel element 2 feet long will expand about 0.25 inch as it is heated to a temperature of 5000° F. Likewise a tungsten reactor core 2 feet in diameter will expand on the order of 0.25 inch in diameter as it is brought up to temperature. It is not possible to construct a monolithic core because the differential thermal expansions that take place due to the nonisothermal condition of the core during normal operation startup, and shutdown would cause thermal stresses to be setup beyond the capability of the materials to absorb them. The core is therefore divided into smaller pieces that are commonly called fuel elements. The core support structure is defined as the structure that is necessary to tie the individual elements together and support the loads that are encountered by the elements and the support structure itself. It must provide room for and control of thermal expansion of the elements.

One technique for core support is to use a cooled front-end support. Incoming hydrogen would be used to cool this structure. The fuel elements are fastened to this cold end support plate. Inasmuch as this structure, which would space the fuel elements, runs cold, clearance must be provided for each element to allow it to expand. If clearance is provided without restraint the elements will bow if there is a temperature gradient across them. The bowing of a bundle of fuel elements and the interactions that may result therefrom can lead to coupling with the reactivity of the core. As discussed in references 64 and 65 this particular problem must be carefully worked out for each fast-reactor design or serious trouble may result. Careful design and testing will be required to eliminate or control this difficulty. Fast-reactor control, while trickier than that for a thermal reactor, has been solved in several fast-reactor designs. One technique of control is to provide a rotating drum system in the reflector region of the reactor. Reflector drums can be rotated so as to move neutron absorbers closer or farther away from the core thus changing the neutron current going back into the core from the reflector. Another type of control scheme that can be used is to move a portion of the reflector to affect a change in the neutron leakage with reflector position.

One particular problem of a fast reactor that is reflected with a moderating material, such as beryllium, is a large thermal power spike at the core reflector interface. This is pointed out in reference 63 and is illustrated in figure 28, which was obtained from this reference. Radial power distributions of a fast reactor that is reflected with beryllium is shown. The vertical line to the right of the curve indicates the core reflector interface. The solid line indicates the power distribution that is obtained with a plain reflector. It will be noted that a large thermal power spike exists at the interface leading to power densities about twice that for the average. One way to eliminate this spike is to use a thermal neutron absorber at the core reflector interface. The power distribution

that results in this case is shown by the dashed line. Another solution is to use a nickel reflector to keep the spectrum of the reflected neutrons at a sufficiently high level so they are not immediately absorbed at the core interface. This leads to a power distribution as shown by the dashed curve. The use of either of these two techniques to minimize this core spike results in reduced effectiveness of the use of the reflector rotating-drum-type control system. This difficulty will have to be taken into account in the design of a fast reactor that uses a reflector control system.

An Aerojet-General Nucleonics fast-core design is shown in figure 29 to illustrate a typical fast-core design. This core was designed to heat a gas to about 1500° F. The fuel elements in the core are composed of hastelloy tubes filled with a fissionable compound and arranged so that the gas flows parallel to and in between the tubes. For a nuclear-rocket application these tubes could be made of tungsten or other refractory material in place of the hastelloy. One difficulty with this design is that the use of tubes or pins, as they are sometimes called, leads to large temperature differences from the centerline to the surface of the fuel pins, particularly if high power densities are desired and the pins are relatively large in diameter. If temperatures are limited at the centerline for some reason, the surface temperatures would be operating at a much lower temperature than the capability of the materials would allow at high power densities. For high power densities, relatively fine pins would have to be used in place of the heavy pins that are shown here. In this particular design, support of the fuel elements is provided at both the hot and cold ends of the core. In the case of a tungsten-reactor hot end support may pose a much more difficult problem.

Other Fast Reactors

The use of uranium carbide solid solution as a fuel-element material leads to reactor weights that are lighter than that for tungsten-UO_2 reactors. The chief reason for the reduced weight is the much lower density of the carbides when compared with tungsten. Reference 63 gives data for zirconium-carbide - uranium-carbide fast reactors. Figure 30 taken from this reference shows the reactor weight as a function of reactor flow area for zirconium-carbide reactors compared with a tungsten-UO_2 fast reactor. The tungsten-UO_2 fast reactor shown is for fuel loading of 50 volume percent. The two curves shown for the zirconium carbide reactors contain fuel that consists of 30-70 and 50-50 mixtures of UC-ZrC. It can be seen that an appreciable weight saving can result from the use of zirconium carbide, particularly for the low reactor flow areas. For example, for zero flow area the reactor weight could be reduced to about one-half that of the W-UO_2 reactor. Although a large weight saving could be obtained with zirconium-carbide reactors, problems already pointed out tend to make the reactor less attractive. For example, from the point of view of evaporation rate, zirconium carbide could not be operated at temperatures much above 3500° F without excessive loss of material. In addition, the capacity for resisting thermal stress is very much lower than for tungsten. Another difficulty of the carbide reactor was discussed earlier in figure 16. The melting point of the UC-ZrC solid solution reduces the

melting point to about 5000° F compared with the melting point of 6300° F for pure zirconium carbide. The tendency therefore, is, to try to use lower percentages of UC in ZrC so that the melting point is not as greatly effected. This, of course, then reduces the weight advantage of the zirconium-carbide reactor.

Hafnium or tantalum carbide could be used in place of the zirconium carbide to minimize both problems that have been pointed out. For example, the vaporization problems would be greatly reduced when compared with zirconium hydride. The melting point problem of UC-TaC or UC-HfC would be about 400° F higher for a 50-50 mixture, since the melting point of tantalum and hafnium carbide is much higher than that for zirconium carbide. The advantage of lower weight would be eliminated because of the much higher densities of the hafnium carbide and tantalum carbide. In addition, thermal stress-wise, neither hafnium carbide nor tantalum carbide would be expected to offer much of an improvement over zirconium carbide when compared to the relatively large thermal stress resistance of tungsten.

It has been proposed in reference 66 that a two-zone reactor with a fast central core and a thermal outer core be considered for nuclear-rocket propulsion. The fast central core, supplied by neutrons from the surrounding thermal core, would permit the use of much lower concentrations of fissionable material within the refractory material. This would tend to permit the use of higher melting point materials than tungsten within the inner zone without regard to its thermal cross section. Such a system would have the potential for attaining a reactor that would have a higher specific impulse than that for tungsten. As pointed out earlier, however, the higher rate of evaporation rates of the carbides compared to tungsten would probably limit the operating temperature of the carbide to values lower than that of tungsten. So that even a two-zone reactor where low concentrations of fissionable material could be used in conjuction with uranium carbide may not lead to a reactor that would have a higher performance than tungsten.

It is possible to contemplate a fast reactor that would use a molten fuel, such as a core composed of tungsten tubes or cans filled with molten UO_2. This would eliminate the problem of destroying the properties of tungsten by large additions of UO_2 to the matrix material. In its place there would be problems of the expansion of the liquid UO_2 in passing from the solid to the liquid phase during cycling.

In summary, criticality studies show that $W-UO_2$ fast reactors can be made lightweight for lower power levels; however, they require large fuel loading that introduces a material problem. Carbides do not look favorable for fast reactors compared with tungsten because of their relatively poor properties. The high vaporization rates and low melting point when combined with uranium carbide make the development of fuel elements with superior performance to tungsten not likely.

THERMAL REACTORS

As pointed out previously, thermal reactors are of interest for nuclear-rocket application because they would permit the use of lower fuel concentrations within the fuel elements thus reducing materials problems that might be anticipated. The use of thermal reactors, of course, entails the complication of using a moderator in conjunction with the reactor that must be cooled by a separate system if good moderating materials are to be used. Homogeneous and heterogeneous types of reactors are discussed and the advantages and disadvantages of each type pointed out. In the case of the heterogeneous type, various concepts using different moderating materials are compared on the basis of weight, fuel investment and reactor diameter.

Homogeneous Reactors

Homogeneous reactors are those in which the fuel is dispersed uniformly throughout the moderating material in the core. As pointed out earlier, this means that the moderator must operate at a high temperature and be a good moderator at the same time. The only two candidates for this application are graphite and beryllium oxide. Graphite, of the two, is a poor moderator and leads to relatively large sized reactors. In addition, graphite is attacked by hydrogen and must be coated with suitable material to prevent distruction of the core at high temperature. Graphite reactors would be suitable for relatively large powerplants where size is not important. Beryllium oxide, however, operates at temperature levels perhaps a thousand degrees less than graphite but would lead to lower weight reactors because of its better moderating characteristics. Inasmuch as specific impulse or high hydrogen temperature is more important than reactor weight, graphite would be the best choice of the two materials for a homogeneous reactor.

Inasmuch as there is no homogeneous reactor that can be expected to be small in size and at the same time operate at a high temperature, homogeneous reactors will not be considered further in this lecture.

Heterogeneous Reactors

Heterogeneous reactors are characterized by the separation of the fuel elements and the moderating material. There are two kinds of moderating material that might be used in a heterogeneous reactor, a solid moderator or a liquid moderator. These moderators are illustrated in table VII. The fuel material that will be considered for the heterogeneous-type reactors, in general, will be the $W-UO_2$ material. The $W-UO_2$ mixture seems to have the greatest potential of all the possible refractory material, fueled material combinations.

Solid-moderator tungsten-fueled reactors. - In general, the solid-moderator tungsten-fueled reactor uses moderating materials that operate

at lower temperatures than the fuel material, which means that the moderator material must be cooled independently from the fuel-element material. There are two ways in which the moderator may be cooled: one way is by flowing hydrogen through the moderator parallel with the flow through the fuel elements and the other is by flowing the hydrogen through the moderator in series with the fuel elements. That is, the hydrogen would first flow through the moderator and then through the fuel element thus making a two-pass system. There is more than an adequate amount of cooling capacity available in the hydrogen propellant before it passes into the core for moderator cooling. Because nuclear-rocket cores are high-power-density cores, there will be large amounts of gamma and neutron heating occurring within the moderator. Even though there is more than adequate cooling capacity available to cool the moderator, the high power-generation rates within the moderator would lead to large temperature gradients within the moderator. This, in turn, leads to large thermal stresses unless the moderator material is broken up into relatively fine pieces. Providing a mechanical design that permits cooling of the moderator, in addition to providing support for all the individual pieces in the moderator and allowing for the large thermal expansion that will take place as the moderator increases in temperature to its operating temperature greatly complicates the design of the core. In addition, cooling passages effectively act as voids to the core thus reducing the average density of moderating material in the core.

Of the solid moderators listed in the previous discussion, lithium hydride was the lightest. It was indicated, however, that lithium hydride probably had the lowest thermal-stress resistance of all the solid moderators. Lithium hydride would therefore be the least attractive for high-power-density reactors. In order to use it for high-power-density nuclear-rocket reactors it would have to be broken up into very fine pieces so as not to cause the material to crack due to thermal stress. Zirconium hydride has the advantage of producing a small sized reactor, but because of the high density of the zirconium hydride it would lead to reactors that would have considerably higher weight than lithium hydride. Beryllium oxide has the advantage of being the moderator with the highest operating temperature. This would tend to minimize the insulation problem that would exist between the high-temperature fuel elements in the moderating region. Beryllium metal is another possibility for the moderating material. It would have a higher thermal stress resistance than lithium hydride, but the moderating characteristics would not be as good.

Liquid-moderator tungsten-fueled reactors. - Ordinary water and heavy water are two liquid moderators that are shown on the table of moderating materials (table VII). It would appear that ordinary water would offer a much smaller core than the heavy water because of the superior slowing down characteristic of the hydrogen in the water (see ref. 11). Although only water was shown as a hydrogenous liquid moderator, other liquid organics could be used. It is anticipated that organic liquids could be found that would be expected to produce reactors equivalent in size and weight to water reactors. In the case of organic moderators, however, one would be concerned about the potential of radiation damage affecting their properties.

The use of the liquid moderator eliminates the thermal stress problem. The gamma and neutron heating that is generated within the liquid moderator can be removed by transporting the moderator material out of the core and passing it through a heat exchanger, which is cooled by the incoming hydrogen. The heat-generation rate in the water will then only be limited by the rate at which water coolant can be flowed through the core without causing boiling. It is anticipated that the limiting power density of the cores using liquid moderators would be determined by fuel element considerations, and not be limited by the cooling of the moderator. Another advantage of liquid moderation is that cooling of liquid moderators or providing clearances for thermal expansion does not introduce voids into the moderator region as in the case of the solid materials.

The liquid moderator has the additional advantage that liquid would be in contact with all the structural components of the core, thus maintaining the structure at an essentially uniform temperature. Conventional materials such as aluminum, zirconium, or stainless steel can be used for the core construction. Overall core-expansion problems are thus eliminated. The only thermal expansion problems existing in the core are isolated within individual fuel elements. The overall core will thus be dimensionally quite stable compared to the fast or homogeneous reactors where the entire core must expand or provide room for expansion of the materials.

Other fuel materials. - Although tungsten - uranium-dioxide has been considered as the fuel-element material for thermal reactors, it is possible to use other fuel materials. Any of the refractory materials that have a sufficiently low thermal cross section can be considered. For example, molybdenum-UO_2 could be used although its temperature capability would be limited when compared with tungsten. Molybdenum is an interesting material to consider inasmuch as it could be used in place of tungsten in the early stages of a nuclear-rocket-powerplant development program. As the tungsten-UO_2 development program progresses, the tungsten-UO_2 elements would replace molybdenum-UO_2 elements without greatly affecting the core design. It would also be feasible to use materials such as nichrome-UO_2 that was used in the HTRE-1 and HTRE-3 reactors for the Aircraft Nuclear Propulsion program. The use of nichrome or molybdenum in a development program would alleviate the early need for tungsten enriched in the tungsten 184 isotope. In addition, while the tungsten isotope was being separated, development work could be continuing on the reactor with substitute fuel elements. Other low-cross-section materials such as zirconium carbide, niobium carbide, or graphite could also be used for the fuel elements. As pointed out previously, carbides have the disadvantage that the introduction of uranium carbide reduces the melting temperature. In a thermal reactor however, as contrasted with a fast reactor, the amount of uranium carbide addition would be relatively small, therefore, having a lesser effect on the melting temperature. Therefore, if carbide is to be used for fuel elements one would expect a higher temperature potential for thermal reactors than for fast reactors. If graphite with a dispersion of a suitable fuel compound is used, the graphite would have to be coated with a low-cross-section protective material to prevent attack by hydrogen.

The point to be made is that the heterogeneous reactor offers the possibility of using a wide variety of fuel-element designs and materials. Within the same core it may be feasible to carry out a major portion of the nuclear-rocket-engine development program utilizing fuel elements made of nichrome, molybdenum, carbide or graphite, while the tungsten-UO_2 fuel element was being developed concurrently. In other words, powerplant development work could be carried out with relatively inexpensive, reliable, or proven fuel-element designs, while more advanced fuel elements are being worked on in the laboratory. Because of the ability to change fuel-element materials and configurations, this type of reactor has the capability of being continually up-rated as better and new fuel elements are developed and become available.

Comparison of Heterogeneous Thermal Reactors

A study has been made comparing the weight, fuel investment, and size of a range of thermal heterogeneous reactors using BeO, Be, lithium hydride and water as the moderating material (ref. 67). All the reactors considered used tungsten enriched in the W^{184} isotope as the fuel-element material.

An important parameter in this study is the weight of tungsten required per unit flow area of the reactor. Figure 31 shows the weight of tungsten per unit flow area as a function of fuel-plate thickness, for various fuel loadings (ratio of volume UO_2 to volume UO_2 plus tungsten). The solid curves are for a passage-length to hydraulic-diameter ratio (l/d) of 300; the dashed curves correspond to an l/d ratio of 600. For a fuel plate thickness of 0.01 inch and fuel loading of 10 percent, the weight of tungsten per unit flow area is about 800 pounds per square foot. As the fuel-plate thickness increases, the weight of tungsten per unit flow area increases in proportion. The weight of tungsten per unit flow area is also proportional to the l/d. If an l/d of 600 rather than 300 is required twice as much tungsten per unit flow area would be necessary. For any desired fuel-plate thickness and desired fuel loading, the weight of tungsten per unit flow area can be determined from this curve. The value of weight of tungsten per unit flow area of 1200 pounds per square foot will be assumed for the following analyses unless otherwise noted. Inasmuch as insulation and core structural materials, such as aluminum, effectively introduce more void into the core than is required for flow, it will be assumed that the flow area should be increased by 50 percent to take this fact into account. The assumed weight of tungsten per unit void area for this analysis, unless otherwise noted, will therefore be 800 pounds per square foot.

Reactor weight. - Figure 32 shows the reactor weight as a function of void area for BeO, Be, LiH, and H_2O moderated reactors. The fuel elements in these reactors are assumed to be tungsten-UO_2 cermets containing 30 volume percent UO_2. The W^{184} enrichment is assumed to be 100 percent and tungsten per unit void area is 800 pounds per square foot. The criticality calculations of heterogeneous reactor size and weight carried out

in reference 67 were made with the assumption that the materials of the core are uniformly distributed. The effect of introducing heterogeneity in the calculations would be expected to reduce the weight and size particularly for large size reactors (perhaps those with 1 sq ft of void area or greater). Heterogeneity would reduce the number of neutrons absorbed in the tungsten resonances. In the case of smaller size reactors, where larger ratios of moderator to tungsten ratios are encountered to achieve criticality, the effective thickness of water between cells may exceed that required for maximum reactivity (ref. 68). This would lead to excessive parametric absorption of neutrons by the hydrogen atoms and would lead to higher reactor weights than those calculated by homogeneous techniques. As would be anticipated, because of its high density and relatively poor moderating ability, the BeO reactor comes out to be the heaviest of all the reactors considered. The beryllium reactor is next and is followed by the lithium-hydride reactor. The water reactor is identical in weight to the lithium-hydride reactor as indicated by the two circled points on the lithium-hydride curve. For a void area of 1 square foot, the water-moderated or lithium-hydride-moderated reactor weighs a little over 1000 pounds. The corresponding weight for the Be reactor is about 2500 pounds and for the BeO reactor it is about 4500 pounds. Lithium-hydride- and water-moderated reactors show up clearly as the lightest weight of the moderated reactors. It should be noted that in place of water an organic material with comparable hydrogen concentration or density could be substituted, and would yield about the same weight.

Fuel investment. - Figure 33 shows the corresponding fuel investment for each of these reactors. The fuel investment is plotted as a function of void area and is shown to be a single line. The fuel investments for all these reactors are identical because of the assumption of 800 pounds per square foot of tungsten for each of the cores and the fact that each contain a fixed percentage of CO_2. Therefore, for each flow area there is only one fuel investment regardless of the moderator used. (The difference in weight shown in fig. 32 between them is due strictly to the difference in weights of moderators required to make a given array of tungsten fuel elements critical.)

Reactor diameter. - The diameter that corresponds to each of these reactors is shown in figure 34 as a function of void area. Because of the superior moderating characteristics of lithium hydride and water the reactor diameter is shown to be the least for the hydrogen-bearing materials. For a void area of 1 square foot, for example, the reactor diameter is about 1.8 feet for the hydrogenous reactors compared to about 3.1 feet for the Be or BeO reactors.

Summary. - It is apparent from these reactor calculations that the hydrogenous moderating materials are superior from the point of view of minimizing reactor weight and size. Lithium hydride is a poor choice for a moderating material because of its poor mechanical properties, as pointed out previously. Further studies of heterogeneous water moderated reactors will therefore be confined to the use of water as the moderator.

TUNGSTEN THERMAL REACTORS

The comparison of the various types of moderators for use in thermal heterogeneous reactors has indicated that water as a moderator eliminates thermal stress problems and produces the lightest weight reactor of all the moderators considered. The following discussion will be limited to water-moderated tungsten reactors. The discussion will include the effect of various concentrations of W^{184}, the effect of fuel loading, and some core design problems that arise from the use of water as the moderator.

Effect of W^{184} Concentrations

In the comparison of heterogeneous thermal reactors with various moderators that was discussed in a previous section, the enrichment of W^{184} was assumed to be 100 percent. Figure 35, taken from reference 67, indicates the effect on reactor weight of reducing the W^{184} enrichment. The reactor weight is plotted as a function of void area. The weight of tungsten per unit void area is 800 pounds per square foot. The UO_2 loading of the fuel elements is assumed to be 15 percent in this case. For a void area of 1 square foot the reactor weight increases from 100 to 1300 to 1500 pounds when the tungsten 184 enrichment is reduced from 100 to 78 to 58 percent, respectively. It can be seen that the W^{184} enrichment can be quite a bit less than 100 percent and still produce a lightweight reactor. The corresponding fuel investment as a function of void area is shown in figure 36. There is no effect of varying concentrations of the W^{184} shown because of the assumption of a definite value of tungsten per unit flow area and a fixed fuel loading. Figure 37 indicates the corresponding effect on core diameter as W^{184} enrichment is decreased. Reducing the enrichment of W^{184} from 100 to 78 percent increases the core diameter from about 2.1 to 2.4 feet at a void area of 1 square foot. A further reduction in W^{184} concentration to 58 percent increases the core diameter to 2.8 feet. For the remainder of the discussion of tungsten - water-moderated reactors the W^{184} enrichment will be assumed to be 78 percent. As pointed out in reference 57 this is a concentration that is readily obtainable from the gaseous diffusion plant at Oak Ridge.

Effect of Fuel Concentration

As pointed out earlier, it is highly desirable to minimize the amount of fuel within the tungsten matrix of a fuel element to minimize the effect of these additions on the properties of tungsten. The less impurities in the tungsten, the more closely will the properties of the fuel element approach those of tungsten. An investigation of the effect of the fuel loading on criticality was conducted in reference 67. The results are shown in the following figures. Figure 38 shows the reactor weight as a function of void area for fuel loadings varying from 10 to 30 percent by volume. The tungsten 184 enrichment in this case is 78 percent and the tungsten per unit void area is 800 pounds per square foot. It is

interesting to note that there is very little effect of fuel loading on
reactor weight with the exception of the case for a fuel loading of 10
volume percent. Below $1\frac{1}{2}$ square feet of void area the reactor weight in-
creases very rapidly for the loading of 10 percent. For higher values of
void area the effect of fuel loading for the range shown (10 to 30 per-
cent) seems to be small. The slight trend that does exist with the fuel
loading indicates that 20 volume percent appears to yield minimum reactor
weight. Considering the fact that lower fuel loadings are desirable from
a materials point of view and the interest in this lecture for small re-
actors, a fuel loading of 15 volume percent will be used for further anal-
ysis of the tungsten - water-moderated reactor. The corresponding effect
of fuel loading on fuel investment is shown in figure 39. The lower fuel
loadings lead to smaller fuel investments because the fuel investment is
directly proportional to the fuel loading due to the assumption of a fixed
value of tungsten per unit void area. Figure 40 shows the effect of fuel
loading on reactor diameter. Again very little effect is noted. A fuel
loading of 30 volume percent shows the lowest reactor diameter while 10
percent shows the highest diameter. However, the range of diameters be-
tween 10 and 30 volume percent of fuel is quite small.

Core Design Problems

Because the moderator is separated from the fuel regions and the mod-
erator operates at a much lower temperature then the fuel, insulation is
required between the two regions. This insulation can be provided by al-
lowing a stagnant gap of hydrogen to exist between the water and the fuel
element (ref. 11). It can readily be shown that a hydrogen gap of about
1/8 inch will reduce the heat load from the fuel element to the water mod-
erator to quite a bit less than 1 percent of the reactor power generation.
Even though hydrogen is a good conductor and a large quantity of heat is
conducted across the gap, the percentage of the total generated power that
is conducted and radiated across this gap is small because of the very high
power density of cores required for nuclear rockets. The insulation prob-
lem thus reduces to one of maintaining a stagnant layer of hydrogen of at
least 1/8 inch between the fuel element and the aluminum core vessel. Be-
cause of side loads that may be encountered during flight maneuvers, the
elements must be supported along their length to prevent them from contact-
ing the cold aluminum tubes. Any support structure introduced between the
elements and the aluminum tubes introduces the possibility for conduction
heat leaks from the fuel element to the water-cooled tubes. Ingenuity is
required to provide designs that provide support and at the same time
maintain the stagnant layer of hydrogen for insulation.

In the case of the water-moderated reactor, the moderator is cooled
by circulating it from the core through a heat exchanger that is cooled by
the cold incoming hydrogen. Heat exchangers must be designed and de-
veloped that cool water with hydrogen flowing at temperatures very much
below the freezing point of water, without freezing the water. In addi-
tion, a water pump and a turbine drive is required to circulate the
water through the core and the heat exchanger.

Reactor control can be accomplished by any number of techniques that have been used or proposed in tne past for thermal reactors. The conventional control-rod system could be used where control-rod poisons are inserted into the core regions. Poison-gas or poison-solution systems could also be used. A reflector rotating-drum control system may be feasible for small reactors with side reflectors.

Schematic Core Layouts

There have been two liquid-moderated gas-core reactors designed, developed, and tested in the United States. The first of these is the HTRE-1 reactor schematically shown in figure 41. The reactor is composed of an aluminum tank of water and aluminum tubes that pass from the top tube sheet to the bottom tube sheet. Water surrounds these tubes and fills the aluminum can. The fuel elements are contained within the tubes of this collandria-type structure. Shown here are concentric-ring-type elements made of nichrome-UO_2 dispersions. The elements are approximately 3 inches in diameter and about 2 inches long and are composed of concentric rings of nichrome-UO_2 dispersed. A number of these sufficient to make up a full length element are arranged one on top of the other in tandem fashion and held together by a support system that holds all the stages together to make one full-length fuel-element assembly. In this case air was used to cool the reactor. Air passes through tne nichrome elements where it is heated to its final operating temperature before being discharged at the reactor exit. In this case, a beryllium reflector was used around the core to flatten the radial power distribution. A large number of control rods were used throughout tne core to more or less uniformly depress the reactor flux without affecting the radial power distribution. The reactor was run successfully for several hundred hours during which time considerable data were obtained. References 59 and 69 give detailed accounts of the design problems of this core as well as some of the operating experience.

If the nichrome elements are replaced with molybdenum or tungsten enriched with tungsten 184 this core could be used for nuclear rockets. Provision must be made, however, to circulate the water moderator through a hydrogen heat exchanger in place of the stationary air-cooled heat exchanger that was used in the HTRE-1 core.

The AGN ML-1 reactor core is shown in figure 42. This then is a top view of the core and shows the arrangement of the fuel tubes. In this particular reactor, the spacing of the fuel tubes is varied regularly so as to produce a flat power distribution. The reactor is moderated by water. You will notice that the outer tubes have a greater water space between them than the inner tubes to assist in flattening the radial power distribution. In this case the fuel elements were a cluster of pin-type elements that are essentially tubes of Hastelloy filled with fissionable material. This reactor was designed to heat nitrogen for a Brayton cycle system that operates a small generator to produce a few hundred kilowatts of power. The reactor has been successfully operated at its full design power.

    The HTRE-1 and ML-1 reactors are examples of gas-cooled reactors
that use water as a moderator that have been built, developed, and
operated at temperatures of about 1500° F. The water-moderated nuclear
rocket must operate at temperatures of about 4000° to 5000° F. A sche-
matic illustration of a tungsten - water-moderated reactor is shown in
figure 43 to show the essential features of such a reactor. The core
consists of an aluminum tank of water with aluminum tubes passing from
the top to the bottom header sheets. The space between the tubes and in-
side the aluminum shell is filled with the water moderator. Fuel elements
are contained within the aluminum tubes. The water moderator is circu-
lated by means of a pump through a hydrogen to water heat exchanger.
Hydrogen coming from the storage tank is pumped through the nozzle for
cooling purposes. It then flows through the heat exchanger to remove the
heat generated in the water moderator. The hydrogen then passes through
the reactor fuel elements where it is heated to its final temperature and
ejected through the nozzle to produce thrust.

    The fuel elements are contained within the aluminum tubes. A sche-
matic cross section through an aluminum tube is shown in figure 43. The
aluminum tube is indicated with the water immediately adjacent to it.
The fuel element is shown schematically as a series of plates that are
fastened to a tungsten tube that runs the full length of the reactor. Be-
tween the tungsten and aluminum tubes is shown a molybdenum radiation
shield to minimize heat transfer by radiation. Stagnant hydrogen is main-
tained in the gaps on both sides of the molybdenum. This stagnant hydro-
gen insulation layer is approximately 1/16 to 1/8 inch thick.

    Solid-moderated gas-cooled reactors have been designed and, in some
cases, constructed and operated. Figure 44 shows an artist's version of
a design by AGN. In this design the fuel is mixed with the BeO moderator
and contained within tubes of Hastelloy that are supported at both the
hot and cold ends of the reactor core. The reactor was designed to heat
inert gases to temperatures approaching 1500° F. This reactor could
actually be considered as a homogeneous thermal reactor in that the fuel
and moderator are uniformly mixed. A reflector rotating-drum control
system is used as the method for regulating this reactor. Because of
the relatively large tubes that contain the fissioning material, this
reactor is suitable for relatively low-power densities only. The large
tubes would lead to large temperature differences between the centerline
and the surface of the tubes for the high power densities required for
nuclear-rocket application. For the nuclear rocket or any other high-
power-density application, the tubes would have to be much smaller in diam-
eter.

    The HTRE-3 is an example of a gas-cooled solid-moderated reactor that
has been designed, built, and tested. This reactor is similar to the
HTRE-1 except that the water is replaced with solid zirconium hydride.
Figure 45 shows a cross section of a typical cell within the core (ref. 61).
A 4-inch-diameter fuel element is shown in the center surrounded by several
triangular shaped pieces of zirconium hydride moderator. Insulation is
provided by the gap that exists between the tube and the moderator itself

and also by the hole in the center of the zirconium hydride. Because of
the relatively thick sections of moderator, this design would not be ap-
plicable to the high power density required for nuclear-rocket applica-
tion. A much finer dispersion of coolant passages would be required to
reduce the effective thickness of the moderator to prevent excessive
thermal stress and over temperatures. Figure 46 shows a photograph of a
HTRE-3 solid-hydride-moderator section (ref. 61). A number of these must
be stacked end on end to complete the full reactor length. Figure 47
shows a gas core homogeneous hydride reactor designed by AGN. The fuel
and moderator in this case are mixed together and formed into hexagonal
blocks that nest together as shown. The coolant gas is heated by flowing
through a multiplicity of flow passages within each element. This re-
actor would, of course, be suitable only for low-temperature operation
because of the limitation of the hydride. For higher temperature opera-
tion, the moderator must be graphite or beryllium oxide.

NUCLEAR ROCKET POWERPLANT PERFORMANCE

Up to this point, only the reactor itself has been considered in
making performance estimates. The nuclear rocket is a complete system
for producing high-velocity hydrogen. As such, a nuclear-rocket power-
plant includes components such as a pressure chamber, a nozzle, a turbo-
pump, and a control system. In the case of the water-moderated nuclear
rocket, a water to hydrogen heat exchanger and a water pump are also re-
quired.

Specific Impulse

The specific impulse of hydrogen is shown in figure 48 as a function
of reactor pressure and reactor exit temperature. Equilibrium expansion
was assumed with the nozzle expansion ratio of 50. A nozzle velocity
coefficient of 0.96 was assumed. The importance of high temperature can
readily be seen from this curve. The specific impulse at a temperature
of 1500° F is about 500 seconds, whereas for 4500° F it is in excess of
900 seconds. Reducing the reactor-exit pressure increases the amount of
dissociation in the nozzle and thereby increases the specific impulse.
At 4500° F, for example, the specific impulse can be increased from 900
to about 1100 seconds by reducing the operating pressure from 100 to 1
psi. Of course, in reducing the pressure this much, the weight of the
powerplant must be taken into account. Roughly speaking, a reactor with
a pressure 1/1000 the pressure of another would weigh perhaps a thousand
times as much. There is an optimum reactor-exit pressure that properly
trades off reactor weight for specific impulse for any given mission.

Powerplant Components

In addition to a nuclear reactor, the nuclear-rocket powerplant is
composed of pressure chamber, nozzle, turbopump system, control system,

and in the case of the water-moderated reactor, a heat exchanger and a
water pump system. Figures 49 to 53 give some estimate of the component
weights that were presented in reference 70. Figure 49 gives the pres-
sure chamber weight as a function of the reactor diameter. Figure 50
gives the weight of the divergent portion of the nozzle as a function of
reactor flow rate and reactor-exit pressure. The weight of the nozzle
convergent section is shown in figure 51 as a function of reactor diameter
for a range of reactor flow rates and pressures. The weight of the turbo-
pump as a function of reactor flow rate and pressure is shown in figure 52
for a range of reactor-exit pressures. The weight that is assumed for the
control system is shown in figure 53. Figure 54 shows the assumed weight
of the heat exchanger weight and water pump as a function of reactor flow.
Inasmuch as the lecture is concerned chiefly with reactors, no further
discussion will be given on the weights of these components except to
refer to reference 70 for further information.

Powerplant Weights

Powerplant weight estimates can be made by using the foregoing as-
sumptions with regard to the component weights of the components and add-
ing them to the weights of the nuclear reactor cores presented earlier.
The weight of the fast-reactor powerplant is then given in figure 55. The
powerplant weight is plotted as a function of reactor power in megawatts
for a range of reactor-exit dynamic pressures in pounds per square inch.
The reactor power was determined with the aid of figure 18. The reactor-
exit pressure is assumed to be 600 pounds per square inch in this case.
The fuel loading was assumed to be 50 volume percent. It should be noted
that in the case of the fast reactor the ratio of the void to flow area
ratio was assumed to be 1. Powerplant weights shown range from about
2000 pounds at a reactor power of about 200 megawatts to 6000 or 7000
pounds at 3000 megawatts. The reactor-exit dynamic pressure is shown
parametrically to indicate the importance of this parameter. The actual
value of this parameter to be used can only be determined by experimen-
tally verifying reactor fuel-element designs under simulated flow condi-
tions. It is obviously of importance to achieve as high a dynamic pressure
as possible.

Figure 56 shows the weight of water-moderated-tungsten - UO_2 power-
plant. The reactor-exit pressure is also 600 pounds per square inch in
this case. The fuel loading is 15 volume percent. The void to flow
area ratio is assumed to be 1.5 and the tungsten per unit void area is
assumed to be 800 pounds per square foot. The powerplant is plotted as
a function of the reactor power in megawatts for various reactor dy-
namic pressures. The powerplant weights are seen to range from about
1000 pounds at 200 megawatts to 6000 or 7000 pounds at 3000 megawatts.
The reactor weights are essentially comparable to those of the fast re-
actor at power levels of 3000 megawatts; the water-moderated reactor is
shown to be somewhat lighter than the fast reactor at the lower power
levels.

SUMMARY

Fast-reactor and thermal-heterogeneous-reactor concepts exist that can be small and which offer the potential of high specific impulse. It appears feasible to conceive of nuclear-rocket powerplants that weigh as little as 2000 pounds or less for power levels of a few hundred megawatts. In the case of the fast reactor, the chief problem is the high fuel-loading requirement of the fuel elements that may lead to difficult mateeral development problems. The fast reactor has the advantage, however, of being simpler in concept because the water-moderator reactor requires an additional cooling system to cool the moderating water. The water-moderated - tungsten reactor has the advantage of requiring relatively low fuel loadings within the fuel elements. This will ease the development of the materials problems associated with this reactor. However, the water-moderated reactor, in order to use tungsten, must use tungsten enriched with the tungsten 184 isotope, which requires the additional complication of separating the isotopes. Although the water-moderated reactor requires a heat exchanger and a water pump system for cooling the moderator, it has the advantage that water cooling of the entire core structure afforded by this concept eliminates many of the difficult problems of the homogeneous type core where expansion problems are difficult to handle. The use of metal in both reactors would be anticipated to give a major advantage over ceramic or graphite-type reactors in that the fuel material should be fully recyclable. Because tungsten has the lowest evaporation rate of any known material and does not react with hydrogen, the longest operating life may be anticipated for tungsten reactors. The recyclability and longer operating life anticipated for tungsten reactors should make possible a simpler, faster, and less costly development program since many more tests could be accomplished with each reactor core. In particular, the water-moderated core offers the advantage of permitting the development of the entire reactor powerplant in steps; that is, the water-cooled core structure and components outside the fuel elements could be developed to a high degree of perfection with the use of nichrome or molybdenum fuel elements. Concurrently, development of tungsten or other advanced fuel-element designs could proceed, which could be used to replace the temporary or early fuel-element designs.

In conclusion then, it is possible to conceive of nuclear-rockets concepts that are lightweight and that are suitable for low-power applications. From a study of the basic properties of the refractory materials such as melting point, vaporization rate, thermal stress resistance, and strength, it is quite clear that tungsten offers the greatest potential for both fast and thermal reactors.

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TABLE I. - MELTING POINTS OF REFRACTORY MATERIALS

Metal	Melting point,		Ceramic	Melting point,	
	$^\circ$F	$^\circ$K		$^\circ$F	$^\circ$K
W (nat.)	6120	3660	HfC	7030	4163
W^{184}	6120	3660	TaC	7020	4160
Re	5740	3450	C	[a]6700	3983
0.74W-0.26Re	5650	3400	NbC	6330	3770
0.90Ta-0.10W	5495	3315	HfN	5990	3590
Ta	5430	3280	ThO_2	5970	3573
Os	4890	2980	TiC	5880	3520
Mo	4710	2880	HfB_2	5880	3520
Nb	4530	2770	ZrC	5750	3450
			TaB_2	5610	3375
			TaN	5590	3360
			ZrB_2	5500	3315
			BN	[a]5430	3280
			NbB_2	5430	3280
			ZrN	5400	3260
			TiN	5310	3210
			WB	5180	3140
			VC	5130	3110

[a]Sublimes.

TABLE II. - NUCLEAR PROPERTIES OF REFRACTORY MATERIALS

Material	Material density, g/cc	Molecule or atom density	Thermal microscopic absorption cross section, barns	Infinitely dilute resonance integral, barns
C	1.67	0.0837×10^{24}	0.003	0
ZrC	6.8	.0397	.18	3
NbC	7.75	.0445	1.1	14
W^{184}	19.3	.0632	2.0	10
Mo	10.2	.0640	2.5	20
W^{183}	19.3	.0632	11.0	414
W(nat.)	19.3	.0632	19.2	354
W^{182}	19.3	.0632	20	584
Ta	16.6	.0553	21.3	590
TaC	14.3	.0446	21.3	590
W^{186}	19.3	.0632	35.0	481
Re	20.53	.0664	84.0	620
HfC	12.6	.0398	105.0	2800

TABLE III. - PROPERTIES OF REFRACTORY MATERIALS

Material	Temperature °F	Temperature °K	Thermal conductivity, $\frac{Btu}{(hr)(ft)(°F)}$	Linear thermal expansion, 1/°F	Modulus of elasticity, psi	Thermal stress parameter, $\frac{Btu}{(sec)(ft)}$	Ultimate tensile strength, psi
W	5000	3035	77	4.0×10^{-6}	6×10^6	2 to 6	[e]2000 to 7000
Ta	4500	2760	~50	5.0×10^{-6}	0.4×10^6 to 1.5×10^6	~3 to 12	1850
Mo	3700	2310	42	5.47×10^{-6}	4.0×10^6	1.1	2000
C	5000	3035	~10	3.3×10^{-6}	[a]1.7×10^6	~0.5 to 2	1600 to 6000
HfC	4000	2480	~24	2.88×10^{-6}	[b]46.5×10^6	[c]~0.12	[f]2500
TaC	4000	2480	22.9	3.05×10^{-6}	[b]~47×10^6	[c]~.27	[f]6000
NbC	4000	2480	21	~3.4×10^{-6}	[b]49×10^6	[c]~0.10	[d]3000
ZrC	1830	1273	20	3.6×10^{-6}	50×10^6	.40	13,000

[a]Estimated.
[b]Room-temperature value.
[c]Calculated by using room-temperature values of modulus of elasticity and other properties at temperature indicated.
[d]At 3650° F.
[e]For tensile strain rate of 0.02 to 2.0 in./min.
[f]One-half of measured bend strength.

TABLE IV. - MELTING POINTS OF

REFRACTORY URANIUM COMPOUNDS

Uranium compound	Melting point	
	°F	°K
UN	[a]5230	3160
UO_2	5075	3080
UB_4	4625	2830
US	4465	2740
UC_2	4350	2670
UC	4350	2670
U	2070	1405

[a]Unstable without N_2 over-
pressure.

TABLE V. - COMPATIBILITY OF REFRACTORY MATERIALS

WITH URANIUM COMPOUNDS AND HYDROGEN

Refractory material	Compatibility with -		
	Uranium compound		Hydrogen
	UO_2	UC	
W	No reaction at least to UO_2 melting point	Reaction at 4540° F (2780° K)	No reaction
Re	---	Reaction after 24 hr at 3270° F (2073° K)	No reaction at 4000° F (2480° K)
Ta	No reaction at least to UO_2 melting point	No reaction up to 3270° F (2073° K)	Reacts below 2000° F (1367° K). No reaction at 4000° F (2480° K)
Mo	No reaction up to melting point	Reaction at 1835° F (1273° K)	No reaction up to melting point
C	Forms UC at 3500° F (2200° K)	Eutectic temperature is 4260° F (2623° K)	Strong reaction above 2800° F (1812° K)
HfC	No reaction at 5000° F (3035° K)	Forms solid solution	Reacts above 4840° F (2930° K)
TaC	Forms UC at 4900° F (2980° K)		Reacts above 4630° F (2830° K)
NbC	Some reaction		No reaction at 4680° F (2855° K)
ZrC	Forms UC at 4500° F (2760° K)	↓	Reacts above 4780° F (2910° K)

TABLE VI. - COMPOSITIONS OF ISOTOPICALLY ENRICHED TUNGSTEN

Isotope	Cross section, barns	Composition, volume percent			
		W(natural)	1	2	3
W^{180}	60	0.14	-----	----	----
W^{182}	20	26.46	13.9	3.4	0.05
W^{183}	11	14.40	27.6	17.1	5.3
W^{184}	2	30.60	57.9	78.4	93.0
W^{186}	35	28.40	.6	1.1	1.6
Thermal (0.025 ev) cross section, barns		17.4	7.2	4.5	3.0
Dilute resonance integral, barns		325	177	88	32

TABLE VII. - MODERATOR PROPERTIES

Material	Estimated maximum operating temperature, $^{\circ}F$	Atom density, atoms/cm^3	Age of thermal neutron from fission source, cm^2	Density, g/cm^3	Thermal stress parameter, Btu/(sec)(ft)
Graphite	≈5000	0.0810×10^{24}	350	1.62	≈2.3 (4350° F)
Beryllium oxide	≈3500	$.0670 \times 10^{24}$	110	2.80	0.05 to 0.20 (2000° F)
Beryllium	≈1500	$.1236 \times 10^{24}$	98	1.85	≈.95 (1100° F)
Zirconium hydride	≈1500	$.041 (N^H) \times 10^{24}$	31	5.92	≈.47 (1000° F)
Lithium hydride	≈1000	$.059 (N^H) \times 10^{24}$	30	.78	No data
D_2O	≈550	$.0662 (N^D) \times 10^{24}$	120	1.10	∞
H_2O	≈550	$.0670 (N^H) \times 10^{24}$	27	1.00	∞
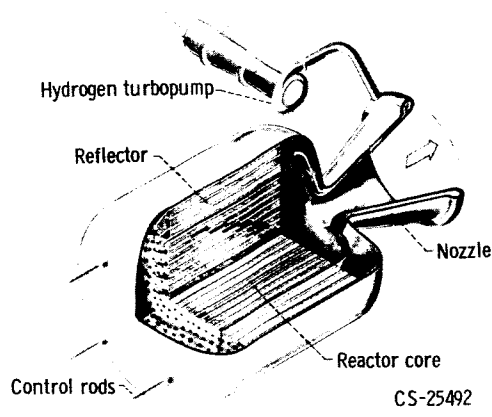
Figure 1. – Solid-core heat-transfer-type nuclear rocket.
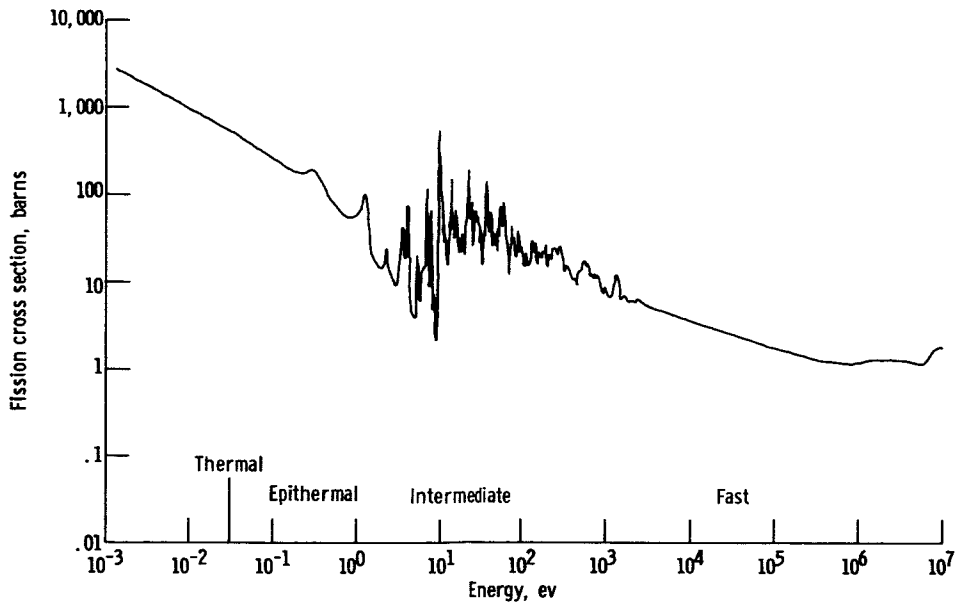
Figure 2. – Fission cross section for U^{235}.
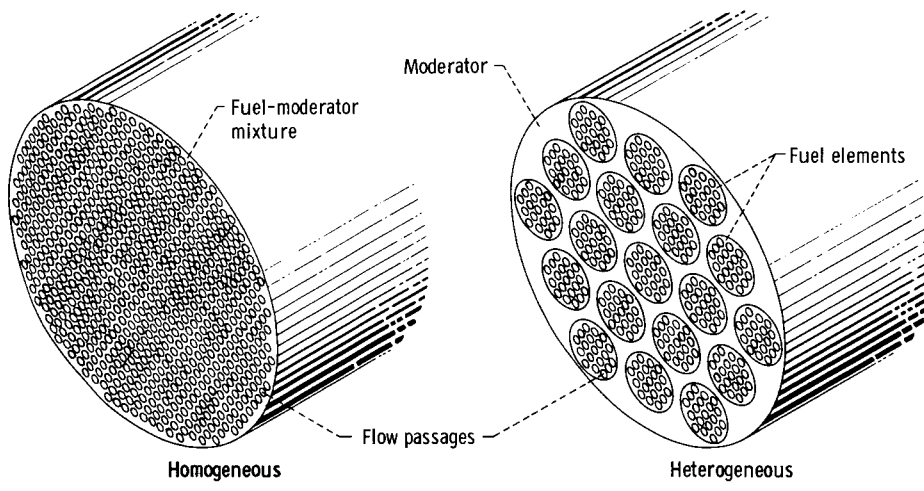
Figure 3. - Reactor types.
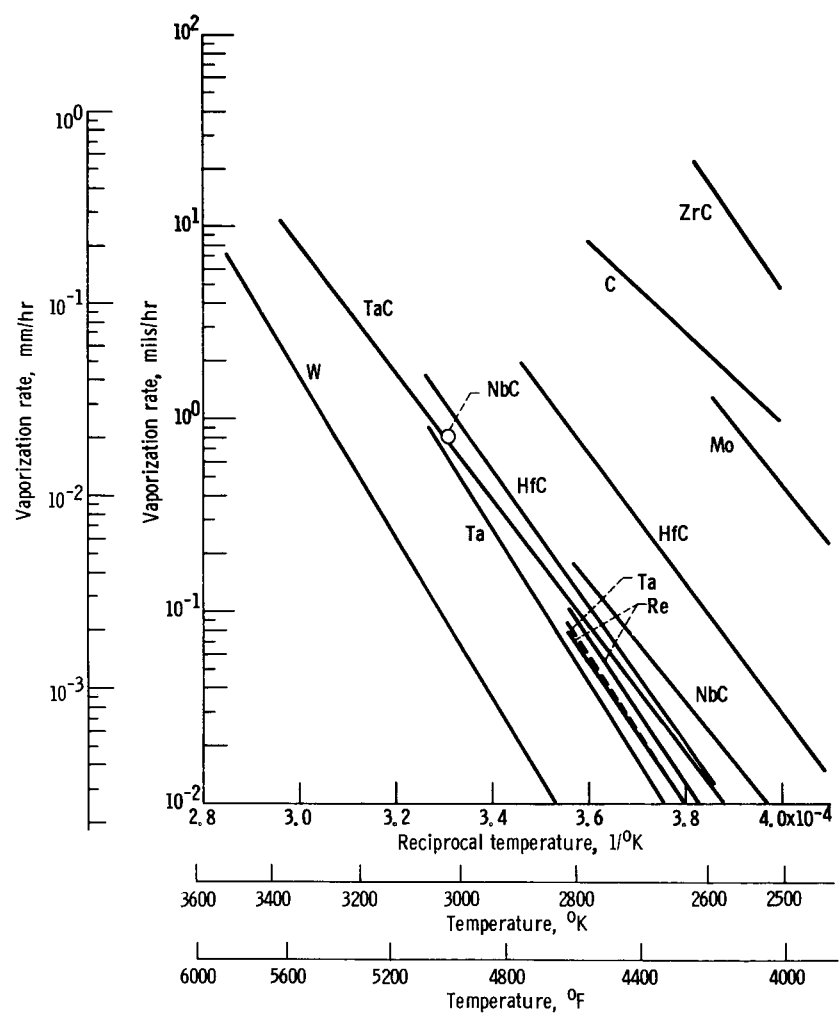
Figure 4. - Vaporization rates of refractory materials.
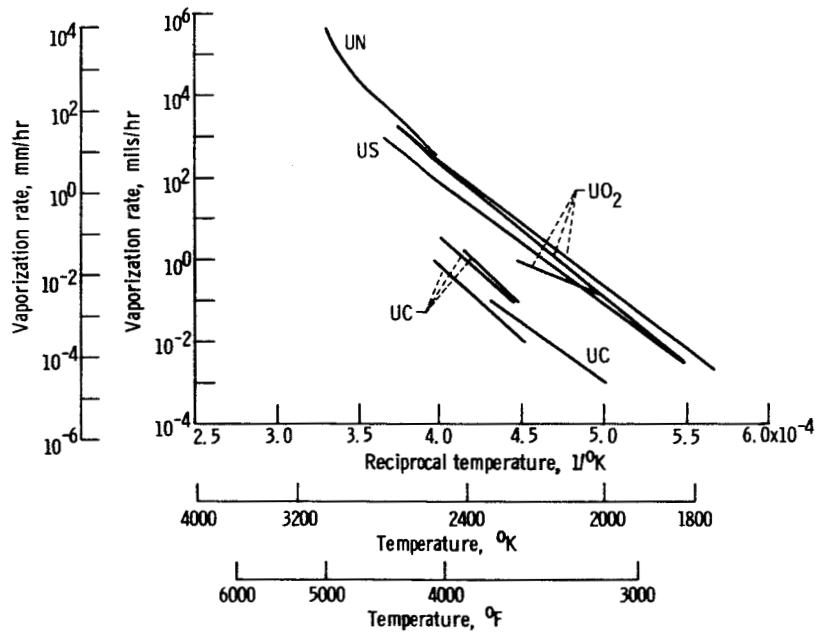
Figure 5. - Vaporization rate of uranium compounds.
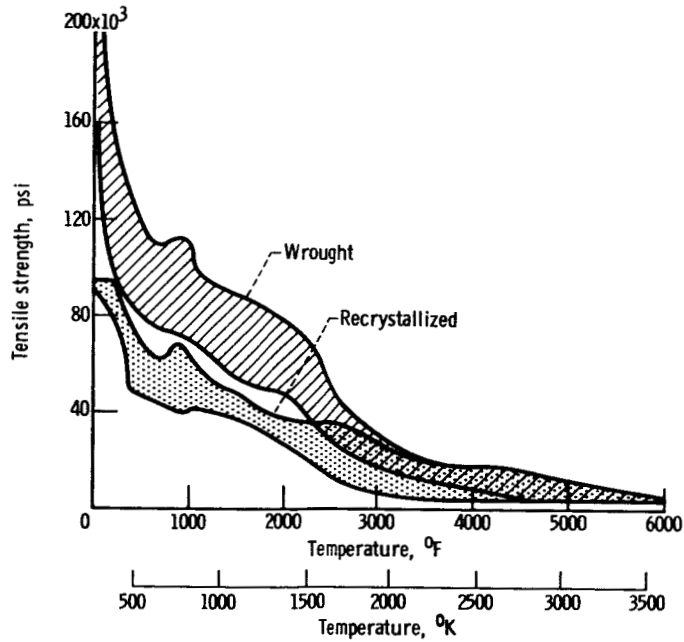
(a) Full temperature range.

Figure 6. - Tensile strength of tungsten.
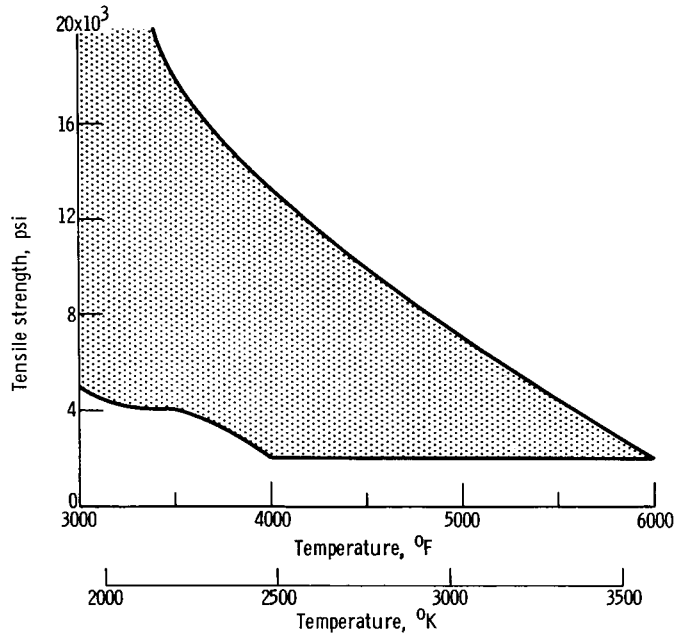
(b) High temperature range.

Figure 6. – Concluded. Tensile strength of tungsten.
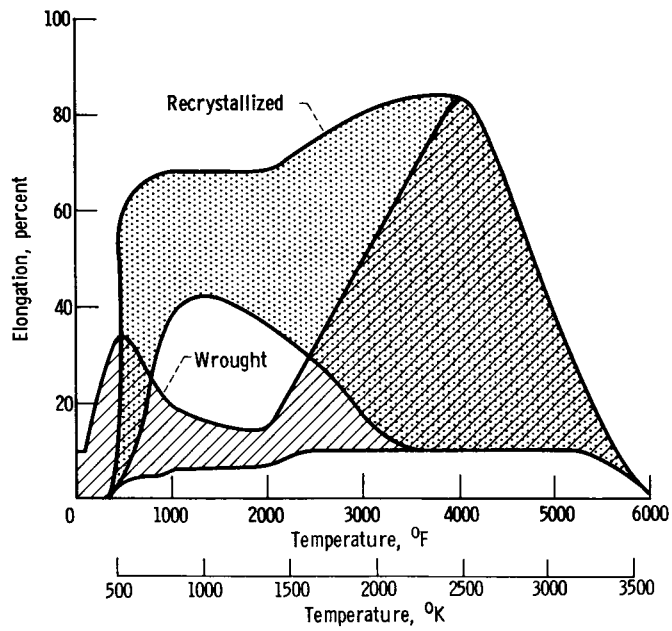
Figure 7. – Elongation of tungsten.
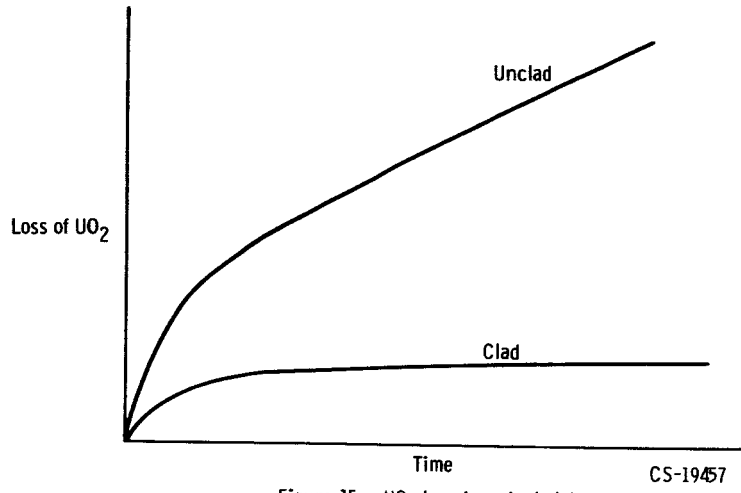
Figure 15. - UO_2 loss from fuel plates.

CS-19457
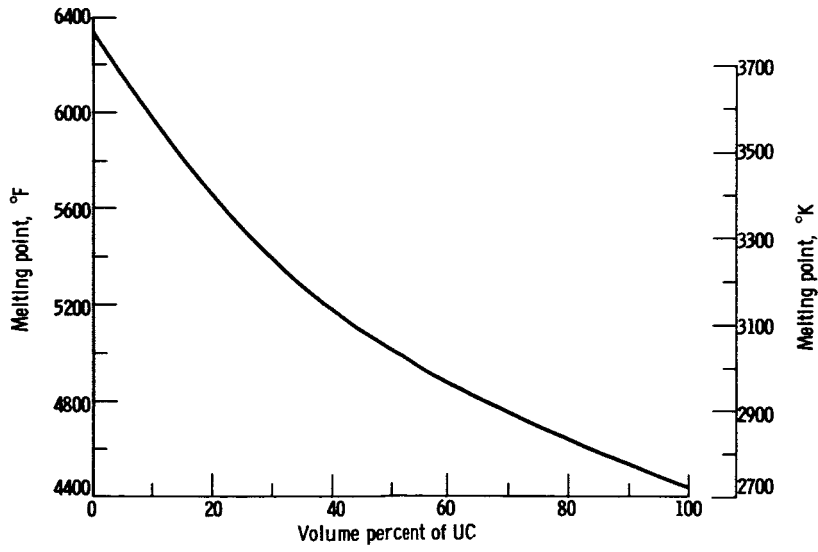
Figure 16. - Melting point of UC-ZrC solutions.

Flat plate   Concentric ring   Tube bundle

Hole matrix   Hexagonal honeycomb   Square honeycomb
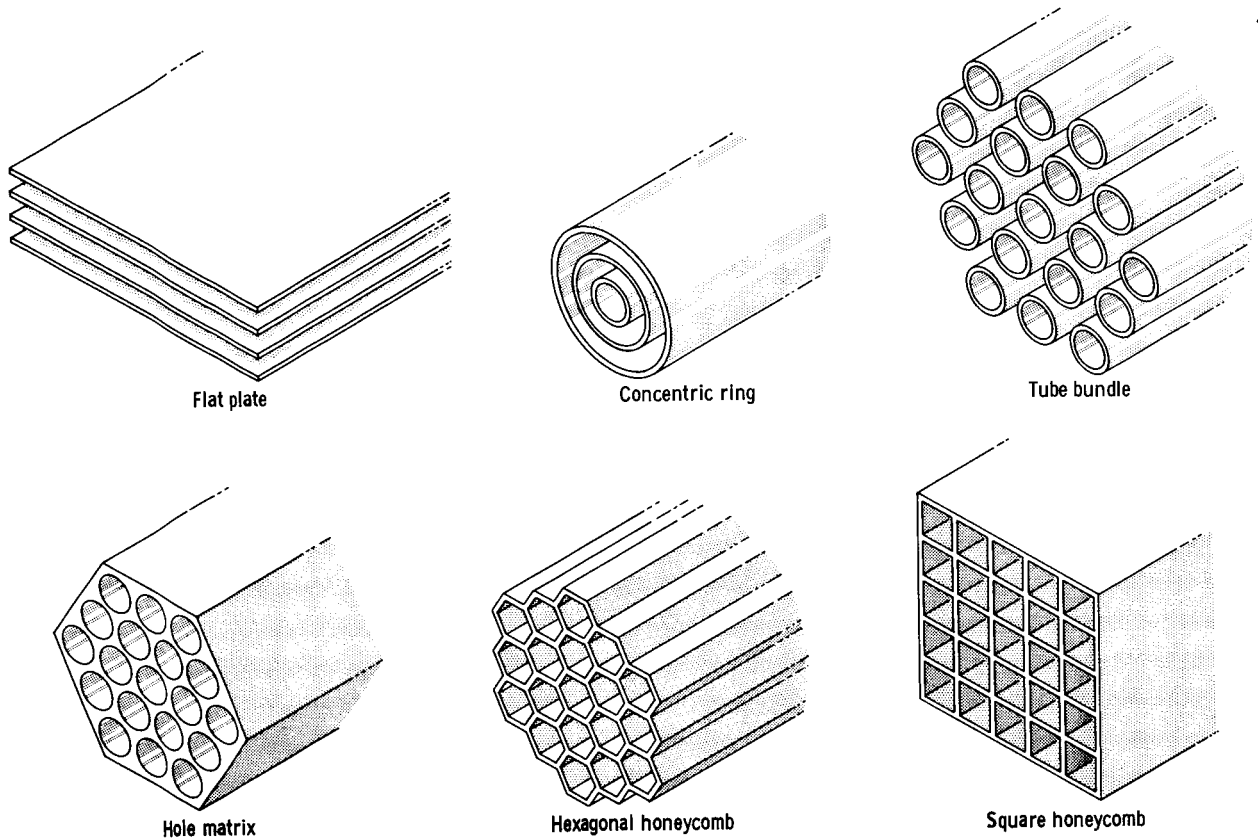
Figure 17. - Schematic fuel element designs.
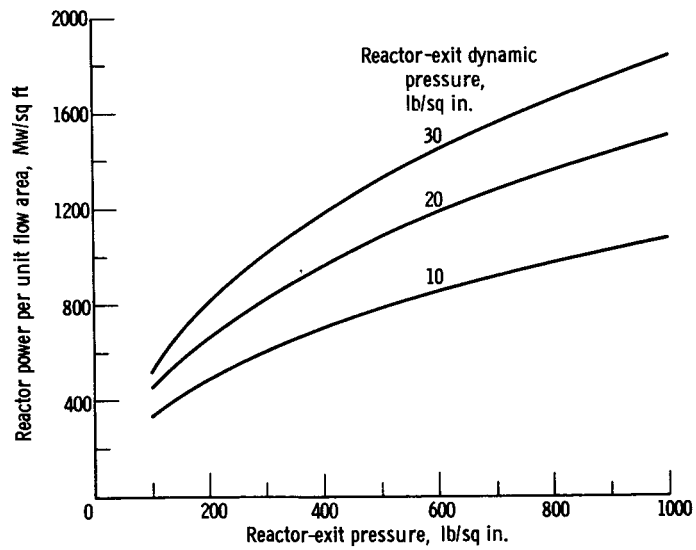
Figure 18. - Flow area requirements for nuclear rockets.
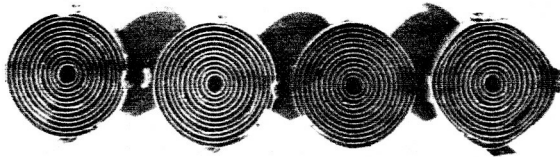
Figure 19. - Flow test of HTRE-1 element.
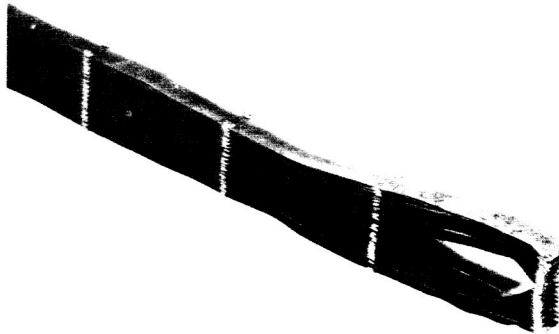
Figure 20. - Flow test of curved-plate element.

Capsule

Specimen

Radiation shield

C-61139
CS-25491
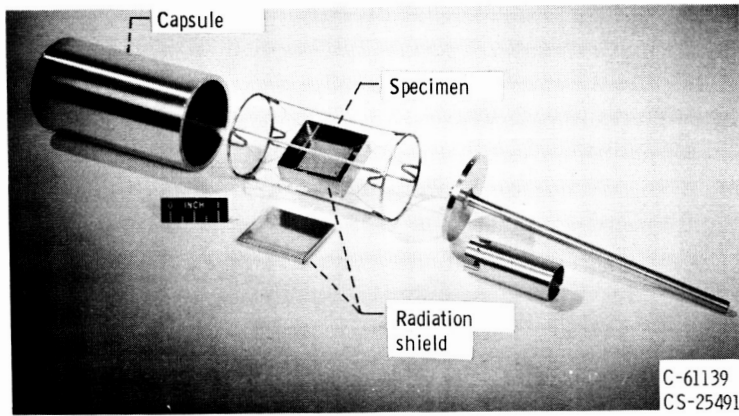
Figure 21. - Capsule test.

CS-25487
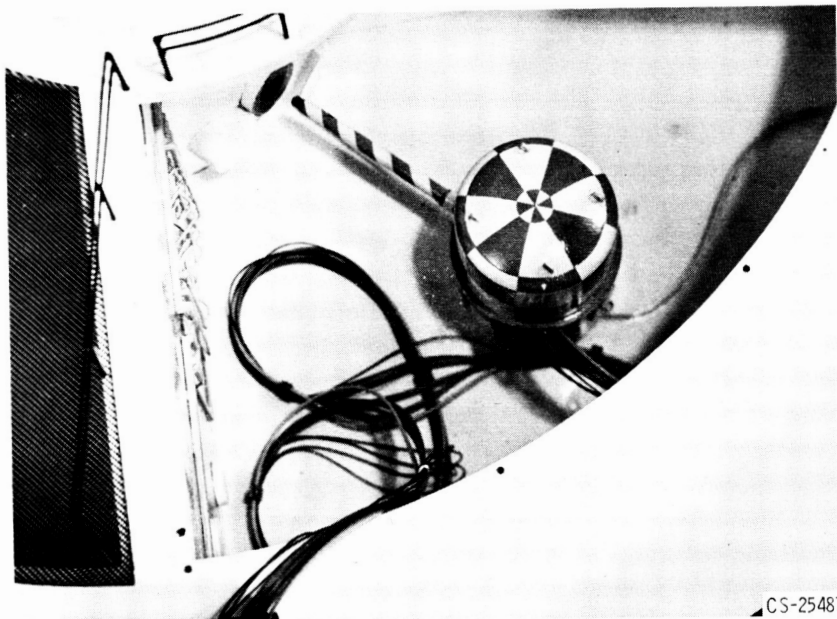
Figure 22. - In-pile flow test.
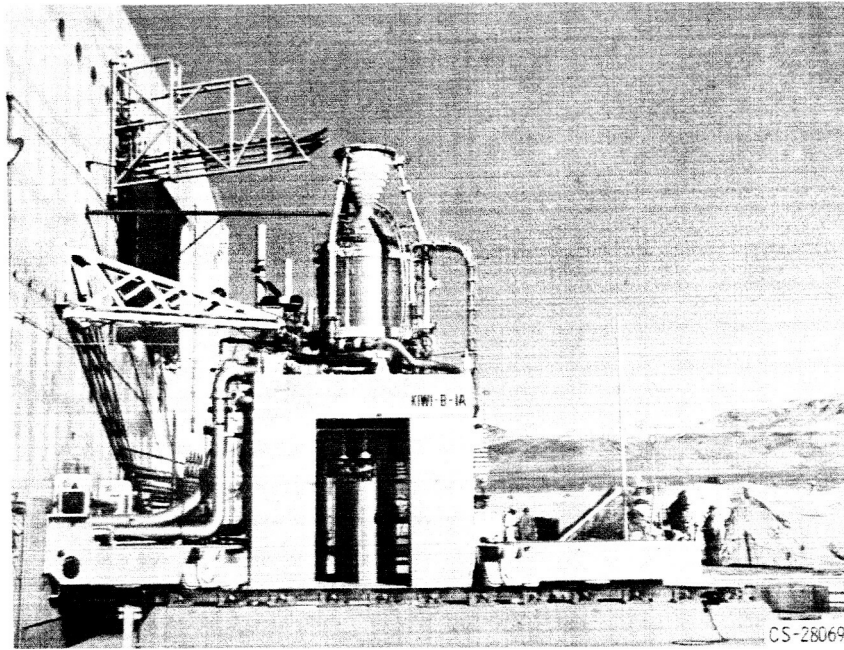
Figure 23. - Kiwi on test stand.
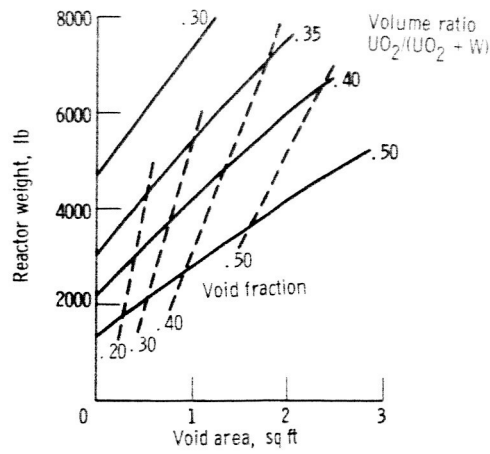
Figure 24. - W-UO₂ fast reactor weight. Side
reflector and front-end reflector 12 centimeters
thick with 25-percent voids for cooling.
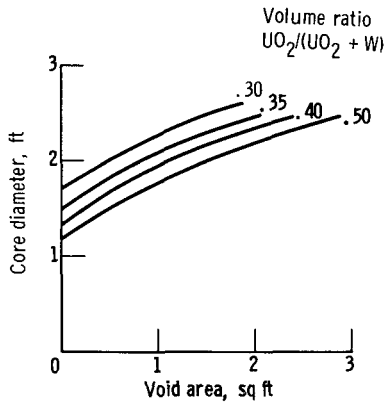
Figure 25. - W-UO$_2$ fast-reactor core
diameter. Side reflector and front-
end reflector 12 centimeters thick
with 25-percent voids for cooling.
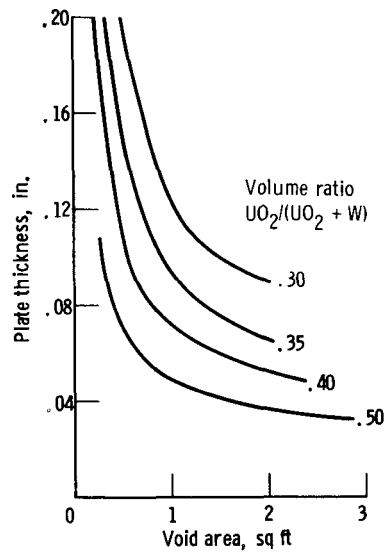
Figure 26. - W-UO$_2$ fast-reactor fuel-
plate thickness. Passage-length to
hydraulic-diameter ratio, 300; side
reflector and front-end reflector
12 centimeters thick with 25-percent
voids for cooling.

Volume ratio,
$UO_2/(UO_2 + W)$
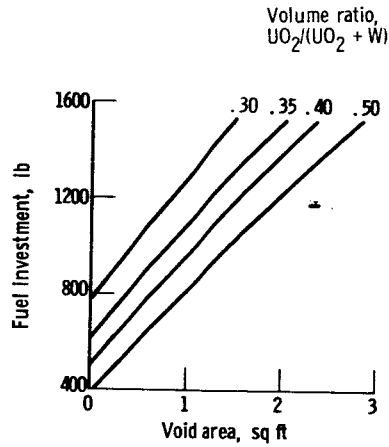
Figure 27. – W-UO_2 fast-reactor fuel
investment. Side reflector and
front-end reflector 12 centimeters
thick with 25-percent voids for
cooling.
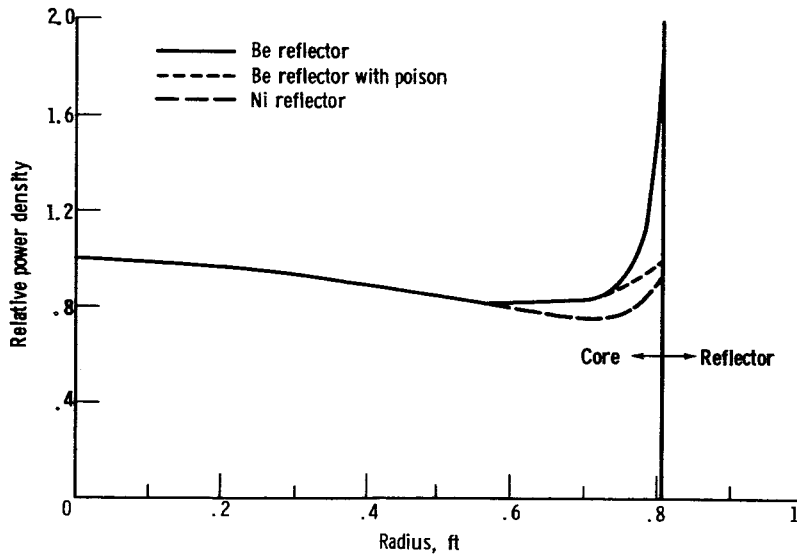
Figure 28. – Fast-reactor radial power density.
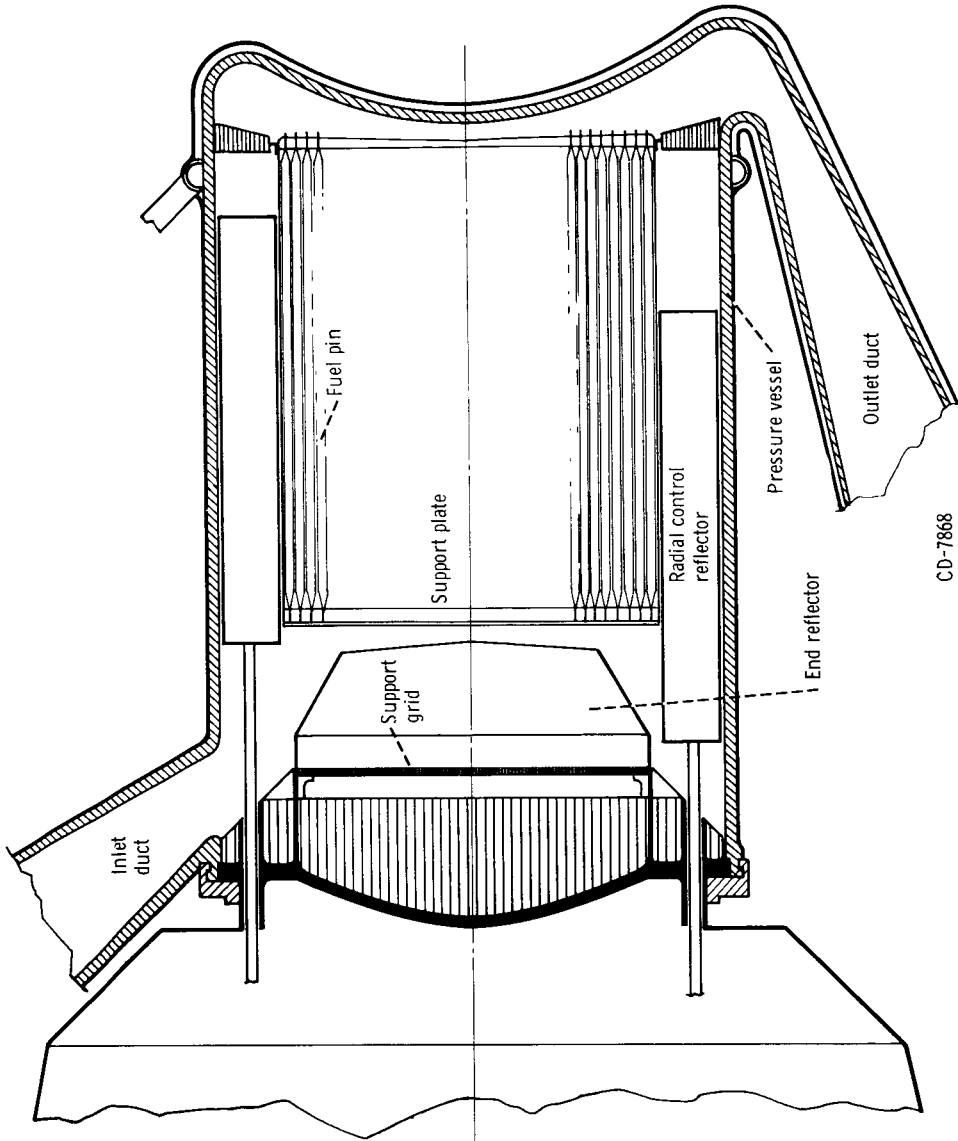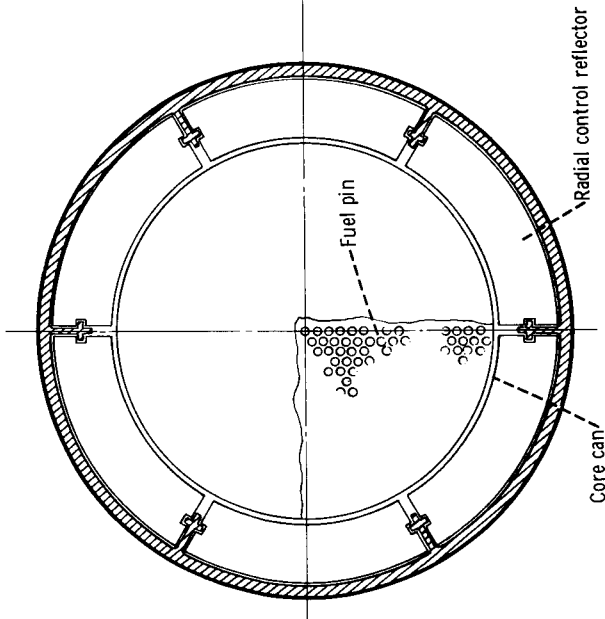
Figure 29. – AGN NBC core design.

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Labels (upper figure): Fuel pin, Support plate, Radial control reflector, Pressure vessel, Outlet duct, End reflector, Support grid, Inlet duct

Labels (lower figure): Fuel pin, Radial control reflector, Core can
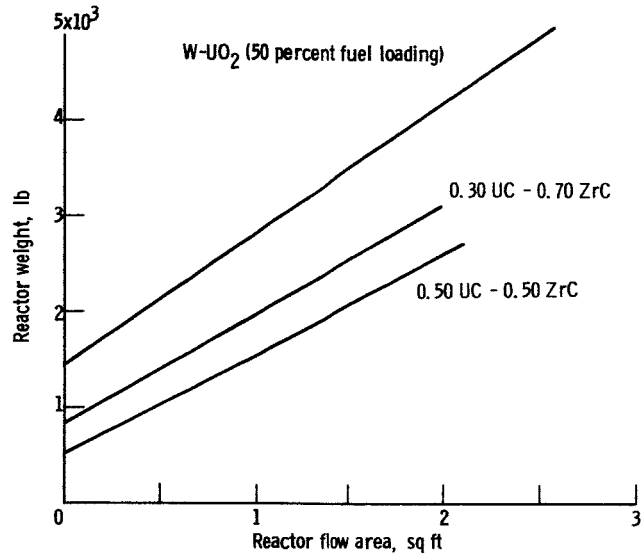
Figure 30. - Comparison of UC-ZrC and W-UO$_2$ fast reactors.
Fraction of tungsten in carbide core volumes, 0.10.
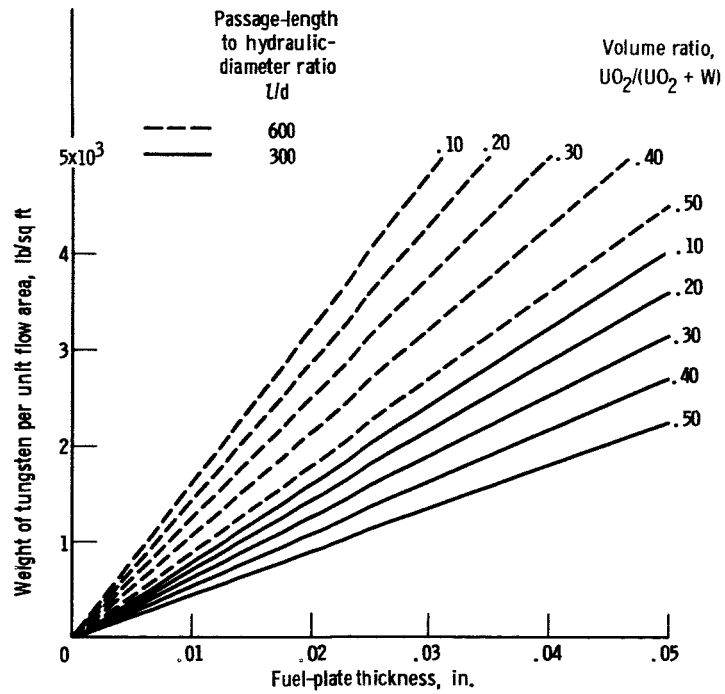
Figure 31. - Fuel-plate thickness for moderated W-UO$_2$ reactors.
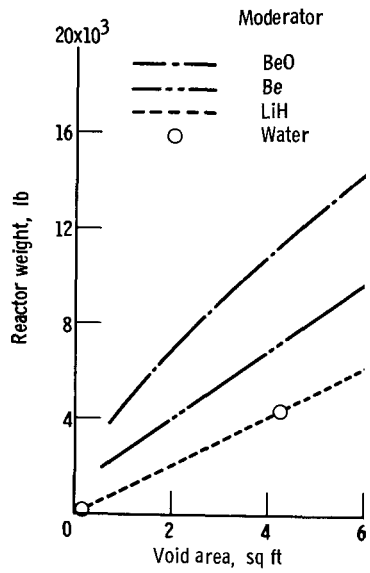
Figure 32. - Moderated W-UO$_2$ reactor weight. Volume ratio, UO$_2$/(UO$_2$ + W), 0.30; W^{184} enrichment, 100 percent; tungsten per unit void area, 800 lb/sq ft.
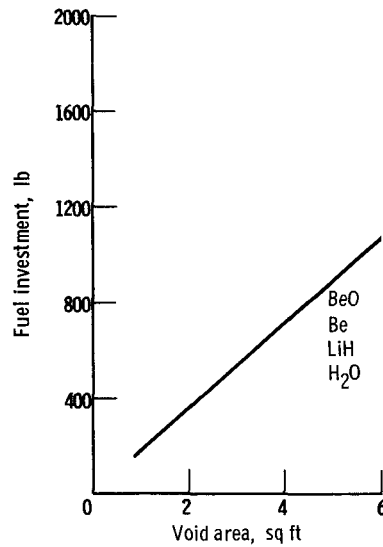
Figure 33. - Moderated W-UO$_2$ reactor fuel investment. Volume ratio, UO$_2$/(UO$_2$ + W), 0.30; W^{184} enrichment, 100 percent; tungsten per unit void area, 800 lb/sq ft.
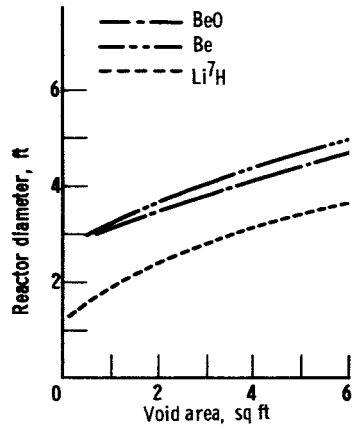
Figure 34. - W-UO$_2$ moderated reactor
diameter. Volume ratio, UO$_2$/(UO$_2$ + W),
0.30; W^{184} enrichment, 100 percent;
tungsten per unit void area, 800 lb/sq ft.
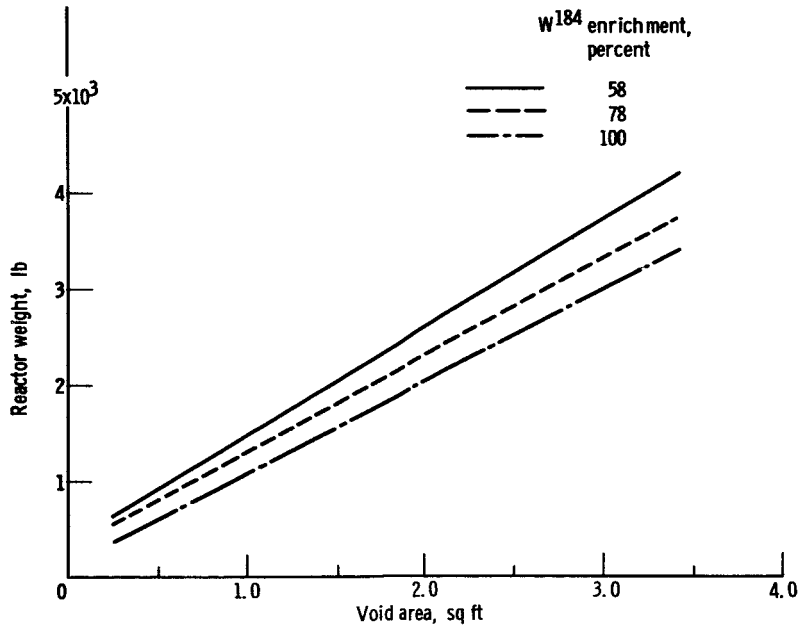
Figure 35. - Effect of W^{184} enrichment on weight of H$_2$O-W-UO$_2$ reactor.
Volume ratio, UO$_2$/(W + UO$_2$), 0.15; tungsten per unit void area,
800 lb/sq ft.
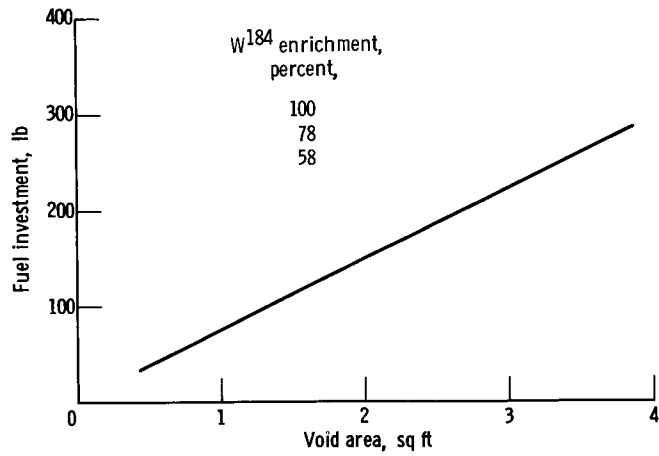
Figure 36. - Effect of W^{184} enrichment on fuel investment of H$_2$O-W-UO$_2$
Volume ratio, UO$_2$(W + UO$_2$), 0.15; tungsten per unit void area,
800 lb/sq ft.
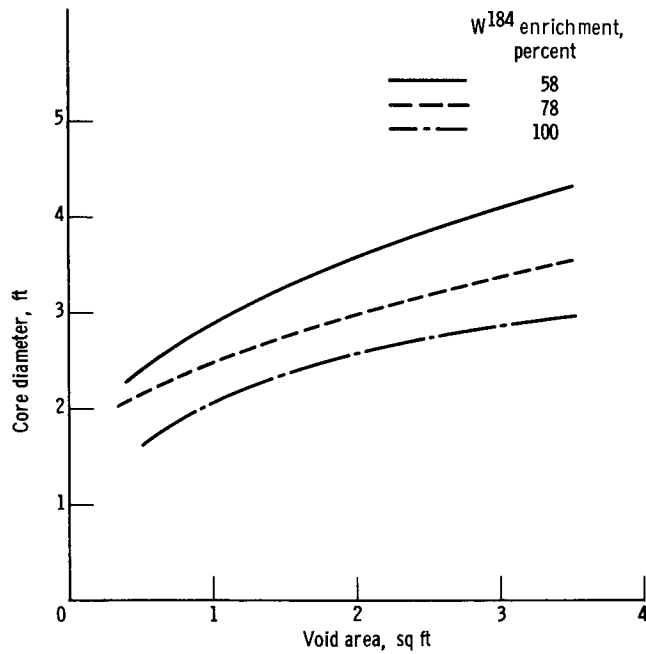
Figure 37. - Effect of W^{184} enrichment on diameter of H$_2$O-W-UO$_2$ reactor.
Volume ratio, UO$_2$(W + UO$_2$), 0.15; tungsten per unit void area,
800 lb/sq ft.

Volume ratio,
$UO_2/(UO_2 + W)$

	0. 30
– – – –	. 20
— · — ·	. 15
— · · —	. 10

5×10^3

Reactor weight, lb
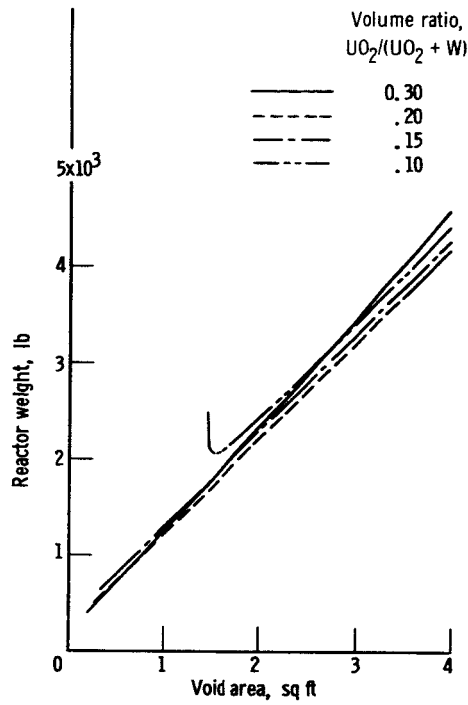
Void area, sq ft

Figure 38. – Effect of UO_2 loading on weight of H_2O-W-UO_2 reactor. W^{184} enrichment, 78 percent; tungsten per unit void area, 800 lb/sq ft.

Volume ratio,
$UO_2/(UO_2 + W)$

	0. 30
– – – –	. 20
— · — ·	. 15
— · · —	. 10

Fuel Investment, lb
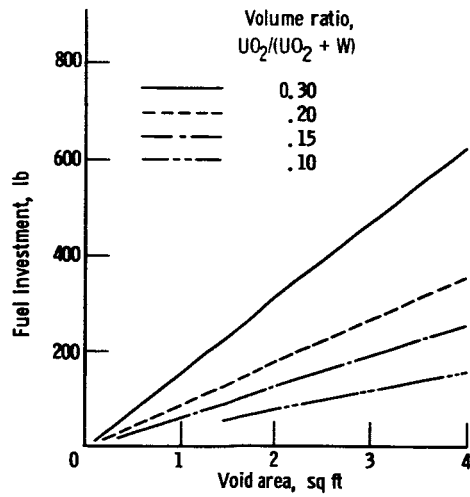
Void area, sq ft

Figure 39. – Effect of UO_2 loading on fuel investment of H_2O-W-UO_2 reactor. W^{184} enrichment, 78 percent; tungsten per unit void area, 800 lb/sq ft.
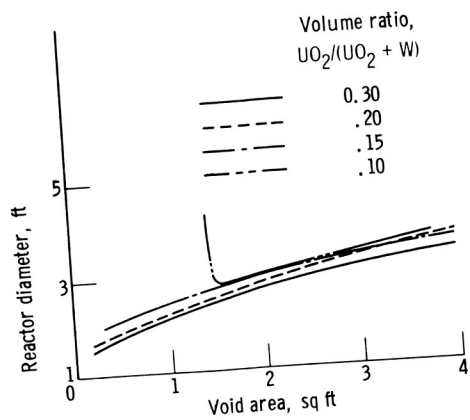
Figure 40. - Effect of UO_2 loading on diameter of H_2O-W-UO_2 reactor. W^{184} enrichment, 78 per-cent; tungsten per unit void area, 800 lb/sq ft.

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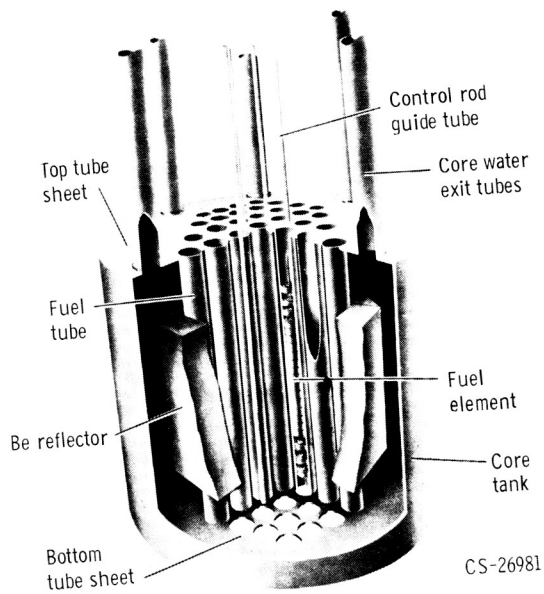
Figure 41. - HTRE-1 core.
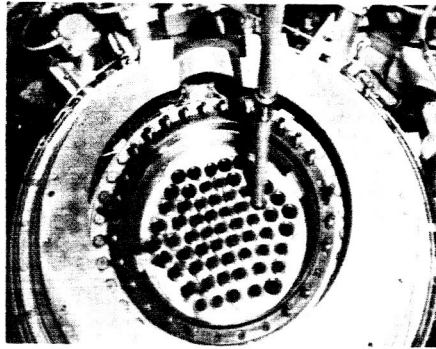
Figure 42. - AGN ML-1 water moderated reactor core.

Hydrogen

Aluminum

Water

Hydrogen

Water

Heat exchanger

Stagnant hydrogen insulation

Molybdenum

Tungsten

Nozzle
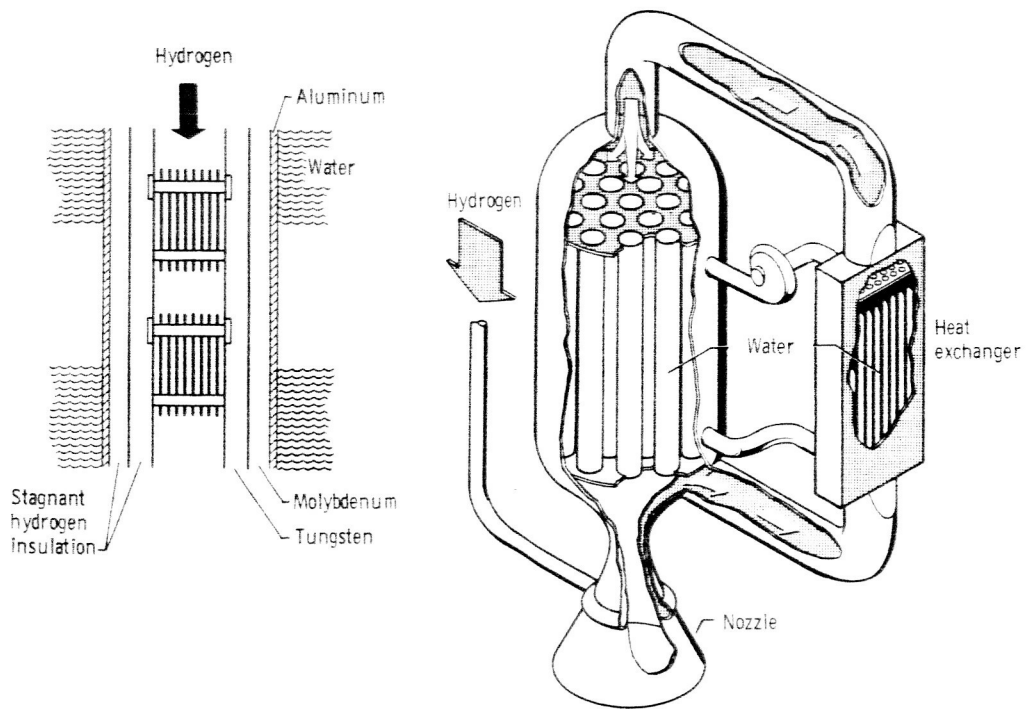
Figure 43. - Schematic drawing of tungsten - water-moderated reactor concept.
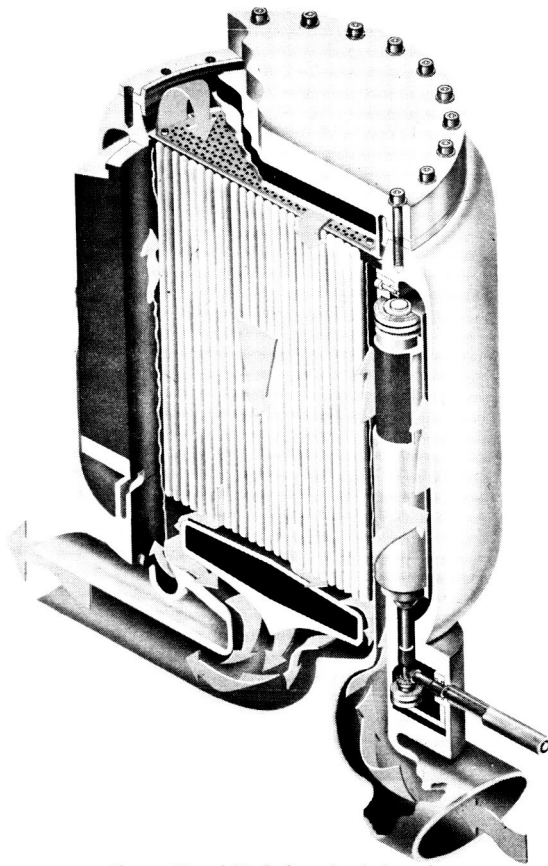
Figure 44. - AGN BeO moderated reactor.
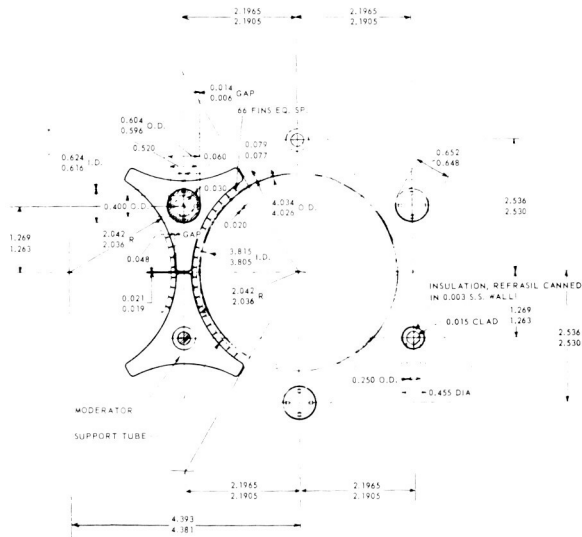
Figure 45. - HTRE-3 solid-moderated reactor core. All dimensions
in inches.
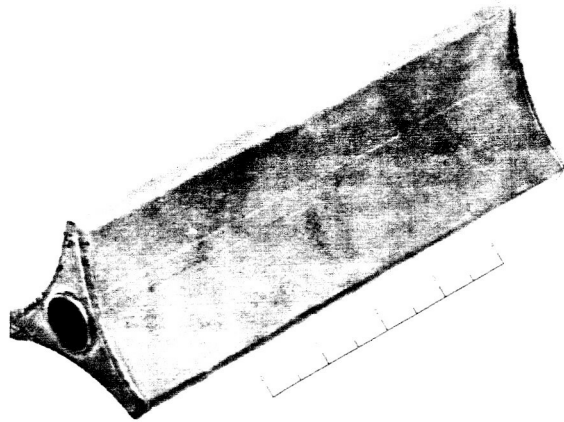
Figure 46. - Section of HTRE-3 solid hydride moderator.
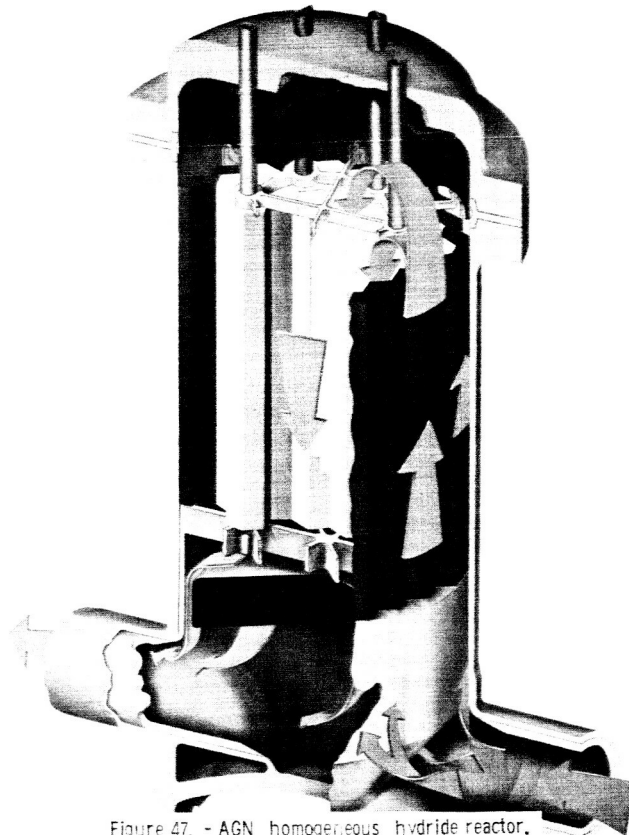
Figure 47. - AGN homogeneous hydride reactor.
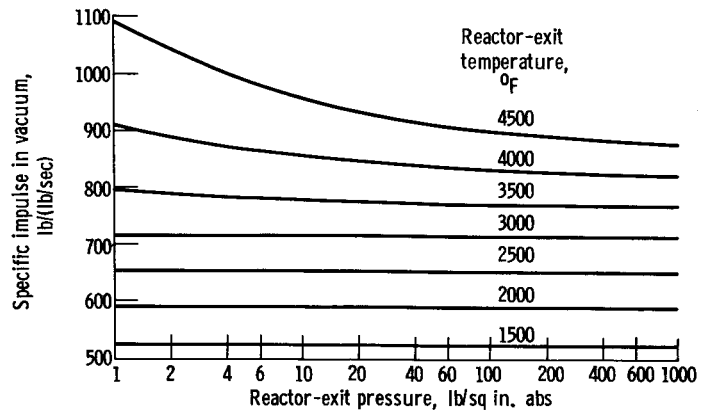
Figure 48. – Specific impulse of hydrogen. Equilibrium expansion; nozzle expansion ratio, 50.
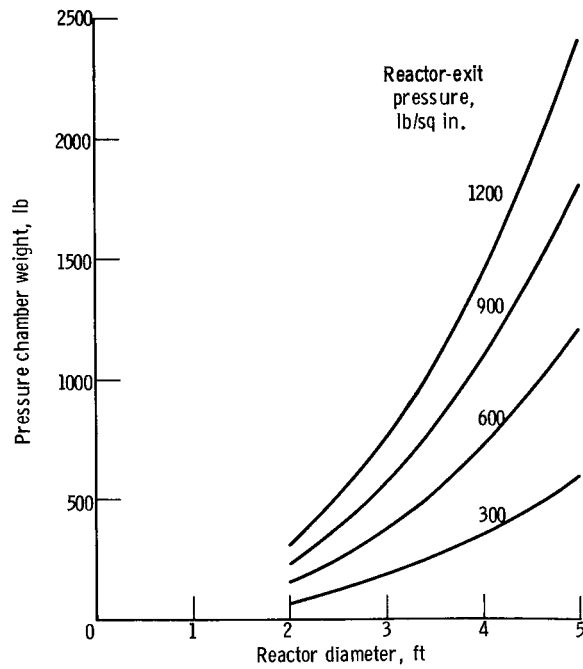
Figure 49. – Pressure chamber weight.
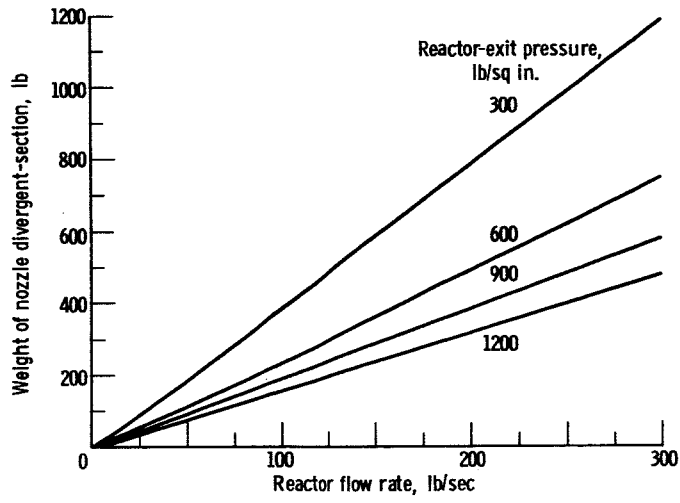
Figure 50. - Nozzle divergent-section weight.
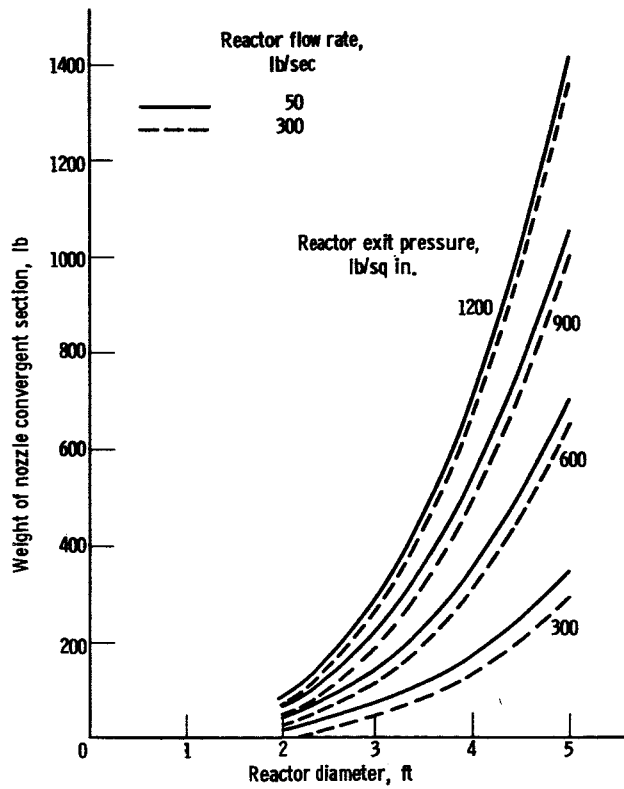
Figure 51. - Nozzle convergent section weight.
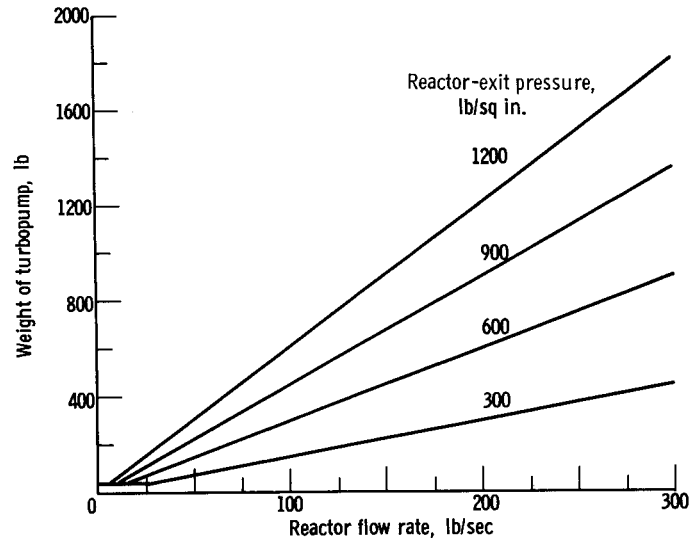
Figure 52. - Turbopump weight.
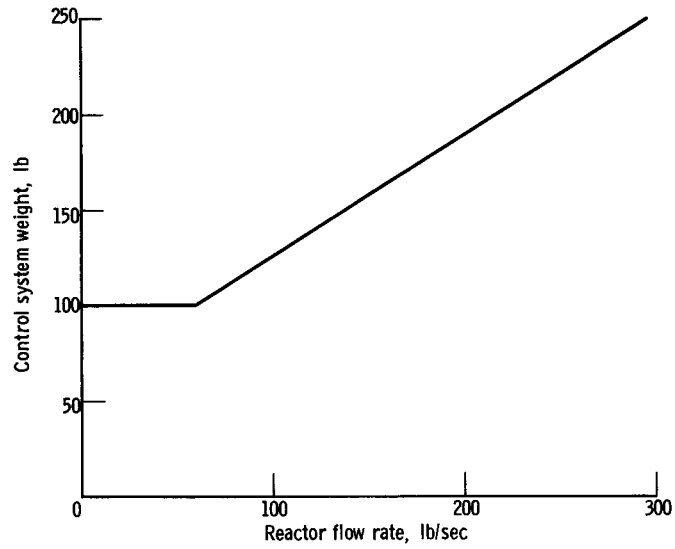
Figure 53. - Control system weight.
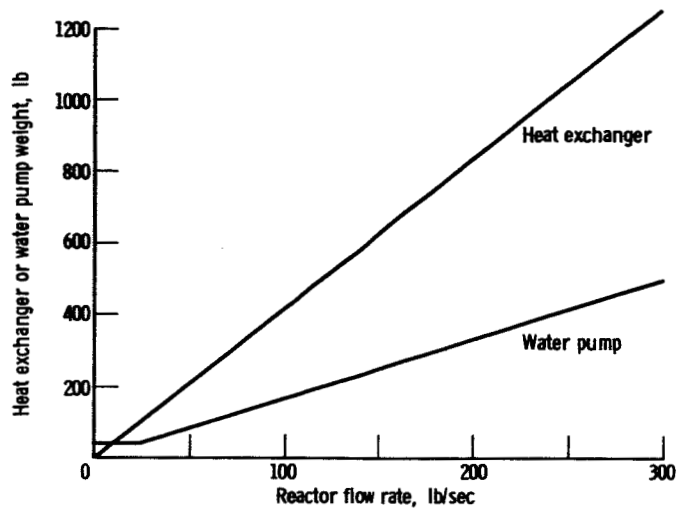
Figure 54. – Heat exchanger and water pump weight.
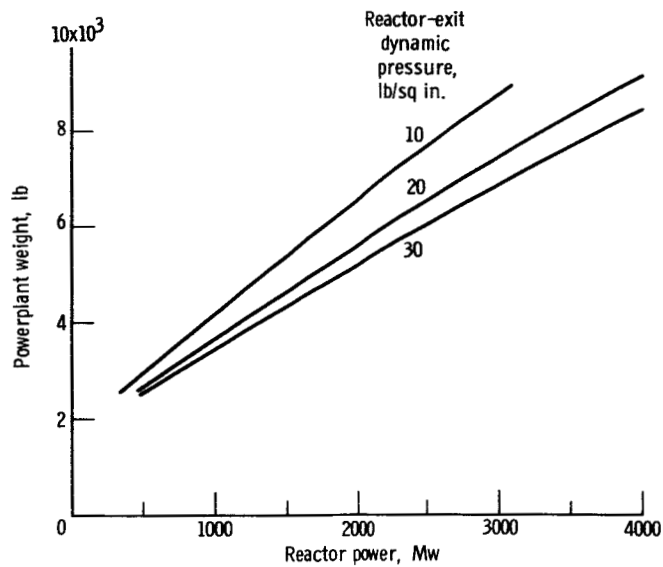
Figure 55. – Fast-reactor powerplant weight. Reactor-exit pressure, 600 lb/sq in.; volume ratio, $UO_2/(UO_2 + W)$, 0.50; void- to flow-area ratio, 1.0.
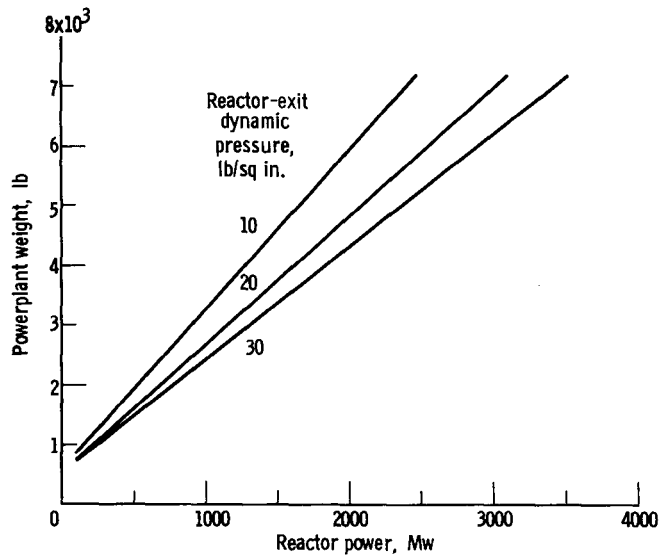
Figure 56. - H_2O-W-UO_2 reactor powerplant weight. Reactor-exit pressure, 600 lb/sq in.; volume ratio, $UO_2/(UO_2 + W)$, 0.15; void- to flow-area ratio, 1.5; tungsten per unit void area, 800 lb/sq ft.
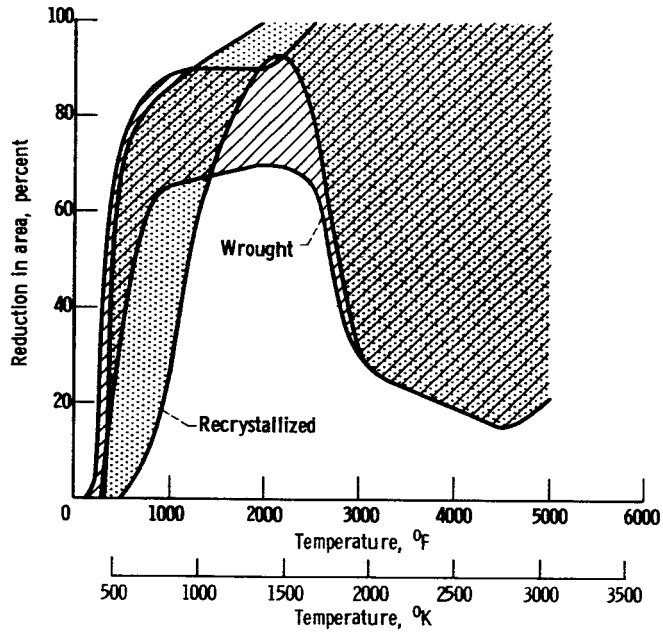
Figure 8. - Reduction in area of tungsten.
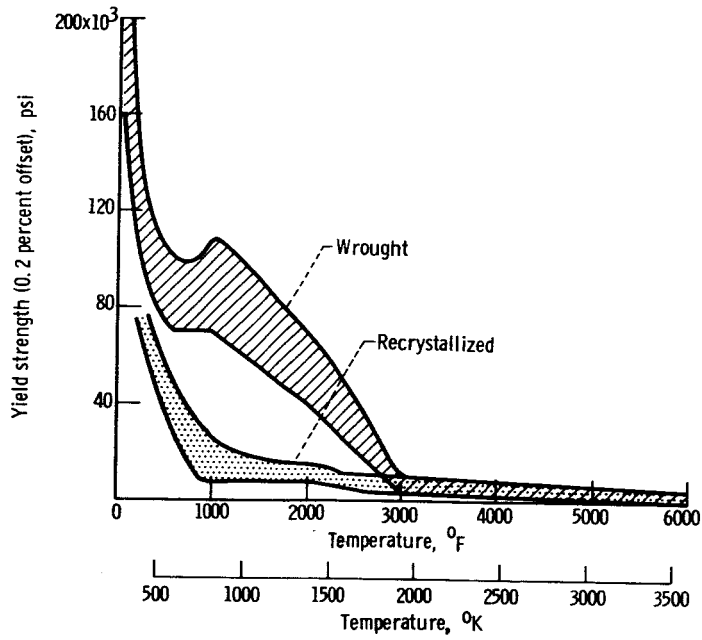
(a) Full temperature range.

Figure 9. - Yield strength of tungsten.
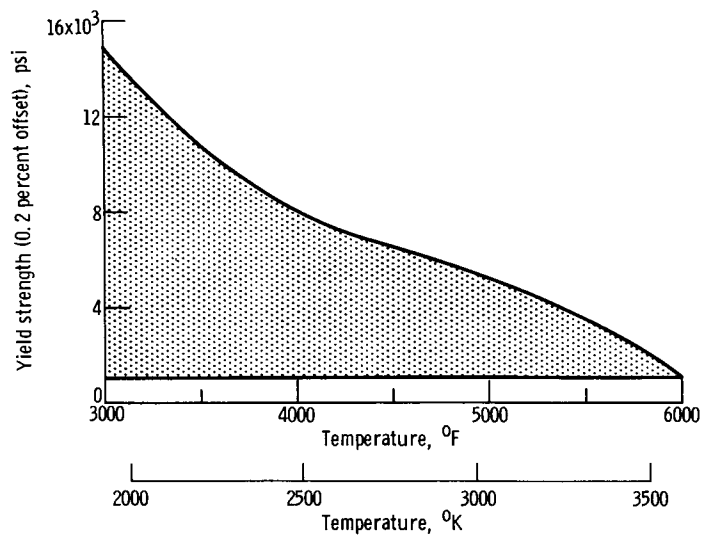
(b) High temperature range.

Figure 9. – Concluded. Yield strength of tungsten.
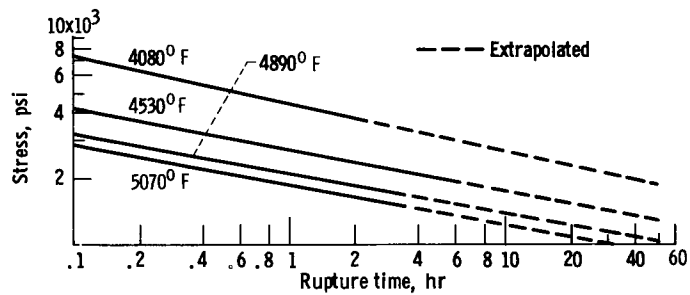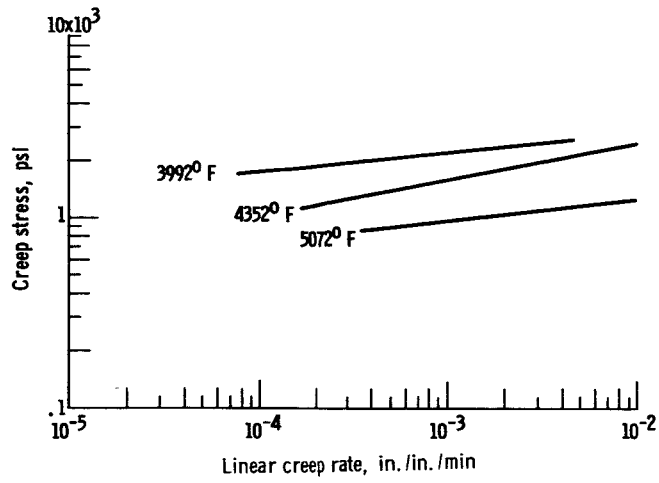

Figure 10. – Stress-rupture properties of tungsten.
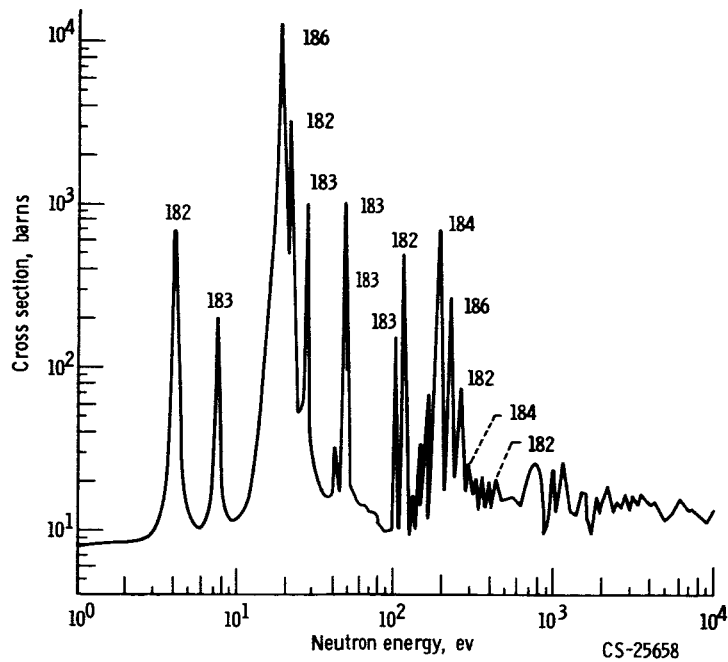
Figure 11. – Creep strength of tungsten.

Figure 12. – Tungsten total cross section.

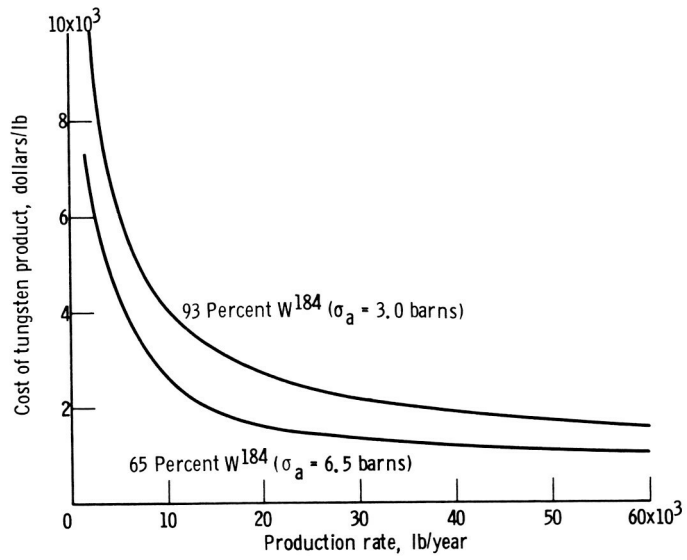Figure 13. - Cost of isotopically enriched tungsten.

Pressed plate
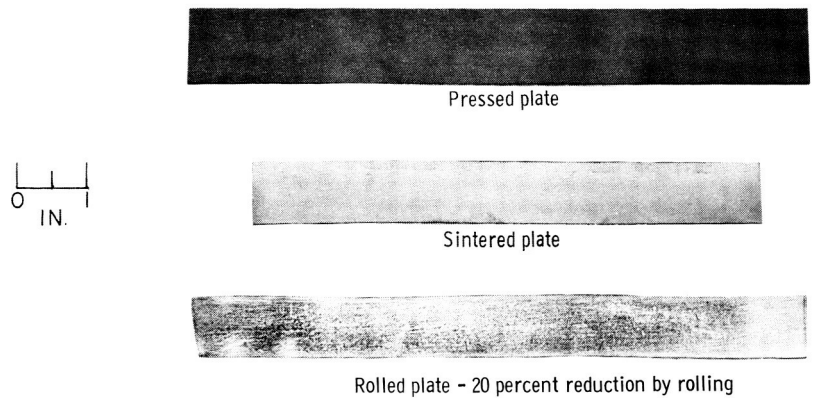
Sintered plate

Rolled plate - 20 percent reduction by rolling

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Figure 14. - Fueled refractory metal plate.