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ORNL/TM-5242

Assessment of Very High-Temperature Reactors in Process Applications

I. Spiewak
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W. R. Gambill
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MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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Engineering Technology Division

ASSESSMENT OF VERY HIGH-TEMPERATURE REACTORS IN PROCESS APPLICATIONS

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The complete report is composed of the following:

ORNL/TM-5242 — *Assessment of Very High-Temperature Reactors in Process Applications*

ORNL/TM-5409 — *Evaluation of the Reactor System*
(Appendix I of ORNL/TM-5242)

ORNL/TM-5410 — *Very High-Temperature Reactor Process Application Studies*
(Appendix II of ORNL/TM-5242)

ORNL/TM-5411 — *Engineering Evaluation of Process Heat Applications for Very High-Temperature Reactors*
(Appendix III of ORNL/TM-5242)

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FOREWORD

This is one of a series of reports on nuclear process heat. The overall summary is *Assessment of Very High-Temperature Reactors in Process Applications* (ORNL/TM-5242). Details and background information are presented in Appendix I — *Evaluation of the Reactor System* (ORNL/TM-5409); Appendix II — *VHTR Process Application Studies* (ORNL/TM-5410); and Appendix III — *Engineering Evaluation of Process Heat Applications for VHTRs* (ORNL/TM-5411).

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ABSTRACT

An overview is presented of the technical and economic feasibility for the development of a very high-temperature reactor (VHTR) and associated processes. A critical evaluation of VHTR technology for process temperatures of 1400 to 2000°F is made. Additionally, an assessment of potential market impact is made to determine the commercial viability of the reactor system. It is concluded that VHTR process heat in the range of 1400 to 1500°F is attainable with near-term technology. However, process heat in excess of 1600°F would require considerably more materials development. The potential for the VHTR could include a major contribution to synthetic fuel, hydrogen, steel, and fertilizer production and to systems for transport and storage of high-temperature heat. A recommended development program including projected costs is presented.

1. EXECUTIVE SUMMARY

1.1. Introduction

In recent years there has been increased international interest in the possibility of using the graphite-moderated high-temperature reactor (HTR) as a source of high-temperature process heat. The Federal Republic of Germany has initiated a substantial program to develop the HTR, associated nuclear coal conversion processes, and a chemical heat pipe system. The Japanese Atomic Energy Research Institute has initiated a comparable program to develop a nuclear steelmaking system.

In the United States, several private sources initiated investigations of nuclear process heat. A topical meeting on the subject, sponsored by the American Nuclear Society, was held at Los Alamos in October 1974.[1] The Atomic Energy Commission (now Energy Research and Development Administration, ERDA), Division of Reactor Research and Development, RRD (now Division of Nuclear Research and Applications, NRA), initiated studies of the subject in the spring of 1974. Contract designs of the very high-temperature reactor (VHTR) were prepared by General Atomic Corporation (GA), by General Electric Company (GE), and by Westinghouse Electric Company (W). The Oak Ridge National Laboratory (ORNL) was requested by RRD to prepare an overall assessment of the incentives for developing the VHTR, the technical and economic feasibility of the reactor and associated process, and the research and development requirements. Many government and private organizations have contributed to this effort, as shown in Fig. 1. This report presents an overview of the assessment. Details and background information for the VHTR assessment are presented in three Appendices — *Evaluation of Very High-Temperature Reactors for Process*.

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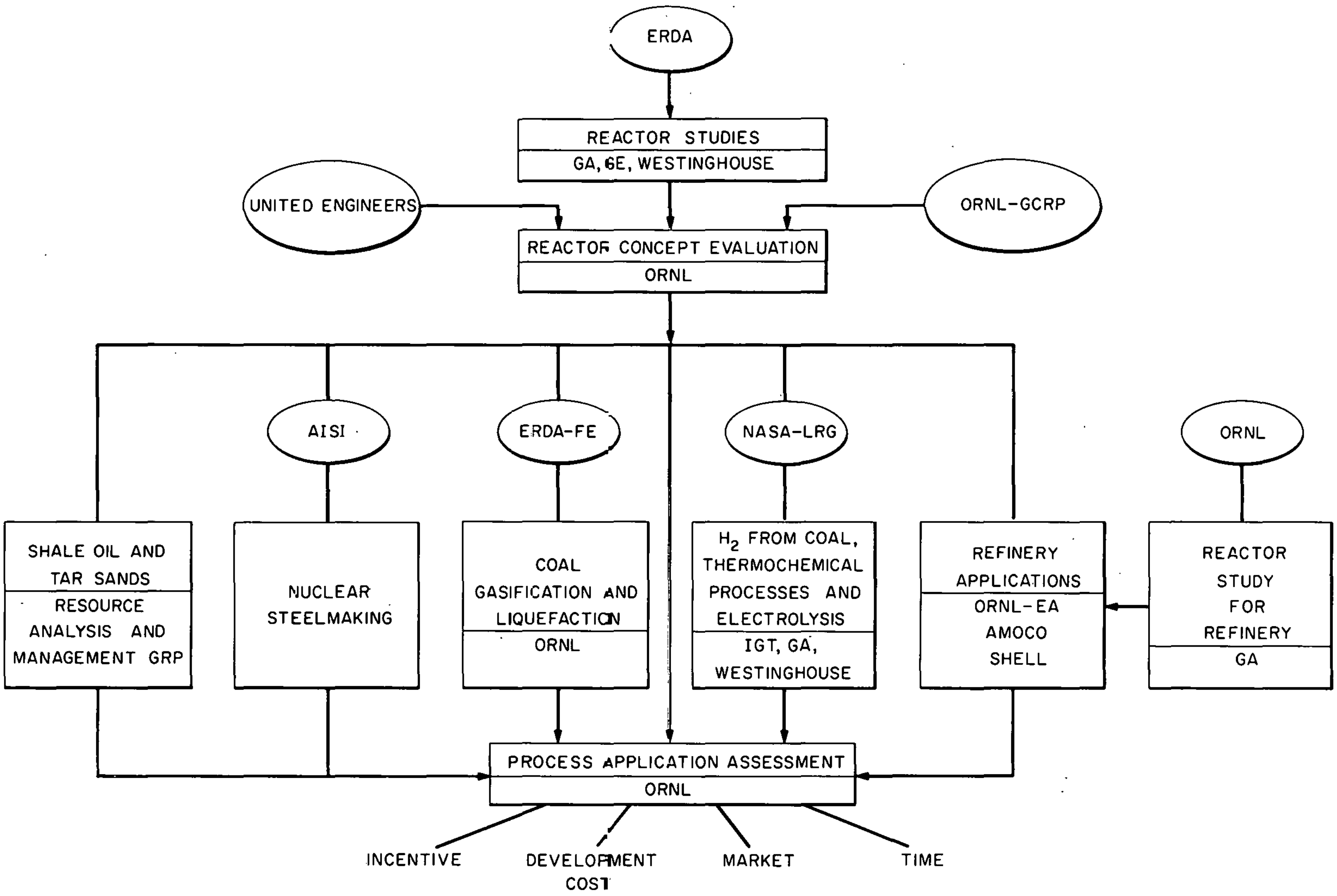

Fig. 1. Government and private agencies that have contributed to the overall assessment of the incentives for developing the VHTR.

Process Applications, (ORNL/TM-5409), *VHTR Process Application Studies*, (ORNL/TM5410), and *Engineering Evaluation of Process Heat Applications for Very High-Temperature Nuclear Reactors* (ORNL/TM-5411).

Major contributing reports are listed as ref. 2-18.

While nuclear process heat is the main focus of this assessment, the VHTR technology has unique applications for electric power production which serve as a secondary incentive for its development.

1.2 Summary and Conclusions

1.2.1 Technical feasibility

The very high-temperature reactor technology builds directly on the technology of steam-cycle gas-cooled reactors such as the Fort St. Vrain Nuclear Generating Station and the VHTR pebble bed reactor. The core and pressure vessel design and materials are very similar. The major change is an increase of helium coolant outlet temperature from 1400°F (typical of steam-cycle reactors) to 1650°F or more for the VHTR. Our assessment indicates that nuclear process heat is a feasible energy source.

Process temperatures up to the 1400 to 1500°F range (corresponding to coolant outlet temperature of 1650 to 1800°F) are achievable with near-term technology. The major development considerations are high-temperature materials, the intermediate heat exchanger (if needed), and the process heat exchanger.

Process temperatuares of 1600°F are somewhat more difficult and will demand an expanded materials program and probably more time. Process temperatures in the range of 1600 to 2000°F are potentially achievable but would require a much larger development program over a longer period of time. Some major uncertainties in this higher temperature range include heat exchanger design and materials (possibly ceramics), ducting and vessel insulation, fission product release and transport, safety, and possibly advanced fuel particle design.

1.2.2 Applications

The VHTR has unique capabilities for applying fission energy to the following:

(1) production of hydrogen via hybrid fossil-nuclear systems or by water-splitting, to be used for production of synthetic fuels, chemical feedstocks and fertilizer, or for reduction of iron ore;

(2) systems for the production of heat which may be used directly in the process industries, transported for use at distant sites, or stored for generation of intermediate-load and peaking power;

(3) high-efficiency electric power systems using direct-cycle gas turbines, combined cycles, or boiling-potassium topping cycles.

The VHTR represents the only intermediate-term alternative to fossil fuels for these applications, which are extremely important to the industrial and transportation sectors of the United States' economy.

1.2.3 Market for the VHTR

The potential market for VHTR process plants consists of a major share of synthetic fuels and hydrogen production, including processes such as iron ore reduction and fertilizer production. Up to about eighteen 3000 MW(t) VHTRs could be deployed by the year 2000, provided a vigorous R&D program is undertaken. The major market is developed after 2000, when replacement of fossil fuels will become a necessity. Over one hundred 3000 MW(t) units would be required by 2030.

1.2.4 Economic feasibility

Based on our analysis, nuclear process heat is expected to be competitive with oil at $8 to $12 per barrel or with coal at $1 to $2 per million Btu (based on constant 1975 dollars). Precise comparisons are not possible, since neither nuclear nor all-fossil synthetic fuel processes are sufficiently developed at this time. Inasmuch as fossil fuel prices by the year 2000 are expected to be much higher than today's prices, the economic competitiveness of the VHTR at the time it is needed seems to be probable. Analysis of the impact of higher uranium prices (up to $100 per pound of U_3O_8) indicates that the economics of nuclear process heat would not be seriously affected by uranium prices in that range.

1.2.5 Commercial feasibility

Three U. S. reactor vendors have expressed a strong interest in developing the VHTR. The response from potential users of nuclear process heat has thus far been limited to strong endorsement from the American Iron and Steel Institute (AISI) and support from the American Gas Association (AGA). Additional indications of long-term user interest should be sought by ERDA.

About the time the initial draft of this report was completed, General Atomic Company announced their withdrawal from the commercial supply of steam-cycle high-temperature gas-cooled reactors (HTGRs). This decision appears to reduce private industry's support of gas-cooled reactor technology, thereby placing a heavier burden on ERDA. For the development program to be meaningful, ERDA will have to encourage (and possibly provide financial incentives to) those organizations that will build and operate the lead plants, in order for suppliers to establish the VHTR as a commercial product.

1.2.6 Environmental considerations

Nuclear process heat systems have environmental advantages over process heat systems based entirely on coal (the only feasible alternative):

(1) possibility of large-scale coal conversion systems with substantially reduced sulfur, NO_x, and particulate emissions;

(2) reduced mining impacts;

(3) reduced needs for coal transportation;

(4) reduced CO_2 emissions;

(5) conservation of fossil fuels and their allocation only to essential uses.

1.2.7 Recommended development program

A matrix of goals for the nuclear process heat program is shown below:

Maximum process temperature (°F)	Type of coupling	Applications	Date of lead plant
1400-1500	Steam reforming of light hydrocarbons	Hydrogen production, nuclear steelmaking, coal hydrogasification and liquefaction, and chemical heat pipe	1995
	Fluidized-bed process heater	Steam gasification of lignite and catalyzed char	1995
1600-1800	Fluidized-bed process heater	Steam gasification of coal	2000
	Process heaters	Thermochemical water splitting	2000 or later

It is recommended that ERDA support a strong R&D program leading to a decision by 1985 or sooner on the construction of a lead VHTR process plant in the U. S. ERDA should also enter into an agreement with the Federal Republic of Germany for a cooperative program to increase the technology base available to us and to cut costs. Other international agreements might also be worthwhile, for example, with Japan.

The cost of the nuclear process heat program through the program definition phase (leading to a decision on the lead plant) includes $110 million for VHTR development and $60 million for applications and process R&D. These costs might be reduced through international cooperation.

In addition, the VHTR program requires technology from the HTGR Base Program and from the Thorium Fuel Reprocessing-Recycle Program. If other HTGR programs such as the steam-cycle plant were discontinued, an additional $110 million is estimated to be required for these supporting programs during the program definition phase. If the main emphasis of the ERDA program on gas-cooled reactors were shifted to the VHTR, it would still be wise to continually reassess the possibility of entering the electric power production market as gas-cooled reactor and thorium fuel cycle technology is improved.

1.3 Key Issues

1.3.1 Technical risk

Although we are optimistic that the technical problems of the VHTR are likely to be solved, no assurance can be given until after materials development is completed and high-temperature components are demonstrated. Materials have not previously been required to operate at high on-stream factors and for many years in the VHTR temperature range.

1.3.2 Customer acceptance

The VHTR would have major impacts on the energy industries (synthetic fuels production, electric utilities, and coal mining) and the energy-using industries (steel and chemicals). ERDA must factor industrial judgments into their planning of the VHTR and associated process development programs. The VHTR would have to gain customer acceptance to be useful to the economy.

1.3.3 Commercial supplier of the VHTR

Although ERDA can provide incentives to the organizations that will build and operate the lead VHTR plant, this step by itself will not assure that vendors will supply commercial VHTRs. In common with other advanced energy systems, the VHTR may require additional incentives during the commercialization phase to reduce vendors' risks.

1.3.4 Resources availability

The conservation of fossil fuel resources is a major incentive for development of the VHTR. On the other hand, the VHTR will increase the demand for nuclear fuel resources. If the breeder were widely used, nuclear fuel supply problems should be minimal. Analysis of high conversion ratio VHTR designs and of other aspects of the resource question should be undertaken.

1.3.5 Thorium fuel cycle

Commercialization of the VHTR would call for development of the thorium fuel cycle, if it were not already developed in support of other reactor systems.

1.3.6 Institutional problems

The energy output of individual VHTR units is likely to be larger than that normally required for individual industrial plants or processes. Some applications may involve multiple customers near a particular site. Others may involve generation of byproduct power to be marketed by an electric utility. Management and operation of a VHTR process plant is likely to involve several organizations. Provision must also be made for VHTR plant outages in the design and/or operation of the VHTR process complex. This may be accomplished during the design phase by using multiple units, a fossil-fired backup or energy storage.

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2. FUEL RESOURCE ANALYSIS

2.1 Overall Fuel Use Trends in the United States

Wood was the major fuel in the U.S. until 1880, when it was rapidly replaced by coal. After World War II, petroleum and natural gas became the fuels of choice, being both convenient and cheap.

Domestic production of oil and natural gas appears to have topped out (Fig. 2); thus we are entering a period during which these fuels will become scarce and their prices will escalate. Users will tend to substitute more available forms of energy, that is electricity and coal, for less available forms. An ERDA spokesman has suggested that the U.S. synthetic fuels program strive to reach 1 million bbl/day (oil and gas equivalent) by 1985, 5 million bbl/day by 1995, and 10 million bbl/day by 2000.[19] The consequences of such a strategy are shown in Figs. 3 through 5.

Figure 5 shows a sharply increasing rate of coal usage in the U.S. — quadrupling in the next 25 years. One would expect increasing prices for coal under the conditions of general energy scarcity both in the U.S. and abroad. An attractive return on investment will be required to generate the capital for development of new mines and coal transport systems at the required rate.

The industrial sector is the largest energy user in the United States, accounting for about 40% of the total primary energy consumption, as shown in Fig. 6. Of the direct process (nonelectric) uses, 51% use natural gas, 27% use oil, and 22% use coal. The use of coal or nuclear fuel in industry would release gas and oil for other uses and would move us an important step toward the goal of national self-sufficiency in energy.

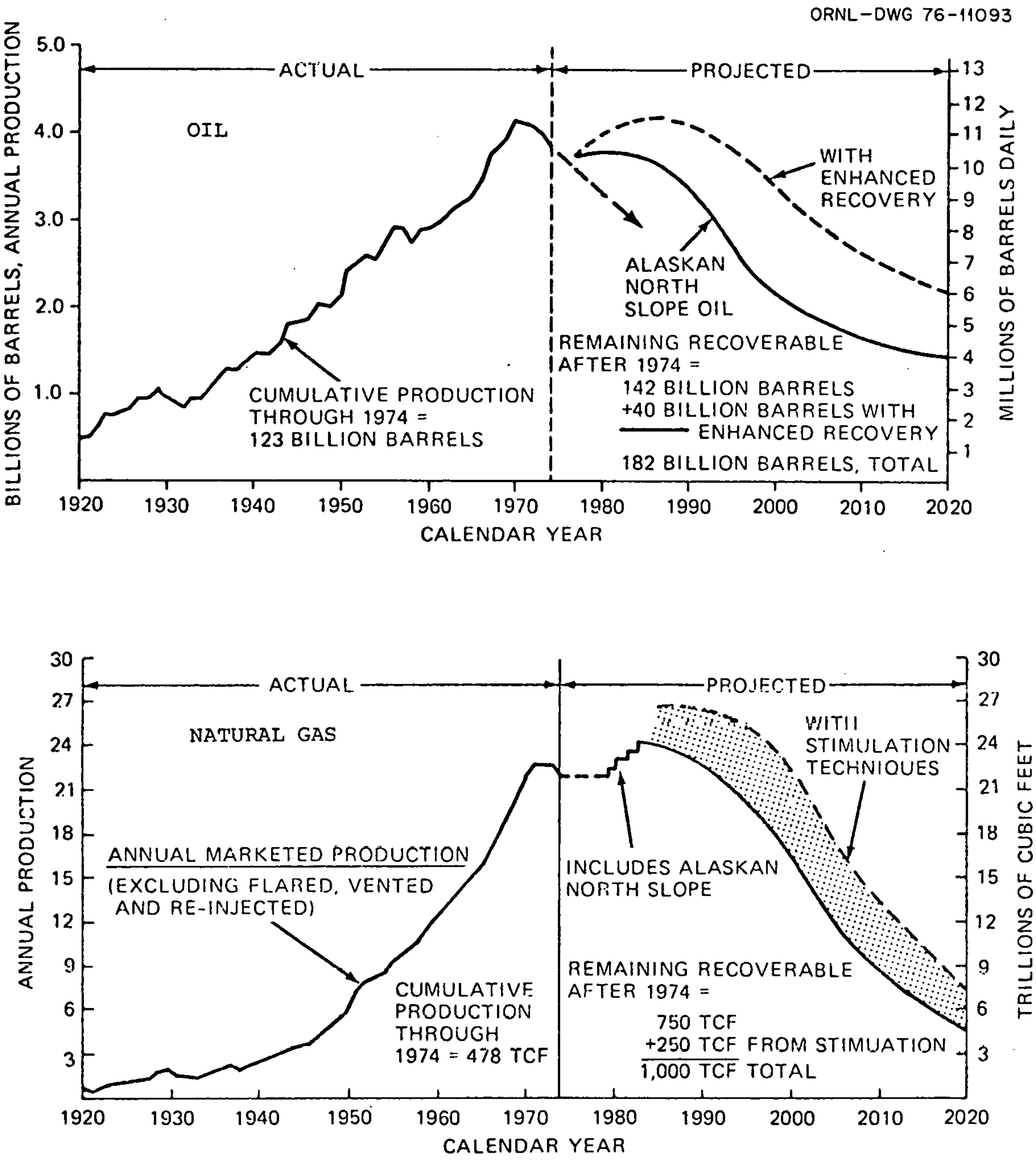

Fig. 2. Domestic oil and natural gas production.

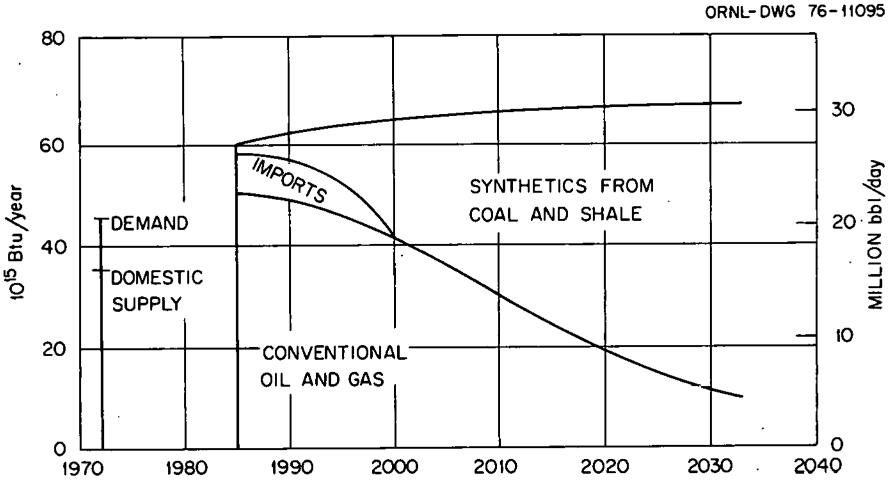

Fig. 3. Anticipated supply of liquid and gas fuels in the United States.

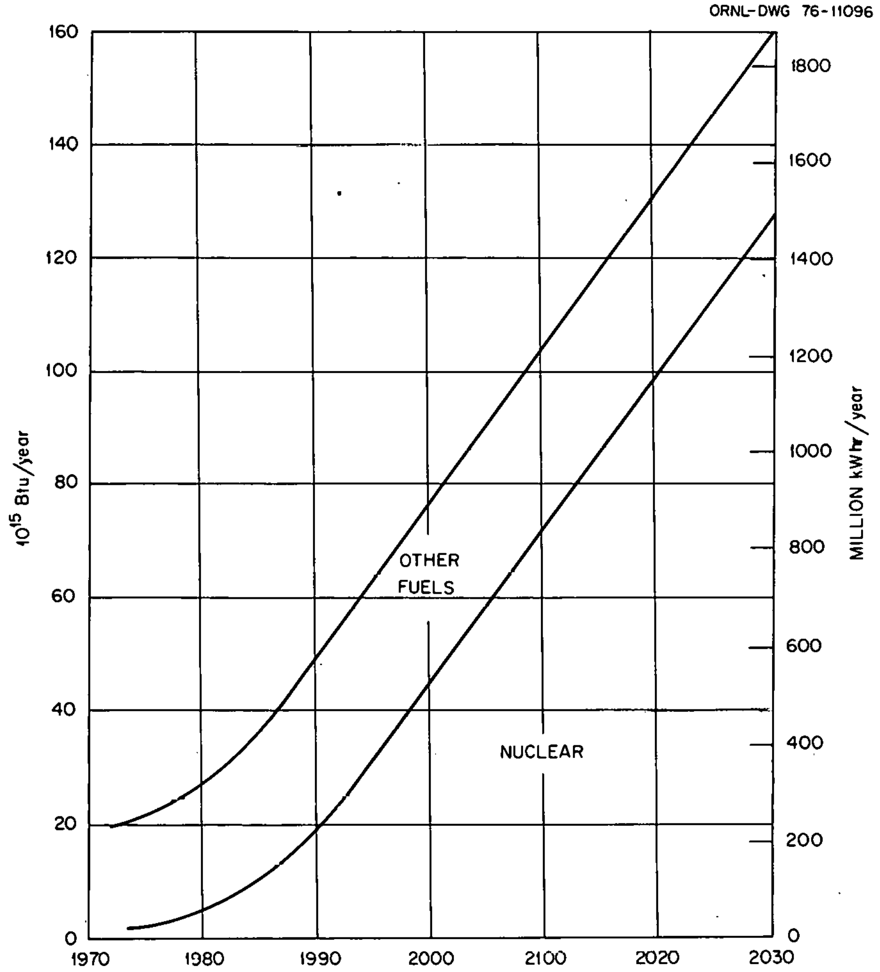

Fig. 4. Anticipated fuel inputs to electricity.

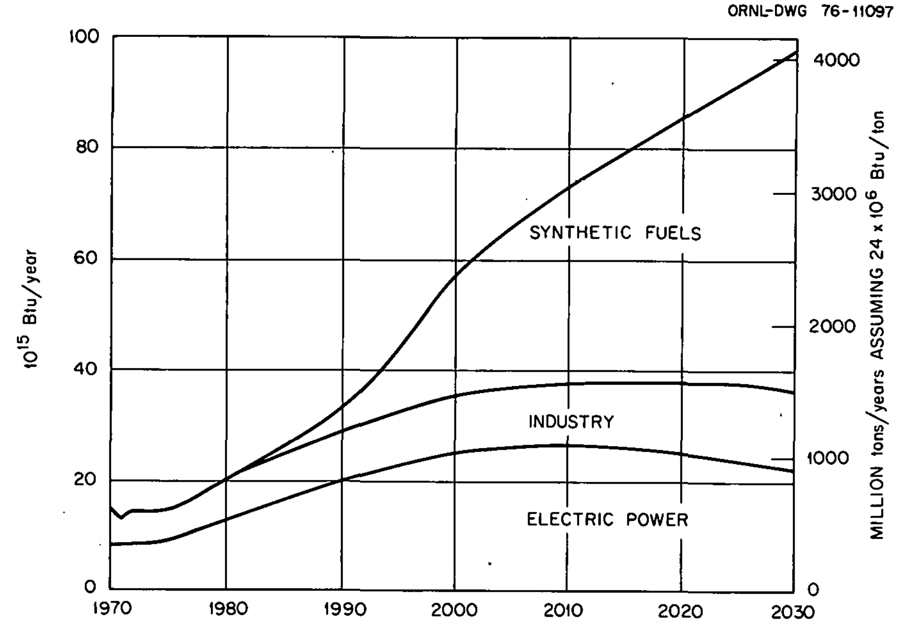

Fig. 5. Projected use of coal in the United States.

During recent studies of industrial energy alternatives (coal and nuclear),[20] it was found that many potentially large industrial process heat applications could not be met by current commercial reactors because the temperature requirements were too high. This is particularly true in the chemical and petroleum industries. Also, the new energy technologies, including coal conversion to synthetic gas or liquid fuels, hydrogen production by thermochemical water splitting, and shale oil and tar sands refining, all appear to require thermal energy at higher temperatures. There appears to be a very large market for hydrogen or synthesis gas (H_2 + CO) in the direct reduction of iron ore, in ammonia production, and in refining petroleum. Production of these reducing gases would require the higher temperatures.

At the present time, nuclear energy is competing with other fuels (mainly coal) in the market for generating base-load energy. Nuclear

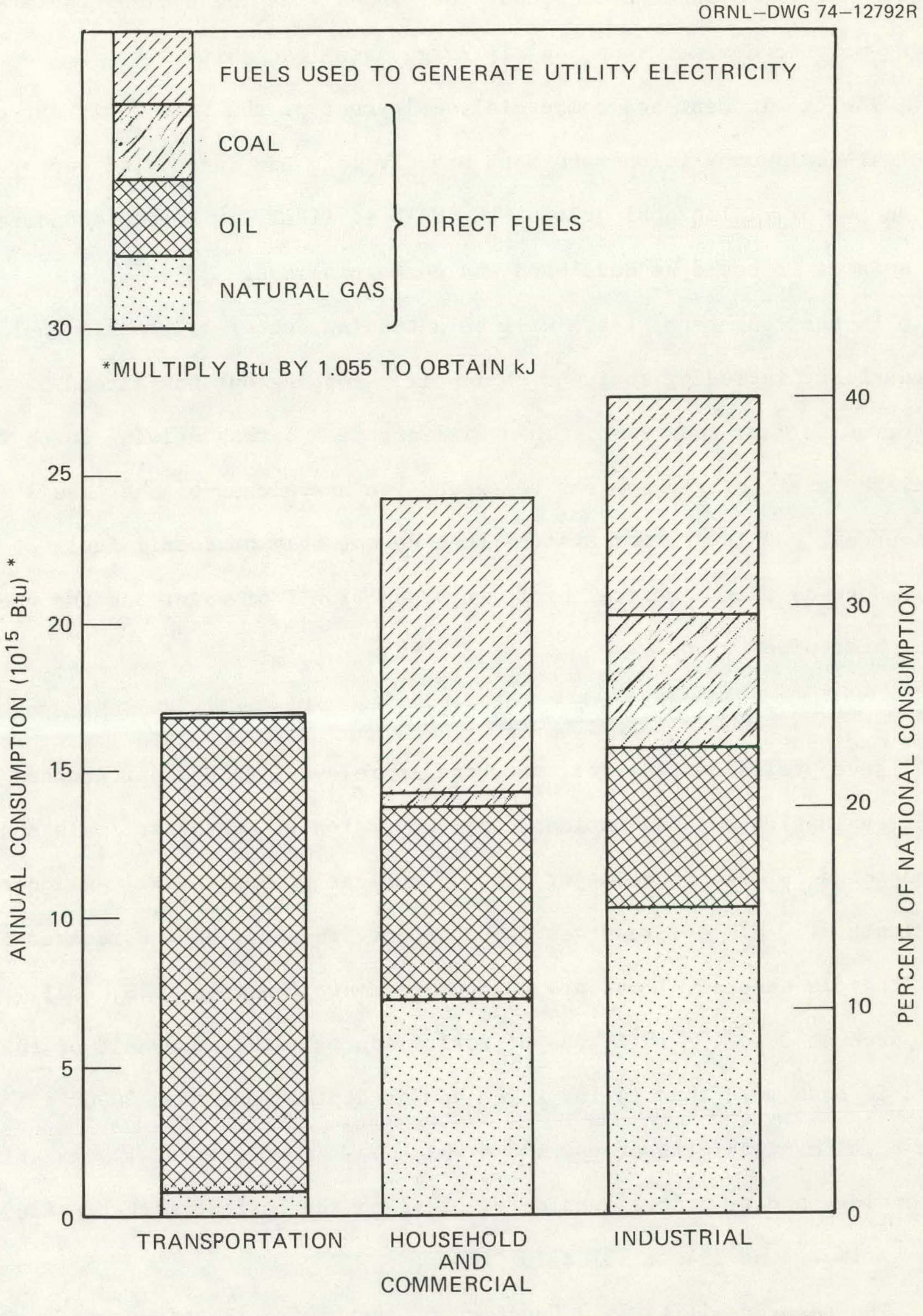

Fig. 6. Energy consumption in the United States, 1971.

plants have been successful because utilities view the nuclear fuels as being more economical than coal in large base-load units.

The development and commercial deployment of the VHTR would extend nuclear-coal competition much more broadly into the industrial sector. In an era of rising coal prices, the VHTR is likely to become economical as soon as it could be developed and commercialized.

In the long term, there will be a topping out of all fossil fuel production, including coal and shale oil. Topping out has already occurred in many countries. This will create a strong driving force for nuclear-fossil hybrid systems to extend the usefulness of the fossil resources, and later, for systems that do not rely on fossil fuels at all, such as thermochemical hydrogen production from water and the chemical heat pipe.

2.2 Coal Resources

An appraisal of the coal resource is relevant to nuclear process heat evaluation because nuclear coal conversion to synthetic fuels and feedstocks is one of the major uses of nuclear process heat. An accurate estimate of U.S. coal reserves is dependent, in part, on the recoverability that is assumed. Most projections estimate the total U.S. coal resource at 3 to 4 x 10^{12} tons of coal. Approximately one-half of this lies in beds more than 14 in. thick and at depths less than 3000 ft. The total available reserves, those which may be recovered with existing technology and at prices considered close to the current market price, are estimated at 394 to 437 x 10^9 tons.

The recoverability is a function of the mining technique used. For example, strip mining is considered to have a recovery factor of 80 to

90%, whereas underground mining recovers only about 50%. About 32% of our reserves are strippable, with the remainder recoverable only by underground techniques (Fig. 7). Therefore, the moderately priced reserves that may actually be recovered are about 175 to 270 x 10^9 tons.[20,21] These moderately priced resources represent 275 to 415 years supply of coal if they are used at the 1975 rate of 635 x 10^6 tons/year, or 47 to 70 years if consumed at the 1973 energy rate of 75 x 10^{15} Btu/year. For the scenario of Fig. 5, moderately priced coal will last about 75 years. However, it should be noted that as coal rises in price, the amount that is economically recoverable will increase. Not only is the potential supply of coal important, but, also, its price relative to nuclear heat is a crucial factor to the economics of nuclear process heat. The price of coal has historically been very stable. For example, the average price of coal in 1969 was exactly the same as it was in 1948. However, in 1970, the spot price rose 25% and almost doubled in 1974. Figure 8 depicts this dramatic rise in price. It is clear this price increase is, in part, due to the higher cost of labor, which has almost doubled in the last five years. In addition, mine productivity has decreased substantially, primarily because of the stricter mine safety standards. However, the price perturbation experienced in 1974 was largely demand induced and not unlike the increase experienced in other fuel sources.

There is much conjecture concerning the future price of coal. Most analysts agree that the demand for coal is increasing and will continue to increase as our supplies of oil and natural gas are depleted. Table 1 depicts factors that influence the future price of coal. The

President's Council on Wage and Price Stability conclude in their March 1976 report that the price of coal will stabilize as the large, cheaper western reserves come into competition with the eastern mines.[21] However, the ability of western coal to meet this demand has yet to be tested and is contingent upon the outcome of several environmental court decisions, legislative actions, and the availability of capital for mining and transportation. The Federal Energy Agency (FEA) coal price projections through the year 1990 indicate that there will be a steady increase in the price of coal.[22] This appears to us to be a realistic estimate based on the restricted availability of capital for expansion, the increased demand, and the cost of production.

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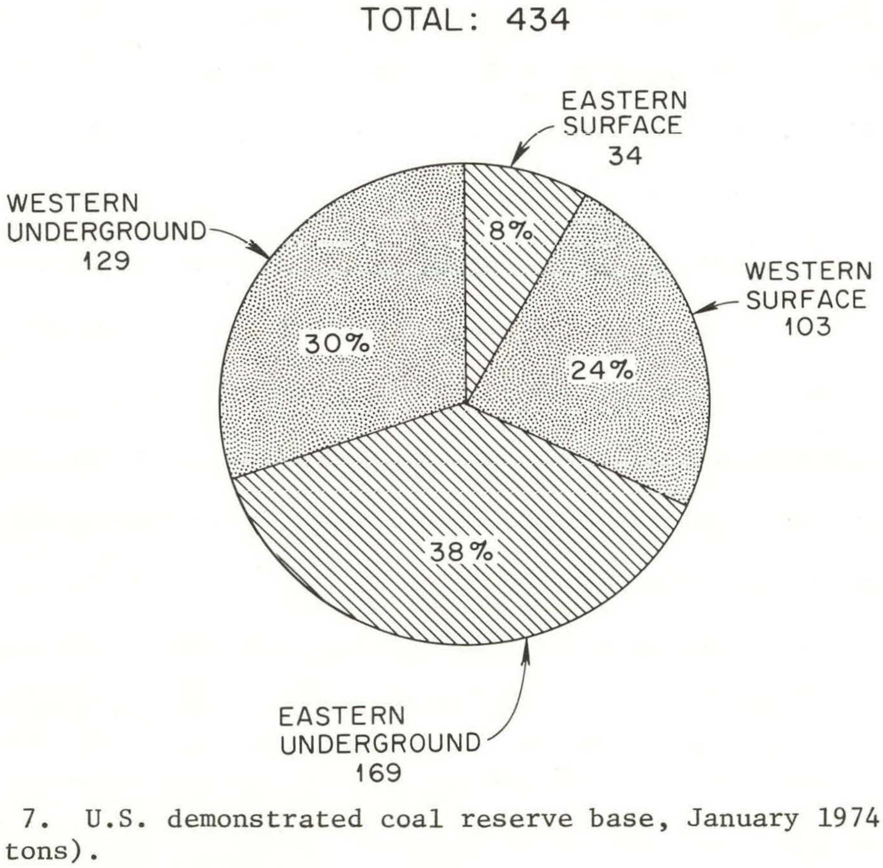

Fig. 7. U.S. demonstrated coal reserve base, January 1974 (billions of short tons).

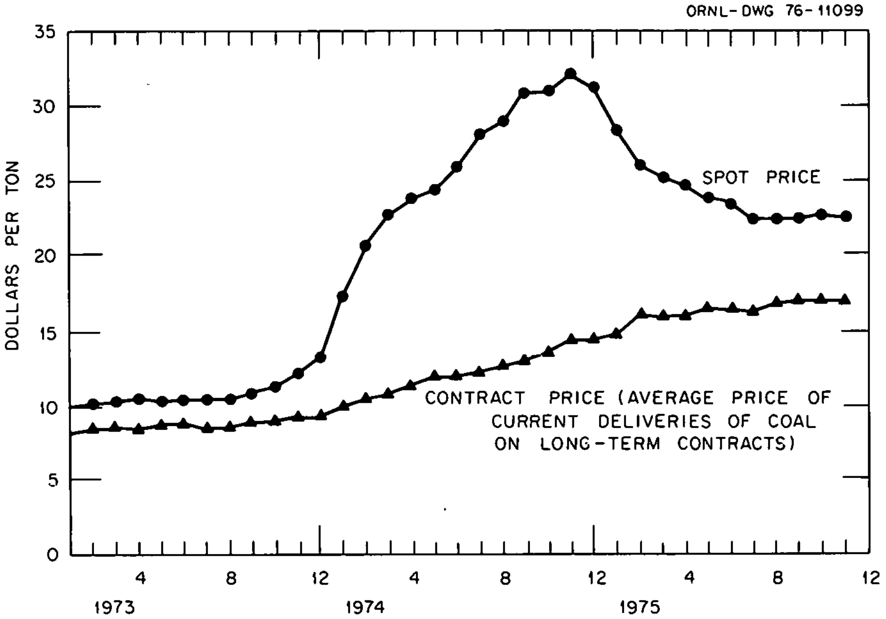

Fig. 8. Electric utility steam coal prices.

It is clear that the coal resource will be available at moderate to rising prices for many decades. Coal will continue to be available beyond the middle of the 21st Century, but at escalating prices as less desirable reserves are mined.

Table 1. Factors affecting the price of coal

Stabilize	Inflate
Expansion of western coal mines	Environmental restrictions
Stabilization of Organization of Petroleum Exporting Countries (OPEC) oil prices	Inflation of OPEC oil prices Increased mine safety standards
Willingness to import oil rather than develop domestic coal	Increased labor costs and/or shortages
Restrictions on coal exports	Interconnection with foreign coal market
	Shortage of capital resources
	Increased cost of transportation

2.3 Uranium Resources

The uranium procurement step is of particular concern, since depletion of the uranium resource would limit nuclear power applications. Is there enough uranium, and, if so, what will it cost?

Uranium is widely distributed, with an average concentration of 2 to 4 ppm in the earth's continental crusts and 0.003 to 0.004 ppm in its oceans. It is typically found in small deposits or in low concentrations. The chief present source of ore (98%) in the United States is from sedimentary sandstone ("conventional" deposits), particularly those found in the Colorado Plateau and Wyoming Basin geologic regions. Most of the known low-cost U.S. uranium reserves are located in these areas.

An ERDA estimate of the cumulative uranium resource up to various cost cutoff levels is given in Table 2. Information is provided on the reasonably assured (known) reserves and for the estimated potential resources. This latter category is divided into three subcategories (probable, possible, and speculative) in order of declining probability. The estimates shown in Table 2 are mainly for uranium resources in sandstone deposits. Such deposits have been found to have an effective cutoff at the $30/lb cost level, with little uranium available in these deposits at higher costs. The cost cutoff levels are so-called "forward" costs. They do not include return on investment interest on preproduction investment, income taxes, or sunk costs (costs already incurred). The ERDA "forward" costs do not imply that uranium can be bought at these prices. They are intended mainly to serve as an index.

In addition to the conventional uranium resources, the U.S. has several low-grade sources of uranium, as indicated in Table 3. The most important of these appears to be Chattanooga shales. The deposits range from northern Alabama through central Tennessee and into southern Kentucky.

Table 2. U.S. uranium resources (10^3 tons U_3O_8)

		Estimated additional resources			
\$/lb U_3O_8	Reserves	Probable	Possible	Speculative	Total
8	200	300	200	30	730
10	315	460	390	110	1275
15	420	680	640	210	1950
30	600	1140	1340	410	3490

Table 3. Low-grade uranium resources

Type	U_3O_8 (10^3 tons)	Grade (ppm)
Shale	5,000	60 to 80
Shale	8,000	25 to 60
Granite	8,000	10 to 20
Shale	200,000	10 to 25
Granite	1,800,000	4 to 10
Seawater	4,000,000	0.003

These deposits lie in two layers, the most important of which contains about 5 million tons of U_3O_8 at concentrations of 60 to 80 ppm. Although actual recovery costs are speculative, the cost of this uranium is likely to exceed $100/lb U_3O_8. Other uranium resources include lower grade Chattanooga shales (25 to 60 ppm U_3O_8), Conway granites (10 to 20 ppm), Dakota lignite, and the ultimate source found in the ocean. The Dakota lignites are of special interest because of the possibility of using them for gasification, liquefaction, or hydrogen production and for extracting uranium from the residue.

There appear to be no large deposits of low-grade uranium ores which can bridge the gap between the sandstone deposits at "forward" costs of $30/lb U_3O_8 or less and the Chattanooga shales at costs of about $100/lb U_3O_8. Uranium is found in the intermediate concentrations (100 to 400 ppm U_3O_8) in many parts of the world; however, these types of deposits have not been found in any abundance in the U.S as yet.

ERDA is currently undertaking a study of the entire country in order to develop a comprehensive assessment of U.S. uranium resources. This National Uranium Resource Evaluation (NURE) will be a detailed resource evaluation but will also include research and development work to improve the technology for finding and extracting uranium. A preliminary evaluation is scheduled for completion in early 1976, and a detailed report is due in 1980.

The HTGR/VHTR system concepts use thorium as a fertile material. Therefore, knowledge of the thorium resource base is desirable. Estimates of the U.S. thorium resource are shown in Table 4. During a 30-year lifetime, a 3000-MW(t) HTGR needs about 500 tons of ThO_2 if the thorium is not recycled, and less if it is recycled. Adequate known reserves at prices less than \$10/lb ThO_2 are therefore available for 130 such systems, and, if the total resource at forward costs of less than \$30/lb and ThO_2 is used, there is enough thorium for about 1200 HTGR systems.

Table 4. U.S. thorium resource (10^3 tons)

Cost cutoff (\$/lb ThO_2)	Reserves	Estimated additional resource	Total resource
10	65	335	400
30	200	400	600
50	3200	7400	10,600

The overall demand for uranium will depend on several factors. The total electric generation and the nuclear penetration are of great importance in making projections of the future. The timing of the introduction of breeder reactors and the availability of plutonium recycle in light-water reactors also will influence the future demand. The possible introduction of laser enrichment would reduce uranium demand by significantly lowering the tails enrichment. Projections of future uranium consumption with and without the liquid-metal fast breeder reactor (LMFBR) indicate that the \$30 uranium resource is likely to be depleted by early in the 21st Century. If the breeder is introduced commercially by 1991, then the \$30 uranium resource may suffice to fuel the nuclear industry. If the breeder is delayed, then a substantial part of the >\$30 resource would be required.

In view of the uranium supply-demand situation, it would seem prudent to develop reactor systems that use the basic U_3O_8 resource efficiently, such as the high-conversion VHTR.

3. POTENTIAL NEED AND MARKET FOR THE VHTR

3.1 Unique Capabilities of the VHTR

The helium-cooled graphite-moderated reactor has high-temperature capabilities many hundreds of degrees above that of other fission reactor types under development. Water reactors, liquid-metal fast breeder reactors, gas-cooled fast reactors, and molten-salt reactors are all limited in coolant outlet temperature as a result of the physical limitations of fuel element cladding, coolant properties, and/or corrosion. These limitations vary with reactor type from about 600°F (315°C) to about 1300°F (704°C) maximum coolant outlet temperature.

The helium-graphite combination in the VHTR core has been demonstrated to be feasible for continuous operation at a coolant outlet temperature of 1742°F (950°C).[23] Proponents of the system have suggested that outlet temperatures up to 2200°F (1200°C) can be developed.

Assuming that the heat transport components can be developed to utilize this high-grade energy, the VHTR would appear to have unique capabilities for applying fission energy to the following:

(1) production of hydrogen via hybrid fossil-nuclear systems or by water-splitting, to be used for production of synthetic fuels, chemical feedstocks and fertilizer, or for reduction of iron ore;

(2) systems for the production of heat which may be used directly in the process industries, transported for use at distant sites, or stored for generation of intermediate-load and peaking power;

(3) high-efficiency electric power systems using direct-cycle gas turbines, combined cycles, or boiling-potassium topping cycles.

Nuclear process heat systems have significant environmental advantages:

(1) possibility of large-scale coal conversion systems with substantially reduced sulfur, NO_x, and particulate emissions;
(2) reduced mining impacts;
(3) reduced needs for coal transportation;
(4) reduced CO_2 emissions;
(5) conservation of fossil fuels and their allocation only to essential uses.

3.2 Scenarios for Large-Scale Introduction of the VHTR

Nuclear plant economics are very sensitive to the size of the reactor, favoring heat sources in the largest rating which can be absorbed practically in the total system. The large size of the heat sources now under study leads typically to very large process plants as illustrated in Table 5.

Another consideration is the strategy to compensate for scheduled and unscheduled nuclear plant outages. The corresponding fossil plants would probably consist of multiple trains, only one of which would be likely to shut down at any one time.

Just how the synthetic fuels market will develop is very much in question. A number of possible scenarios have been discussed. Future fossil energy systems will depend strongly on coal. In the long run the price of coal will be influenced by (1) mining costs, including environmental considerations; (2) transportation costs; (3) value as a boiler fuel and as a synthetic fuel feed-stock; and (4) the international market for fuels.

Table 5. Size characteristics of 3000-MW(t) VHTR process plants

Product	Typical VHTR process plant	Typical nonnuclear alternatives
Synthetic pipeline gas	540×10^6 ft^3/day	250×10^6 ft^3/day
	0.21×10^{15} Btu/year	0.083×10^{15} Btu/year
Liquids from coal	180×10^3 bbl/day	100×10^3 bbl/day
	0.3×10^{15} Btu/year	0.2×10^{15} Btu/year
Liquids from shale	250×10^3 bbl/day	100×10^3 bbl/day
	0.45×10^{15} Btu/year	0.2×10^{15} Btu/year
Nuclear steel plant	14×10^6 tons/year	1 to 5×10^3 tons/year
Thermochemical hydrogen plant	320×10^6 ft^3/day 0.037×10^{15} Btu/year	

Low-sulfur bituminous and subbituminous coal and metallurgical coal are likely to command premium prices for direct use in boilers and in steelmaking. Higher-sulfur bituminous coal and lignite are the most likely choices for the synthetic fuels industry because they are the least attractive and are the most difficult to use directly.

Lignite is promising for synthetic fuels because extremely large reserves are available at relatively low mining costs. Also, the shipping costs of lignite are very high because of the large distance to markets and the high water and ash content. Conversion to synthetic liquid fuel or pipeline gas would be one approach to providing a more marketable and transportable fuel from this resource.

Although VHTR energy costs are not likely to be less than lignite energy costs near the mine, they must be reasonably competitive for the VHTR to be applied for lignite conversion. In addition, the anticipated reduced environmental impact of nuclear coal conversion relative to all-fossil systems is likely to become a very important consideration as the scale of operation is increased.

High-sulfur bituminous coal in the east is also likely to be utilized in synthetic fuels production because of the very difficult problems and additional expense of satisfying the environmental regulations while using this fuel directly in boilers. In this case the coal is higher grade than lignite, nearer to the major markets, but mining costs are higher. Therefore, the competitive position of the VHTR as an energy source for coal conversion processes appears likely to be favorable earlier than for lignite conversion processes.

One logical approach (Fig.9) is the conversion of lignite and high-sulfur coal to pumpable liquids and pipeline gas near the mines and the transport of liquid syncrude via pipeline to syncrude petroleum refineries around the country for further processing. Another approach that has been considered is the production of methyl fuel (crude methanol) near the mine which is then slurried with finely ground coal. The methyl fuel-coal slurry ("Methacoal") would be piped to appropriate points of use and separated.

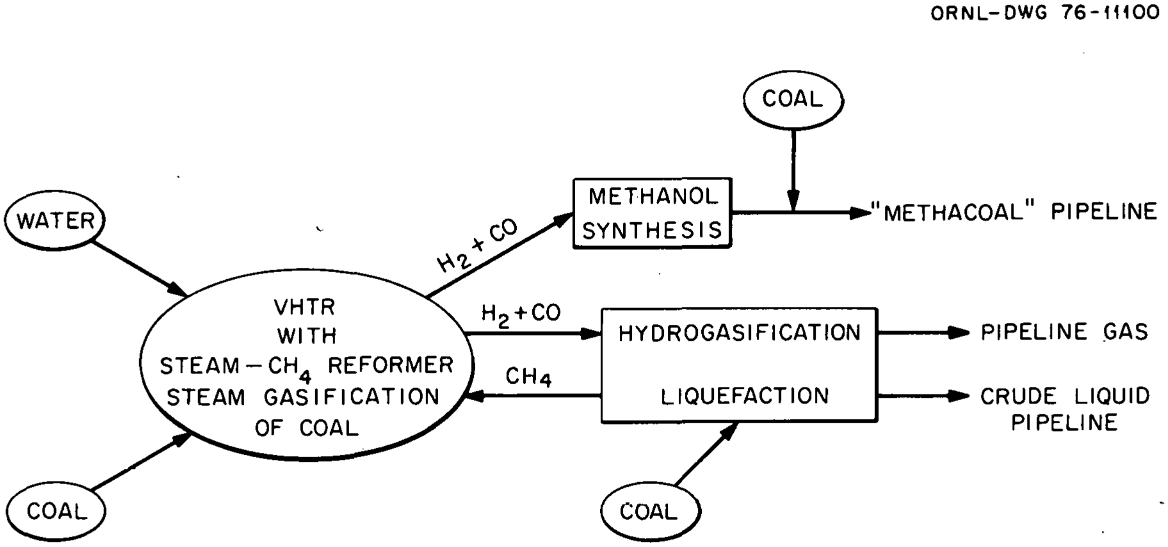

Fig. 9. Production of primary synthetic fuels.

Another scenario (Fig. 10) for major introduction of the VHTR might be termed the secondary energy depot. Such plants would supply merchant reducing gas, hydrogen, and process heat to a variety of industrial users: refineries, ammonia production plants, steel-making plants, coal conversion plants, etc. Markets for such plants are expected to exist along the Gulf Coast of Texas, the lower Mississippi River, the Great Lakes, and in the Pittsburgh area.

Utilities might represent another major market for introduction of the VHTR. Many companies sell both electricity and gas and could support VHTRs that produce pipeline gas and electricity.

Scenarios for introduction of water-splitting systems relate to the competitiveness of water-splitting with other sources of hydrogen. All of the end products discussed above can also be derived using water-splitting as one input. Water-splitting will become a dominant industrial process as fossil fuels become scarce and their prices escalate.

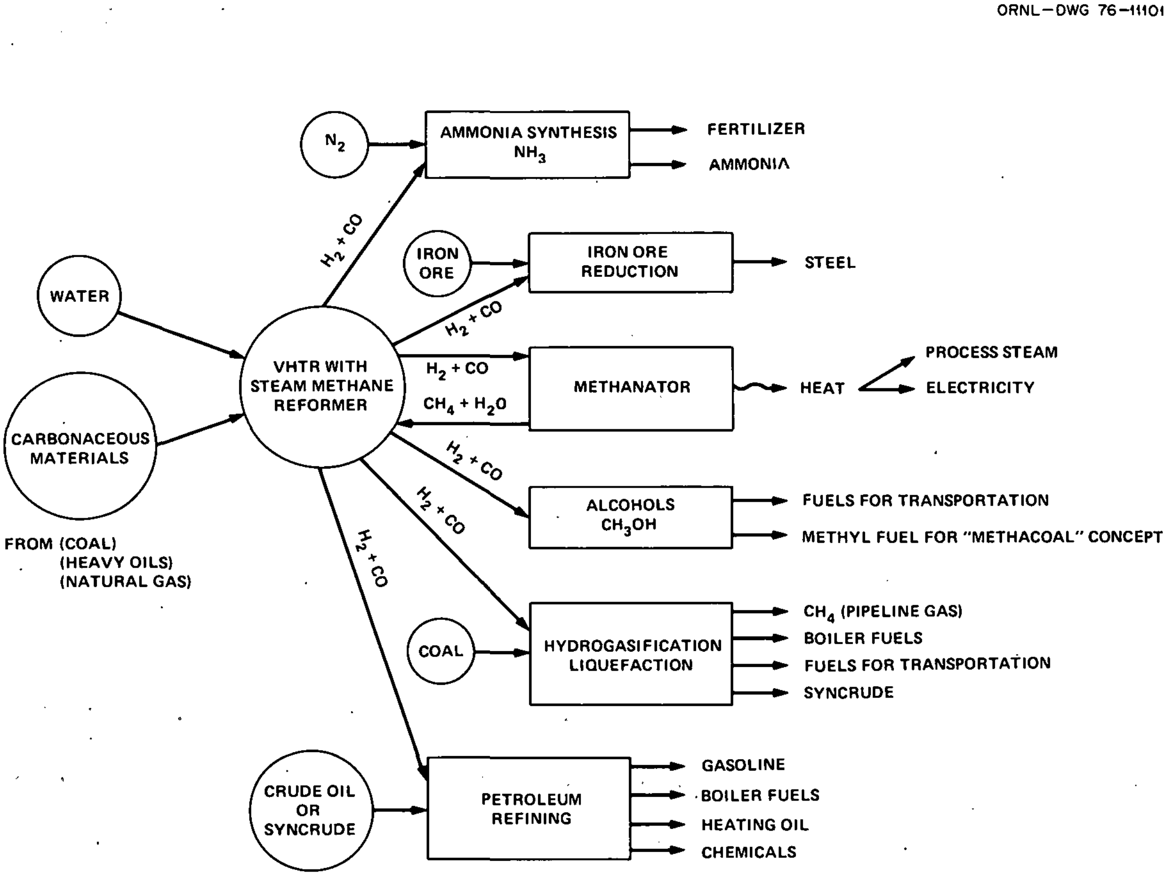

Fig. 10. Secondary energy depot.

3.3 The Synthetic Fuels Market

A number of projections of future demand for synthetic fuels and for hydrogen have been published recently. The *Project Independence Report*[24] presents two scenarios of interest. The "BC" scenario represents a continuation of the trends emerging in the near term which continues present policy with only minor changes. Overall energy consumption grows at a rate of about 2.5% per year from 1985 through 2020. The "MS" scenario assumes conservation plus a major shift to electric power. Under the "MS" scenario, overall energy consumption is projected to grow at a rate of 1.6% per year. In the "BC" scenario, production of synthetic fuels reaches about 30 x 10^{15} Btu by 2000 and 130 x 10^{15} Btu by 2030. In the "MS" scenario, the respective predictions are 12 x 10^{15} and 33 x 10^{15} Btu.

The ORNL prediction of Fig. 3 shows 22 x 10^{15} Btu of synthetic fuels in 2000 and 55 x 10^{15} Btu in 2030.

Table 6 presents the number of 3000-MW(t) VHTRs required to satisfy each of these projections, assuming that the VHTR captures 20% of the synthetic fuels market by 2000 and 60% by 2030.

NASA and its contractors have provided independent estimates of the U.S. demand for hydrogen between now and 2000[5-7] (Table 7.) These range between 5 and 22 x 10^{15} Btu for the year 2000, compared with 12 to 30 x 10^{15} Btu for all synthetic fuels discussed above.

The AISI Task Force on Nuclear Steelmaking projects the following potential for new steel plants during 1985-2000:[14]

(1) 46 million net tons/year increase in capacity,
(2) 39 million net tons/year replacement plants,
(3) 9 million net tons/year to feed electric furnaces,
(4) 94 million net tons/year total.

The Task Force envisions that steel plants would share reducing gas with other industries and thereby could support a total of 18 VHTRs. ORNL considers that the net reducing-gas production for new steelmaking capacity would be the equivalent of 6.7 VHTRs (0.82 x 10^{15} Btu/year).

We might expect that the nuclear share of this market might be the equivalent of about two VHTRs by the year 2000.

The above estimates present one scenario of the maximum process deployment of VHTRs in the U.S. if their technical and economic promise

Table 6. Number of 3000-MW(t) VHTRs potentially required for the synthetic fuels market[a]

	Year							
	2000		2010		2020		2030	
Findings	VHTRs	10^{15} Btu	VHTRs	10^{15} Btu	VHTRs	10^{15} Btu	VHTRs	10^{15} Btu
Project Independence "BC"	24	6	66	16.5	162	40.5	312	78
ORNL	18	4.5	40	10	79	20	132	33
Project Independence "MS"	10	2.5	24	6	47	12	79	20

[a] Average output of 0.25 x 10^{15} Btu/year from each nuclear synthetic fuel plant. VHTR hybrid plants capture 20% of synthetic fuels market by 2000 and 60% by 2030.

Table 7. Estimates of U.S. hydrogen requirements in 10^{15} Btu

	1972-1973		2000					
						Westinghouse		
Process	JPL[a]	GA	JPL[a]	JPL[a] Maximum	GA[b]	Low[c]	Base	High
Ammonia, methanol, and miscellaneous chemicals	0.46	0.60	2.37	9.25	2.81	0.76	1.47	2.14
Petroleum refining	0.47	0.48	0.78	0.77	0.60	0.58	2.41	2.41
Synthetic fuels	--	--	1.71	7.6	6.99	5.82	10.32	13.33
Steelmaking	--	--	0.22	0.65	2.11	0.09	0.18	0.36
Transportation, utility other	0.07	0.06	0.40	4.21	0.37	--	0.39	1.14
Total	1.00	1.14	5.48	22.48	12.88	7.25	14.77	19.38

[a] California Technological Jet Propulsion Laboratory, *Hydrogen Tomorrow: Demands and Technology Requirements* (Review Draft), Report 5040-1, October 30, 1975.

[b] General Atomic Company, *Studies of the Use of High-Temperature Nuclear Heat from an HTGR for Hydrogen Production*, September 30, 1975, prepared under contract for NASA.

[c] Westinghouse Astronuclear Laboratory, *Studies of the Use of Heat from High Temperature Nuclear Sources for Hydrogen Production Processes* (Draft Final Tasks I and II Report), July 1975.

were validated through research, development, and demonstration. A much greater deployment of VHTRs would occur if thermochemical hydrogen became the primary mode of hydrogen supply during this period, because the hydrogen yield per reactor is less than for the nuclear-fossil hybrids. If 18 VHTR process plants were in operation in the year 2000 and if they were to average about a 10% advantage in synthetic fuel product cost over alternatives, then the benefit of VHTR process heat to the economy would be about \$1 x 10^9/year (1975 dollars).

4. VHTR TECHNOLOGY AND ECONOMICS

In the spring of 1974, the Atomic Energy Commission Division of Reactor Research and Development initiated a program of conceptual studies and evaluations of the application of very high-temperature gas-cooled reactors to process heat generation. Important elements of this program included conceptual design contracts with General Atomic Corporation, General Electric Company, and Westinghouse Electric Corporation to develop conceptual designs of such reactors to deliver process heat at 1200°F (649°C), 1400°F (760°C), 1600°F (871°C), 1800°F (982°C), and 2000°F (1093°C).[2-4] Details of ORNL's evaluation of VHTR technology and economics appear in Appendix I and in ref. 10.

4.1 Discussion of VHTR Concepts

The VHTRs are thermal reactors utilizing helium as coolant and having all-ceramic cores composed of graphite moderator and enriched uranium-thorium fuel. This combination has enabled the gas-cooled reactor to develop coolant outlet temperatures far higher than those of other reactor systems. For production of electricity, these temperatures permit the production of high-temperature, high-pressure steam, leading to high-cycle efficiency. Similar designs, at more elevated temperatures, are believed to be useful for generating process heat. The three vendor design studies present features that encompass most of the available technology (Table 8).

General Atomic developed the HTGR as a commercial steam-generating reactor for use by utilities. The Peach Bottom Reactor [115 MW(t), 40 MW(e)] was operated successfully by Philadelphia Electric Company from June 1967 to October 1974 and proved the feasibility of the concept.

Table 8. Comparison of the three vendor concepts

	General Atomic	General Electric	Westinghouse
Basis of very high-temperature nuclear reactor design	Modification of HTGR concept	Pebble bed concept based on German technology	Prismatic fuel concept based on nuclear rocket technology
Reactor core type	Hexagonal graphite blocks containing separate coolant and fuel passages, solid cylindrical fuel rods	Pebble bed core Graphite sphere fuel element	Hexagonal graphite blocks, hollow cylindrical fuel rods with central coolant channel
Reactor coolant	Helium	Helium	Helium
Reference thermal power	3000 MW(t)	3000 MW(t)	3000 MW(t)
Pressure vessel concept	Prestressed concrete reactor vessel	Prestressed concrete reactor vessel	Prestressed cast iron reactor vessel
Fuel composition	Fully enriched U feed (UC_2) with thorium (ThO_2) fertile material TRISO coating for both fissile and fertile particles	Low enriched (9.01%) ^{235}U fuel Uranium-thorium fuel alternate TRISO-coated UO_2 fuel particles	Fully enriched U feed (UC_2) with thorium (ThO_2) fertile material TRISO-coated fissile particles BISO-coated fertile particles
Average fuel residence time	3 years	3.8 years	4 years
Power density of core	8.4 W/cm^3	5 W/cm^3	10 W/cm^3
Reactor core ΔP	16 psi	6 psi	5 psi
System pressure	725 psi	600 psi	1000 psi
Core inlet temperature	770°F	482°F	807°F
Reference maximum process temperature	1400°F (without IHX)	1500°F (with IHX)	1600°F (with IHX)
Core outlet temperature	1600°F	1742°F	1850°F
Maximum fuel temperature	2475°F	2030°F	2158°F
Type process	Steam-hydrocarbon reformer	Steam-hydrocarbon reformer	Hybrid thermochemical-electrolytic water splitting

General Atomic has built a much larger HTGR at Fort St. Vrain Nuclear Generating Station [842 MW(t), 330 MW(e)] which has thus far been operated at low power levels. The standard HTGR (helium outlet temperature of 1400°F or 760°C) is modified for process heat purposes by placing a process heat exchanger in series with and upstream of the steam generator.[2] As in other HTGR designs, all the primary system components are contained in one large prestressed concrete reactor vessel (PCRV) because of the advantages offered by this form of construction. Steam-methane reforming was selected by GA as a typical high-temperature process; the reformer was assumed to be located within the PCRV. The GA study was based on the assumption that an intermediate heat exchanger (IHX) would not be required. If an IHX is required, reactor exit helium temperatures would have to be increased well above the reference 1620°F (882°C) to reach the 1400°F maximum process temperature.

The pebble-bed reactor (PBR) developed by Kernforschungsanlage (KFA), Julich,[25] differs from the HTGR primarily by having the fuel contained in graphite moderator balls. These balls are loaded into and withdrawn from the reactor during operation. The PBR concept was selected by GE for their VHTR design.[3]

KFA has built and is operating the Arbeitsgemeinschaft Versuchsreactor (AVR) [46 MW(t), 15 MW(e)], and experimental steam-generating PBR. The AVR has operated at a helium core outlet temperature of 950°C (1742°F) since February 1974. A larger PBR, the high-temperature reactor (THTR) [768 MW(t), 300 MW(e)], is under construction and is scheduled for 1978 operation. This steam-generating reactor will have a helium outlet temperature of 750°C, in the same range as do commercial HTGRs.

The GE PBR places all primary system components into a PCRV. Primary helium coolant flows through the core and exits into five loops, each containing an IHX and a steam generator. A secondary helium stream is heated in the IHX and is transported out of the reactor vessel to an external process heater, which GE assumes to be a methane-steam reformer.

The Westinghouse VHTR contains a number of novel features.[4] The reactor and its coolant loops are contained within a multicavity prestressed cast iron reactor vessel (PCIV). The reactor core is located within the vessel's central cavity. The vessel walls contain 12 smaller vertical cavities, or pods, in which are five high-temperature intermediate heat exchangers and circulators, five gas turbines and low-temperature intermediate heat exchangers, and two auxiliary cooling systems for shutdown and emergency cooling of the reactor. Reactor helium coolant enters and discharges from the pods through coaxial piping at the upper end of the cavity, while the intermediate loop, or secondary, helium coolant is introduced and leaves through the bottom of the pod. The PCIV has a continuous internal steel liner to act as a primary coolant boundary and leak-tight membrane. A thermal barrier and insulation system is used to limit the temperature of the liner and minimize the heat loss to the PCIV.

The process heat exchangers and the gas turbine-generators provide energy for a thermochemical water-splitting process based on the sulfur cycle.

All three vendor concepts appeared to have potential to achieve process temperatures in the range 1200 to 2000°F (649 to 1093°C). The GE concept has the most applicable operational background in that the

AVR has been operated successfully at 950°C for extended periods. General Atomic, on the other hand, has developed technology applicable to 3000-MW(t) designs and currently has the broadest technological base. The Peach Bottom reactor outlet temperature was only 715°C; however, it appears likely that the HTGR technology, with development, would be applicable to more elevated temperatures as well. The Westinghouse concept does not have a commercial technological base comparable to the other two concepts; it is based on the fuel element technology successfully demonstrated in the nuclear rocket program at temperatures up to 2200°C.

The GA design was the only one not to use an IHX; however, GA stated that the need for an IHX had not been ruled out. General Electric included an IHX, with implications of some hope that additional studies would show that it could be eliminated. Westinghouse made a case for the necessity of the IHX. Because there does not appear to be any basic design feature or innovation that would allow one concept only to use the direct system, it is assumed that this difference at the present time is one of vendor philosophy. Further analysis of reactor safety and of radioactivity transport is required to establish whether the IHX can be eliminated for some range of process choices; the issue is discussed in more detail in Sects. 4.2.3 and 4.2.5.

The process temperature of each of the reference concepts of Table 8 is indicative of the historical development of the concept. The HTGR has evolved from a strong technology program focused on steam generation. The lowest temperature required for a reasonable process efficiency, 1400°F (760°C), has been chosen to minimize extrapolation of existing designs and technology. The PBR concept is based on the technology of the AVR scaled up to commercial size; the process temperature selection of 1500°F (815°C) is a logical consequence of the AVR helium outlet temperature of 950°C, assuming that the heat transport systems can be developed. The Westinghouse concept is derived from the very advanced Nerva technology, which operated for short times at extremely high temperatures. The water-splitting process coupled to the Westinghouse reference design was based on a 1600°F peak process temperature.

4.2 Discussion of Technical Problem Areas

4.2.1 Core and fuels

The unique capabilities of the VHTR are built around the exceptional high-temperature strength of graphite and the ability to encapsulate nuclear fuels in nearly impermeable graphite coatings. All the design concepts benefit from these advantages. Core and fuels do not seriously limit VHTR temperatures, assuming continued R&D.

Maximum fuel temperatures for various process temperatures are given in Table 9, derived by ORNL with data provided by vendors. Los Alamos Scientific Laboratory independently evaluated the maximum fuel temperatures in the GA design and achieved results in reasonable agreement with that of the vendor.[26]

Maximum fuel temperature in the steam-cycle HTGR design is 2560°F (1404°C). One might infer from Table 9 that present fuel bead technology might be adequate for a 1600°F (871°C) process temperature for all designs and for 1800°F (982°C) and 2000°F (1098°C) for the GE and Westinghouse designs.

Table 9. Maximum fuel temperature, °F (°C)

Reference design	Process temperature 1200 (648)	1400 (760)	1600 (871)	1800 (982)	2000 (1098)
GA[a]	2513	2475	2562	2792	3010
GE	1730	1930	2130	2330	2530
Westinghouse	1758	1958	2158	2358	2558

[a] Does not include IHX.

Reactor operation and irradiation tests conducted to date indicate that the GA (buffered prismatic) and GE (spherical) fuel should perform well at reference conditions. The Westinghouse (extruded directly cooled prismatic) fuel, while relatively untested at VHTR conditions, may provide an excellent design following development.

Additional fuel development is desired for the following reasons:

(1) to qualify fuels for licensing of early gas-cooled reactors,

(2) to qualify recycle fuels,

(3) to maximize reactor plant availability by minimizing frequency of fuel failures and/or fission product deposition on components,

(4) for the higher-temperature VHTRs.

Avenues to be investigated in VHTR fuel development include the following:

(1) tigher fuel-particle coatings such as ZrC;

(2) improving heat conduction from kernel to coolant;

(3) development of extruded fuels and possibly of improved spheres if the PBR design is chosen.

The fuel management strategy has a very strong impact on the maximum fuel temperature. The PBR core couples a two-zone core fueling system to the once-through-then-out (OTTO) fuel cycle to minimize fuel element temperatures. With the OTTO fuel cycle, the fuel makes a single downward pass through the core (parallel to the coolant flow), and the decreasing power output in the lower half of the core coupled to the increasing gas temperature gives a fuel temperature that is very nearly flat through the latter one-half to three-fourths of its life. Similar fuel management schemes could be developed for the HTGR at the price of more compex refueling procedures.

The PBR concept introduces special problems of ball flow distribution through the core and control rod operation in the pebble bed. These features of the design must be demonstrated in model tests.

4.2.2 Materials

Maximum operating temperatures of components of proposed VHTR systems may range from 1600 to 2200°F (871 to 1204°C). For many components that will operate below 1000°F (538°C), well established commercial alloys are suitable for use. For temperatures of 1000 to 1600°F (538 to 871°C), much of the technology of conventional gas-cooled reactors which has been and is being developed is applicable to many of the components. Temperatures above 1600°F (871°C) place stringent limitations on the selection of materials. Strength properties of iron- and nickel-base alloys decrease rapidly above 1500°F (815°C), and reactivity with corrosive environments increases. In addition, some of the components in the VHTR systems are unique — in particular, the process heat exchanger, where a material will simultaneously be exposed to both high-temperature helium and process environments.

Two recent evaluations of VHTR materials[10,13] indicate that this is the key technological area which limits maximum process temperature. Metals are currently not ASME-code qualified for use above 1500°F (815°C), and very few alloys are approved at that temperature. Alloys heated to high temperature often undergo microstructural changes that generally affect their properties. This is a very serious concern for long-time high-temperature components because it can result in a loss of mechanical strength and ductility during operation.

The most important factors that must be considered in the selection of materials for this application are temperature, stress, environment, and exposure time. The stress on a particular component will depend upon the design conditions selected. For example, it is assumed that the process fluid in the process heat exchangers (PHX) will operate at a pressure close to the primary coolant (helium) pressure to keep tube stresses and creep low in the high-temperature portion of the system. The environments to which materials will be exposed are impure helium, hydrogen, steam, and various hydrocarbons. It is expected that materials should be able to withstand the above conditions for as long as 300,000 hr.

The critical factors that must be known and evaluated before a material can be recommended for use are:

(1) Mechanical properties — environmental effects and pressure vessel code requirements;

(2) Compatability — impure helium, process gases, and steam water;

(3) Structural stability;

(4) Fabricability — formability, weldability, and availability and cost.

The principal high-temperature components of a VHTR process system are the hot ducts, insulation covers, PHX, optional IHX, steam generators, and various valves and seals. Some typical materials that might be used in constructing these components are presented in Tables 10 through 13, covering the range of 1400 to 2000°F (760 to 1093°C). We have also attempted to evaluate the probability that the materials suggested will be satisfactory in these applications. It has been assumed that HTGR steam-cycle materials will satisfy most requirements for the 1200°F process temperatures.

Table 10 lists the candidate materials for a system that provides heat for a 1400°F (760°C) process temperature. For this application, several candidate materials are available for all of the components. The major problem areas are the hot ducts and PHX, because none of the candidate materials have been Code approved. In addition, materials compatibility with the process environment is unknown in most cases. Nonetheless, considering experience with petrochemical processes, we feel that there is a high probability that suitable materials can be obtained and qualified for components to be used in a 1400°F (760°C) process system.

If the process temperature increases to 1500°F (815°C), the hot duct will operate at 1650–1850°F (899–1010°C), depending on the design. The PHX and IHX components will also operate in this same range, and the probability of finding satisfactory materials decreases markedly relative to the 1400°F (760°C) process, primarily because important material properties are unknown.

Table 10. Material candidates for critical components of the 1400°F process temperature VHTR

Component	Maximum operating temperature range (°F)	Typical candidate materials	Potential problem areas	Probability of ultimate applicability
		Without IHX		
Hot-duct insulation covers	1550-1650	Solid-solution-strengthened Ni-base alloys such as Hastelloy X, Hastelloy S, and Inconel 617	Thermal stability; effects of helium environment; not ASME Code approved; cobalt contamination (Inconel 617)	Good
PHX	1550-1650	Same as above	Same as above; effects of process environment	Potentially good, but effect of process environment largely unknown
Steam generator	1050-1250	Incoloy 300H, 304 SS, stabilized high-alloy ferritics	Effects of helium and steam environments; Code approval of high-alloy ferritics	Excellent
Valves and seals	1350-1450	Ni-base alloys and austenitic steels such as Inconel 718 and 347 SS	Effects of environment; thermal stability; Code approval; wear and galling problems	Good
		With IHX		
Hot-duct insulation covers	1650-1750	1. Same as without IHX 2. Mo-base alloy 3. Advanced super alloys 4. Ceramics	1. Same as without IHX, strength 2. Fabricability, environmental effects, Code approval 3. All aspects from alloy development through Code approval 4. Fabricability, shock resistance, environmental effects, Code approval	1. Fair 2. Potentially good, but unknown 3. Unknown 4. Unknown
IHX	1650-1750	Same as above	Same as above	Same as above
PHX	1500-1600	Same as PHX without IHX	Same as PHX without IHX	Potentially good but effect of process environment largely unknown
Steam generator	1050-1250	Same as steam generator without IHX	Same as steam generator without IHX	Excellent
Valves and seals	1500-1600	Ni-base alloys, austenitic stainless steels	Effects of environment; thermal stability; Code approval of materials; wear and galling problems	Fair to good

Table 11. Material candidates for critical components of a 1500°F process temperature VHTR

Component	Maximum operating temperature range (°F)	Typical candidate materials	Potential problem areas	Probability of ultimate applicability
		Without IHX		
Hot-duct insulation covers	1650-1750	1. Solid-solution-strengthened Ni-base alloys 2. Mo-base alloys 3. Advanced superalloys 4. Ceramics	1. Thermal stability, effects of environment, ASME Code approval, strength 2. Fabricability, enviornmental effects, Code approval 3. All aspects from alloy development through Code approval 4. Fabricability, shock resistance, environmental effects, Code approval	1. Fair 2. Potentially good but many unknowns 3. Unknown 4. Unknown
IHX	1650-1750	Same as above except omit Mo-base alloys	Same as above plus effects of process environment	As above
Steam generator	1125-1325	Alloy 800H, 304 SS, stabilized high-alloy ferritics	Effects of helium and steam environment; Code approval of high-alloy ferritics	Good to excellent
Valves and seals	1450-1550	Ni-base alloys, austenitic stainless steels	Effects of environment, thermal stability, Code approval for >1500°F applications (class 2, 3), and all class 1 uses, wear, and galling	Good
		With IHX		
Hot-duct insulation covers	1750-1850	Such as hot duct without IHX except solid-solution Ni-base alloys	Same as hot duct without IHX	Same as hot duct without IHX
IHX	1750-1850	Same as above	Same as above	Same as above
PHX	1600-1700	Same as PHX without IHX	Same as PHX without IHX	Fair to good but applicability of ceramics and advanced superalloys unknown
Steam generator	1125-1325	Same as steam generator without IHX	Same as steam generator without IHX	Good to excellent
Valves and seals	1600-1700	1. Same as valves and seals without IHX but more restrictive 2. Cast Ni-base alloys	1. Effects of environments, thermal stability, Code approval, wear and galling, strength 2. Same as above but perhaps more serious stability problems and fabricability questions	1. Fair to good 2. Fair

Table 12. Material candidates for critical components of a 1600°F process temperature VHTR

Component	Maximum operating temperature range (°F)	Typical candidate materials	Potential problem areas	Probability of ultimate applicability
		Without IHX		
Hot-duct insulation covers	1750-1850	1. Advanced superalloys 2. Mo-base alloys 3. Ceramics	1. All aspects from alloy development through ASME Code approval 2. Fabricability, environmental effects, Code approval 3. Same as (2) plus shock resistance	1. Unknown 2. Potentially good but unknown 3. Unknown
PHX	1750-1850	Advanced superalloys and ceramics	Same as above plus process environment	Unknown
Steam generator	1400-1500	Austenitics	Effects of helium and steam environment, Code approval	Good
Valves and seals	1500-1650	Ni-base and high-alloy austenitic steels	Effects of environment, thermal stability, strength, Code approval, wear and galling	Fair to good
		With IHX		
Hot-duct insulation covers	1850-1950	1. Mo-base alloys 2. Ceramics	1. Fabricability, environmental effects, Code approval 2. As above plus shock resistance	1. Potentially good but unknown 2. Unknown
IHX	1850-1950	Same as above	Same as above	Same as above
PHX	1700-1800	1. Advanced superalloys 2. Ceramics	1. Alloy development through Code approval 2. Fabricability, environmental effects, Code approval, shock resistance	1. Unknown 2. Unknown
Steam generator	1400-1500	Austenitics	Effects of helium and steam environment, Code approval	Good
Valves and seals	1700-1800	1. Advanced superalloys 2. Cast superalloys 3. Ceramics	1. Alloy development through Code approval 2. Environment, stability, fabricability, wear and galling, Code approval 3. Same as (2) plus shock resistance	1. Unknown 2. Fair 3. Unknown

Table 13. Material candidates for critical components of 1800°F and 2000°F process temperature VHTR

Component	Maximum operating temperature range (°F)	Typical candidate materials	Potential problem areas	Probability of ultimate applicability
		Without IHX (1800°F)		
Hot-duct insulation covers	1950-2050	1. Mo-base alloys 2. Ceramics	1. Fabricability, environmental effects, Code approval 2. Same as (1) plus shock resistance	1. Potentially good, but unknown 2. Unknown
PHX	1950-2050	Ceramics	Same as (2) plus process environment compatibility	Unknown
Valves and seals	1750-1850	1. Advanced superalloys 2. Cast superalloys 3. Ceramics 4. Mo-base alloys	1. Alloy development through Code approval 2. Environment, stability, fabricability, wear and galling, Code approval 3. Same as (2) plus shock resistance 4. Same as (2)	1. Unknown 2. Fair 3. Unknown 4. Poor to unknown
		With IHX (1800°F)		
Hot-duct insulation covers	2050-2150	Same as hot duct without IHX	Same as hot duct without IHX	Same as hot duct without IHX
IHX	2050-2150	Same as above	Same as above	Same as above
PHX	1900-2000	Ceramics	Same as PHX without IHX	Unknown
Valves and seals	1900-2000	1. Cast superalloys 2. Mo-base alloys 3. Ceramics	1. Same as valves and seals without IHX plus strength 2. As without IHX 3. As without IHX	1. Poor to fair 2. Poor to unknown 3. Unknown
		With and without IHX (2000°F)		
Hot-duct insulation covers	2250-2350	Ceramics and Mo-base alloys	All problem areas apply, strength of Mo-base suspect at upper end	Unknown
IHX	2250-2350	Same as above	Same as above	Unknown
PHX	2100-2200 (2150-2250)	Ceramics	All problem areas apply	Unknown
Valves and seals	2100-2200 (1950-2050)	Same as valves and seals for 1800°F process temperature with IHX		

At process temperatures of 1600°F (871°C) and higher, molybdenum or molybdenum-base alloys, ceramics, and/or ceramic-coated materials will undoubtedly be required for the hot ducts and the IHX, and in some cases for the PHX. Each of these materials poses difficult fabrication and joining problems. In addition, the probability of compatability problems increases as temperature is increased. Since we cannot as yet identify specific candidate materials for these higher temperatures, the chances of constructing such a system cannot be assured.

4.2.3 Coupling of reactor and process: potential need for an IHX

The decision on whether to use an IHX has important repercussions on the public acceptance, feasibility, cost, and safety-environmental effects. These questions are sufficiently complex that a good deal of time and possibly some actual licensing actions will be required for complete resolution.

Proponents of the methane-steam reformer type of coupling have concluded that this process can be carried out without an IHX.[2,25] Their analyses show that the radioactivity in the product gas is negligible and that the reactor safety problems can be resolved.

The other nuclear process couplings, steam-coal gasifiers and thermochemical hydrogen process, are generally believed to require IHXs. The failure of process heat exchangers in these systems could significantly damage the reactor.

The advantages of having an IHX are that it would:

(1) reduce or eliminate the transport of radioactivity into the product;

(2) reduce or eliminate the ingress of water and hydrogen into the reactor;

(3) improve maintainability of the process heat exchanger;

(4) reduce reliability demanded of the PHX;

(5) reduce possible hazardous interactions of process and nuclear plant, such as explosions that could damage reactor equipment;

(6) reduce size of the PCRV and possibly of PCRV penetrations;

(7) improve public acceptance.

The disadvantages are:

(1) the cost — process heat costs may be increased by up to 20%;

(2) need to develop higher-temperature materials (by 50–100°C) for the primary system to achieve the same process temperature or to accept a lower efficiency consistent with reduced process temperatures;

(3) need to develop the IHX and high-temperature containment valves operating in the secondary helium;

(4) more operating components, increasing probability of plant outages.

The analysis of the IHX is further complicated by the spectrum of choices between a "pure" primary process heat exchanger and a "pure" IHX. This spectrum includes at least the following:

(1) primary PHX inside the reactor vessel;

(2) primary PHX inside the containment building but outside the reactor vessel; this would improve maintainability;

(3) IHX-PHX inside the reactor vessel consisting of double-walled tubes with helium pressure in between;[27] this could reduce steady-state material transport between process and nuclear systems, but may not improve safety scenarios;

(4) IHX for process, but steam generator still inside the reactor vessel and directly coupled;

(5) IHX inside PCRV, and PHX inside containment vessel;

(6) IHX inside PCRV; PHX and steam generator outside containment vessel ("pure" IHX system).

Any VHTR development program will have to include development of the IHX, since it may be required. Because the IHX raises helium outlet temperatures by 50 to 100°C to achieve a given process temperature, it makes the materials development problem more difficult, as discussed in the previous section.

The double-walled PHX inside the reactor vessel deserves special attention as a potential means of controlling radioactive contamination of the process side without introducing the technical problems and cost of the IHX into a given VHTR plant.

4.2.4 Reactor components

The GA and GE concepts use large conventional prestressed concrete reactor vessels that are typical of those currently in use for gas-cooled reactors. These units are within current technology but require completion of present R&D, particularly on penetrations and head closures, and completion of a scale model test to prove the final design.

The Westinghouse concept specified a PCIV. The recommended design is that of gray cast iron sections (of 60 to 65 tons each) mechanically assembled around a welded steel liner. The vessel is prestressed circumferentially and axially in the same manner as the PCRV with which the PCIV is compared in this study. The primary advantages cited for choosing cast iron over concrete are that cast iron has a compressive strength 20 times that of concrete, whereas its density and Young's modulus are three times that of concrete. It is also stated that the use of cast iron will result in a superior structure with reduced weight and size and reduced sensitivity to overtemperature incidents. It is felt that the PCIV concept offers some potential advantages and merits further study, but it would require considerable R&D. The results of the ongoing development at Siempelkamp Giesserei KG, Krefeld, Germany, should be factored into the program.

An insulation system is required to protect the pressure vessel from the hot coolant gas and to minimize the heat losses from the primary coolant and thus the heat load on the pressure vessel cooling system. There are two basic approaches to the problem. The first method is to use a high-temperature insulation attached to the inside of the ducts and cavities and which is exposed to the maximum coolant temperatures. The second method, which reduces the insulation requirements, is to use concentric ducting with the hot helium in the inner duct and the cooler return helium in the outer annulus.

Attaching the insulation to the inner surface of the reactor vessel liner is the method currently used with gas-cooled reactors in the United States. The ducting insulation consists of a blanket of alumina-silica or a combination of alumina-silica and pure silica fibers held to the liner by metal cover plates and is limited to a continuous average operating temperature of 1500°F and local hot spots or streaks of about

1700°F. Additional insulation in the form of silica blocks capable of withstanding higher localized temperature is used on the bottom of the reactor cavity below the core. Thus, the currently used insulation materials and techniques are limited to a reactor outlet temperature of about 1500°F or a process temperature of about 1300°F.

In addition to the temperature and thermal conductivity requirements, the insulation must be capable of withstanding a system depressurization accident without damage to the insulation that would interfere with the auxiliary cooling system; that is, the insulation must not be displaced in such a manner as to block flow passages essential to the removal of the decay heat following all postulated accidents.

The problem associated with the insulation of the ducting and cavities is primarily one of developing an adequate mechanical design, using currently available insulating materials. The development program will require tests to prove the adequacy of the design in regard to heat losses in a flowing system, noise and vibration effects, and system depressurization accidents.

The gas circulators required for the VHTR do not appear to offer difficult development problems.

The current U.S. gas-cooled reactors use isolation valves for the containment system and the main steam lines, split butterfly-type valves for the core auxiliary cooling system, and shutoff valves to prevent flow reversal through the primary coolant loops. These valves or adaptations should be adequate for the VHTR. The VHTR would also require isolation valves for an intermediate helium loop. The GE concept for these valves is a rotating ball type of design with a closing time of the order of 15 to 30 sec. Materials of construction include a combination of Inconel, carbon, and graphite. Some cooling of the valve body might be required which could be done by a low-temperature helium stream; internal insulation would also be used. A development and proof testing program would be required for these valves.

The Westinghouse system, using gas turbines, will require additional primary systems valves for control and overspeed protection of the turbomachinery, as in the HTGR–gas turbine concept. Large, quick opening valves will probably be required to protect the turbine from excess speed in the event of a loss of electrical load on the unit. Smaller valves, or variable vanes, for speed control will probably also be required. We believe that the operating requirements for these controls will be more severe than for the intermediate loop isolation valves and will require an extensive development and proof testing program.

The high-temperature intermediate heat exchangers are major items affecting the near-term feasibility of the VHTR and will be the key items in the development of the concept. For process temperatures in the range of 1400 to 1600°F (760 to 871°C), the temperature requirements for the IHX are in the range of 1600 to 1850°F (871 to 1010°C), which is borderline for the available superalloys. Although there are a number of candidate materials for this temperature range, a major development program will be required to prove their compatibility with the primary coolant and to obtain sufficient physical data to qualify the materials to some form of American Society of Mechanical Engineers (ASME), Nuclear Regulatory Commission (NRC), or other codes or standards.

4.2.5 Fission product behavior

Transport of fission products along the release pathway into the coolant circuit and, in a large measure, the distribution along the coolant circuit are primarily temperature-dependent processes. Fuel failure mechanisms, on the other hand, exhibit a complex interrelationship between temperature, temperature gradient, irradiation history, chemical composition, and, possibly, time.

All designs attempt to maintain fission product transport at an acceptable level by limiting fuel temperature and by providing gas cleanup systems. The GA and GE designs provide an unfueled graphite barrier between fuel kernels and coolant. Westinghouse indicates that an unfueled barrier could be extruded in their design if necessary. Irradiation experience in the AVR, in the Peach Bottom HTGR, and in test loops indicates that the fission product content of the coolant is low. Nevertheless, the designer must carefully consider potential fission product release paths, both during normal operation and following failures.

Tritium is another radioactive species formed in gas-cooled reactors, and is formed in the HTGR system in three ways: by ternary fission in the core, by neutron reaction with lithium impurities in core materials, and by neutron reaction with ^{3}He in the helium coolant. Tritium from the first two sources is largely retained within the coated fuel particles, so that the ^{3}He reaction becomes the principal source of tritium in the coolant. Tritium will readily diffuse through metals at VHTR temperatures if a concentration gradient exists and if there is no adherent oxide film. This poses a threat of contaminating the process stream unless there is an effective oxide barrier and/or a tritium removal mechanism such as exchange with hydrogen in steam. The designer must consider tritium behavior as one of the elements in analyzing the need for an IHX.

4.2.6 Safety and environmental considerations

Section 4.2.3 has discussed the need for an IHX, which is an issue fundamentally related to safety-environmental considerations. The issue creates a challenge to the designer-developer of the VHTR to perform thorough analysis of safety-related problems at a relatively early state of the development program.

Prior to the licensing of a reactor for construction, it is necessary for the applicant to submit a preliminary safety analysis report (PSAR) and an environmental report (ER). These reports must prove the feasibility of the proposed nuclear system to operate within legal and regulatory constraints at the proposed site. Prior to the granting of an operating license, a final safety analysis report (FSAR) and final environmental impact statement (FES) are issued and approved. The nuclear process system will have to go through this regulatory procedure. Emphasis in the PSAR and the FSAR will be on the nuclear reactor, but it will be necessary to show that the process does not reduce nuclear safety factors. The ER and the FES will have to deal with all impacts of the nuclear process system, will have to demonstrate a demand for the products of the system that can best be supplied by the proposed facility, and will have to show that the benefits of the system exceed the costs.

While the VHTR will operate at a higher temperature than the steam-generating gas-cooled reactor, safety considerations are expected to be similar. Deployment of the HTGR for power production would resolve many of the safety and environmental questions pertaining to the VHTR, other than those pertaining to the IHX and the possible interactions with process. Some of the special safety analyses that will be required of the VHTR will include:

(1) Sudden failure of heat exchanger tubes. It will be necessary to show that the product will not be excessively contaminated and that the reactor will not be seriously impaired.

(2) Process leak to containment. It will be necessary to avoid explosive mixtures in the containment. This may require an inert atmosphere in the containment building.

(3) Steam ingress. The high graphite temperatures of the VHTR will accelerate steam-graphite reactions. It will be necessary to ensure that critical graphite structures, such as core supports, will not be selectively damaged by steam.

Some of the special environmental considerations of the VHTR include:

(1) Radioactivity emission to environment. Design of fuel and of gas cleanup systems must take into account the higher temperatures of the VHTR relative to steam-cycle reactors.

(2) Radioactivity in product. Steady-state leakage of fission products and tritium into products such as synthetic fuels must be kept below NRC regulations.

(3) General impacts of nuclear process systems. The nuclear synthetic fuels system has cumulative impacts on land, water, air, and society which must be compared with the impacts of alternatives. There are clear advantages with respect to the amount of coal mining and

transport disturbance and from less air pollution. Disadvantages accrue from the impact of a larger national nuclear fuel cycle and from the local nuclear safety risks.

4.3 Economics of the Nuclear Process Heat Supply

4.3.1 Nuclear process heat cost

Oak Ridge National Laboratory, with assistance from United Engineers and Constructors, has estimated VHTR process heat cost. Figures 11 and 12 give the range of estimated costs of nuclear process heat when supplied from a 3000-MW(t) VHTR, considering the presence or absence of an intermediate heat exchanger as a parameter. The economic ground rules used in obtaining these estimates are given in Table 14.

Table 14. Economic ground rules employed in VHTR evaluation

Reference plant size, MW(t) — 3000

Process heat cost is evaluated assuming all energy from the reactor has the same value independent of the form of the energy or how it is used

July 1974 dollars — no escalation

80% plant factor

15 and 25% fixed-charge rate

Capital costs include: Direct costs
Indirect costs
Interest during construction — 8%/year

Fuel cycle cost basis: U_3O_8, \$/lb — 30
Enrichment, \$/SWU — 75

O&M costs — 9×10^6 \$/year

These costs are based on preliminary, conceptual designs and rely heavily on vendor information. The costs that are presented may change as a result of further research and development and of more detailed design.

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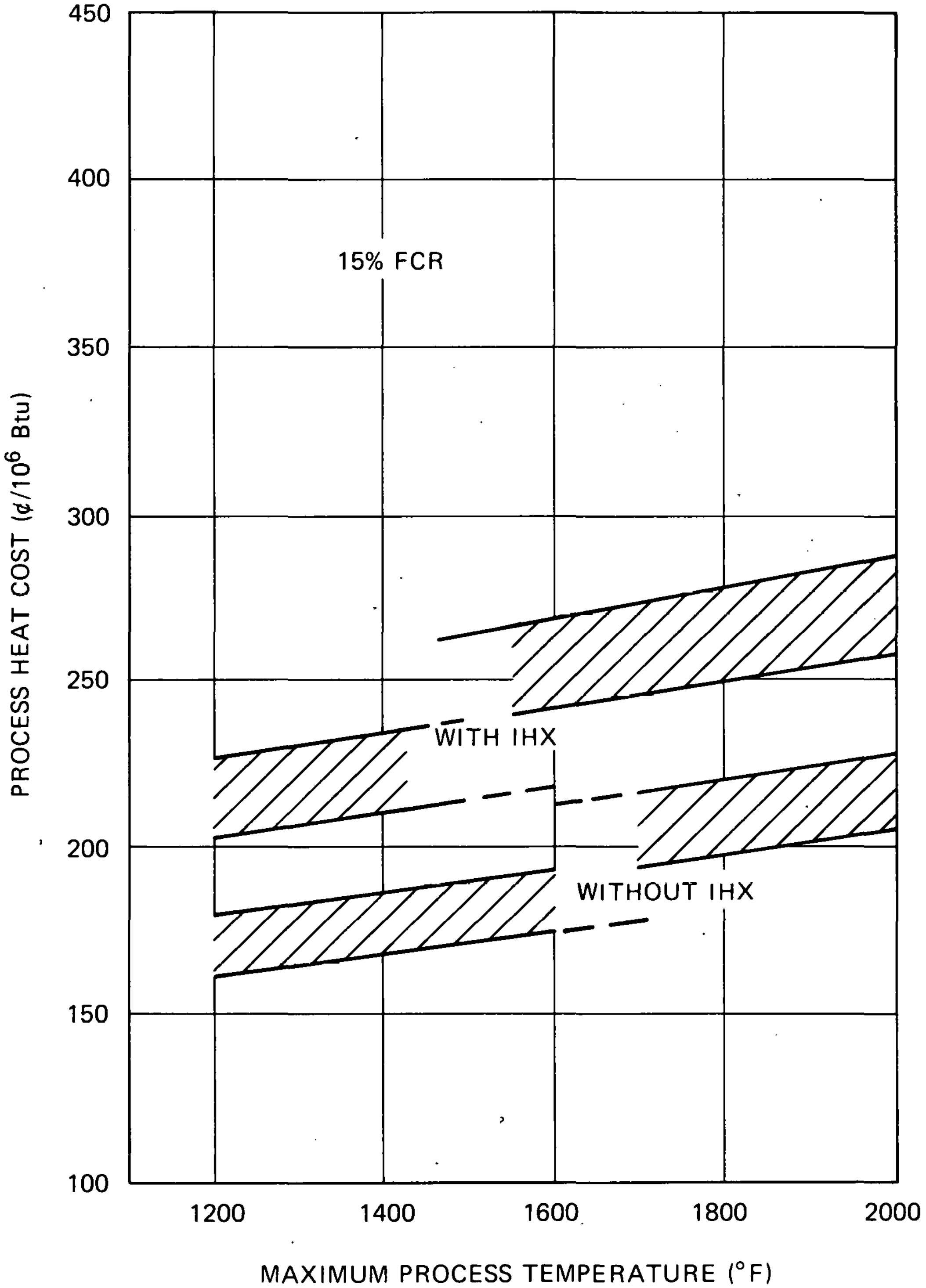

Fig. 11. Process heat cost from a VHTR vs maximum process temperature, utility financing.

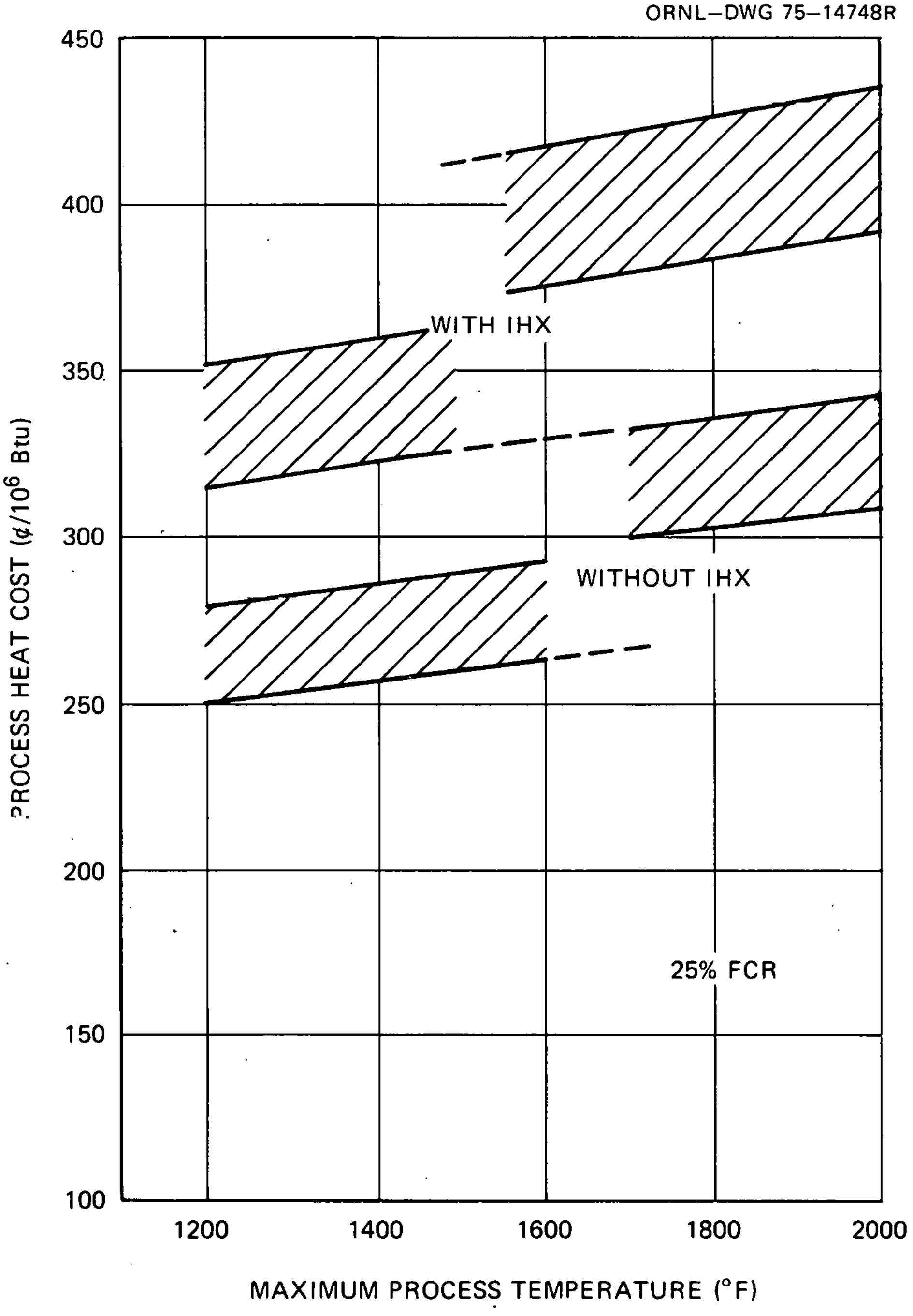

Fig. 12. Process heat cost from a VHTR vs maximum process temperature, industrial financing.

The general trend of increasing heat costs with increasing temperature results from increased costs of materials and components and from more elaborate systems to maintain the fuel at acceptable temperatures. The discontinuity in cost above 1600°F process temperature stems from the need to introduce exotic high-temperature alloys and/or ceramics into the high-temperature components.

While process heat costs increase with temperature, the usefulness of the process heat is also increased. Table 15 illustrates the effect of maximum process temperature on the efficiency of a typical nuclear coal conversion process (production of hydrogen via the General Atomic/ Stone and Webster process). Efficiency is expected to increase from 52% at 1200°F maximum process temperature to 69% at 2000°F.

The effect of size on energy cost is given in Fig. 13. A recent design study by GE of a 500 MW(t) PBR heat source indicated heat costs in the range of \$4 to \$6/10^6 Btu.[28] There is clearly a significant advantage of scale in VHTR process heat cost.

Another important aspect of VHTR economics is that the capital cost predominates in relation to fuel cost, as indicated in the following breakdown of costs of a 3000-MW(t) plant (with IHX, 1600°F process).

	15% Fixed charge rate		25% Fixed charge rate	
	¢/MBtu	%	¢/MBtu	%
Capital cost	167	74.5	278	80.5
O&M	13	6	13	4
Fuel cycle	44	19.5	54	15.5
Total	224	100	345	100

Table 15. Estimate of the efficiency of hydrogen production plants using the General Atomic/Stone and Webster process

Maximum process temperature, °F	1200	1400	1600	1800	2000
Heat inputs, 10^9 Btu/hr					
Nuclear	10.24	10.24	10.24	10.24	10.24
Coal	9.76	18.47	19.40	20.85	21.79
Hydrogen production rate, MMscfd[a]	520	763	882	949	1092
Total gas product production, 10^9 Btu/hr	8.53	15.04	16.57	17.66	18.78
Liquid fuels production, 10^9 Btu/hr	1.47	2.76	2.86	3.09	3.23
Export electric power, MW	138	57	31	18	7
Efficiency, %[b]	52	63	66	67	69

[a] At 32°F, 1 atm.

[b] Defined as fuel and electricity outputs/heat inputs.

Source: *Studies of the Use of High-Temperature Nuclear Heat from an HTGR for Hydrogen Production*, Report GA-A13391, General Atomic Company, September 30, 1975 (prepared under contract for NASA).

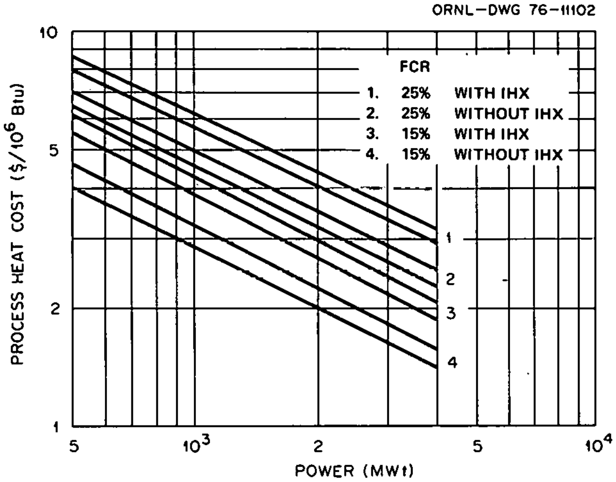

Fig. 13. Effect of size on energy cost — 1400°F process temperature (1 — 25% FCR with IHX; 2 — 25% FCR without IHX; 3 — 15% FCR with IHX; 4 — 15% FCR without IHX).

4.3.2 Projected costs for fossil-fueled process heaters

The foregoing estimates may be compared with estimates of process heat cost using oil and coal shown in Figs. 14 to 17 respectively. The process heat costs displayed in Figs. 11 to 17 do not take into account the relative usefulness of the process heat delivered from the respective sources. Generally, nuclear process heat is expected to be competitive with oil and with coal in many locations.

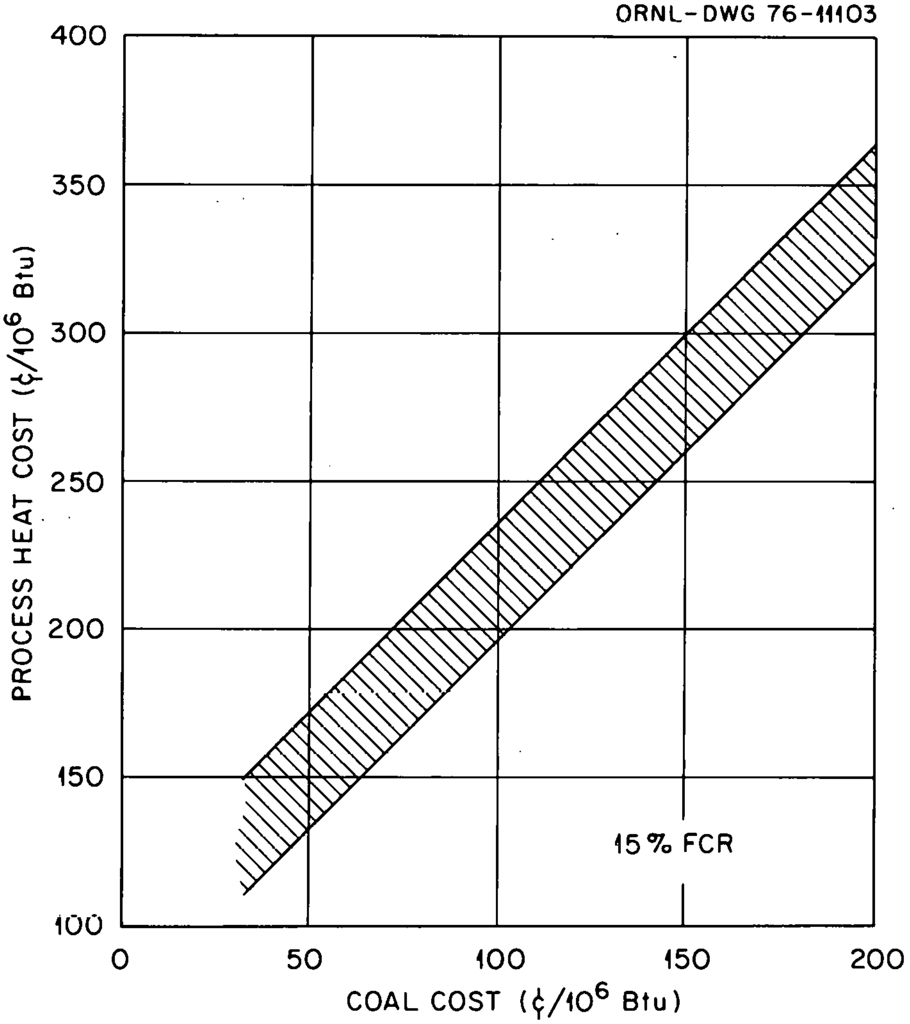

Fig. 14. Cost of process heat from a coal-fired process heater, utility financing.

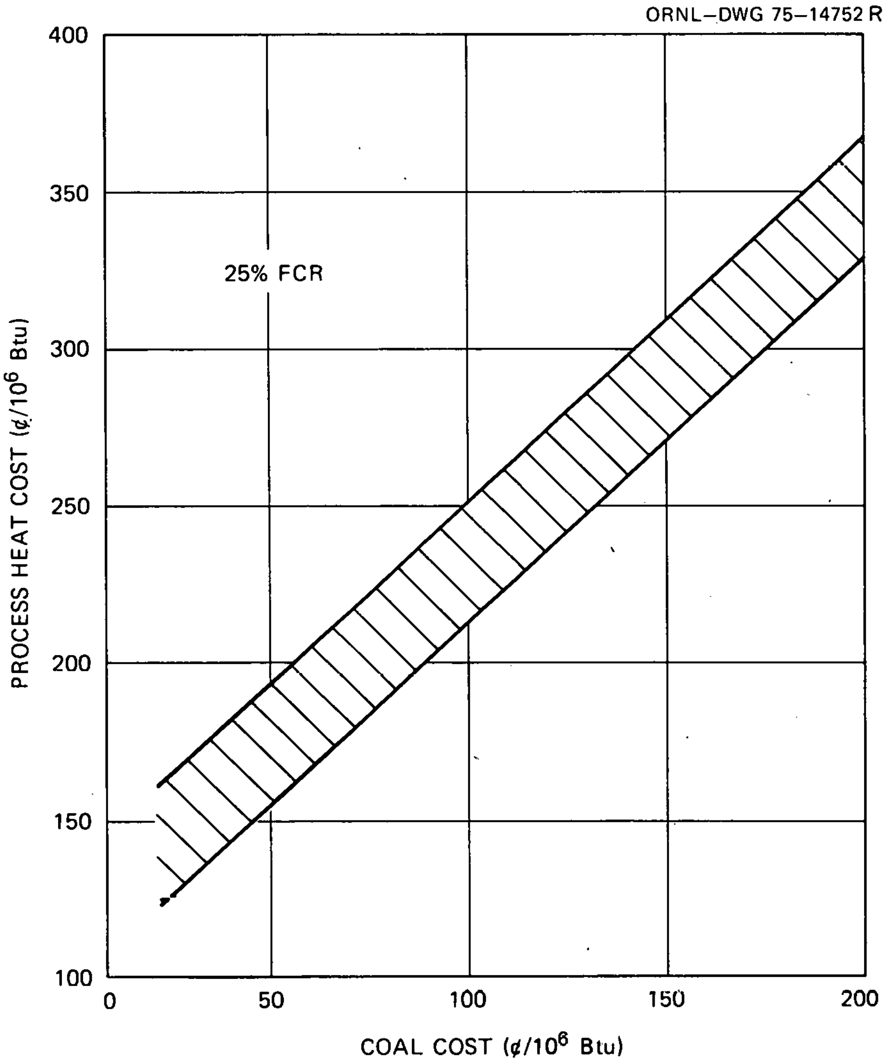

Fig. 15. Cost of process heat from a coal-fired process heater, industrial financing.

Process heat cost from a coal-fired process heater is based on that from a coal-fired boiler. The minimum cost projected for the process heat is based on an 80% boiler efficiency and the capital and O&M costs of a conventional coal-fired boiler. The cost of stack gas cleaning equipment, estimated at 32¢/10^6 Btu, is also included since much of the coal to be used for synthetic fuels production is high-sulfur coal.

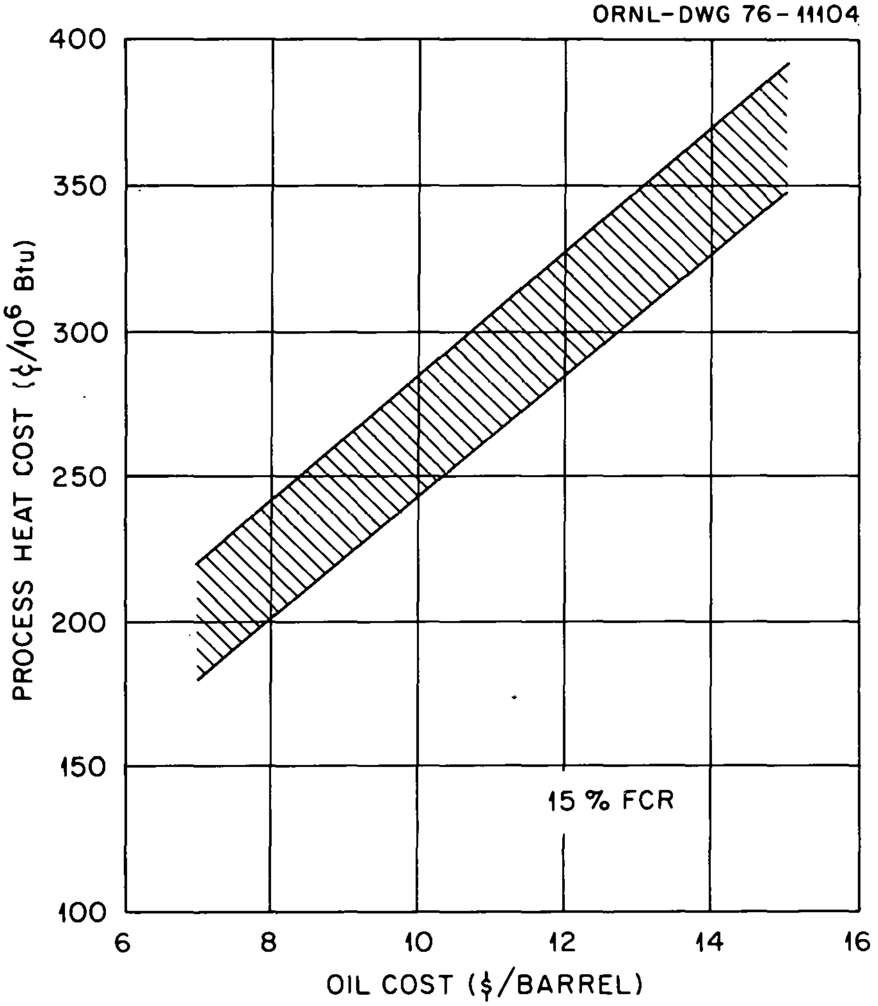

Fig. 16. Cost of process heat from an oil-fired process heater, utility financing.

The process heat cost is presented in Figs. 14 and 15 for a representative range of coal costs from 50¢/10^6 Btu to 175¢/10^6 Btu. Costs are presented on this basis rather than dollars per ton because the heating value of coal varies substantially. The following are representative values.

Rank	Heating value 10^6 Btu/ton
Bituminous	24
Subbituminous	17
Lignite	13.5

The band width of these costs is based on the assumption that the capital and O&M costs for the process heater could be a maximum of approximately twice that of a conventional boiler.

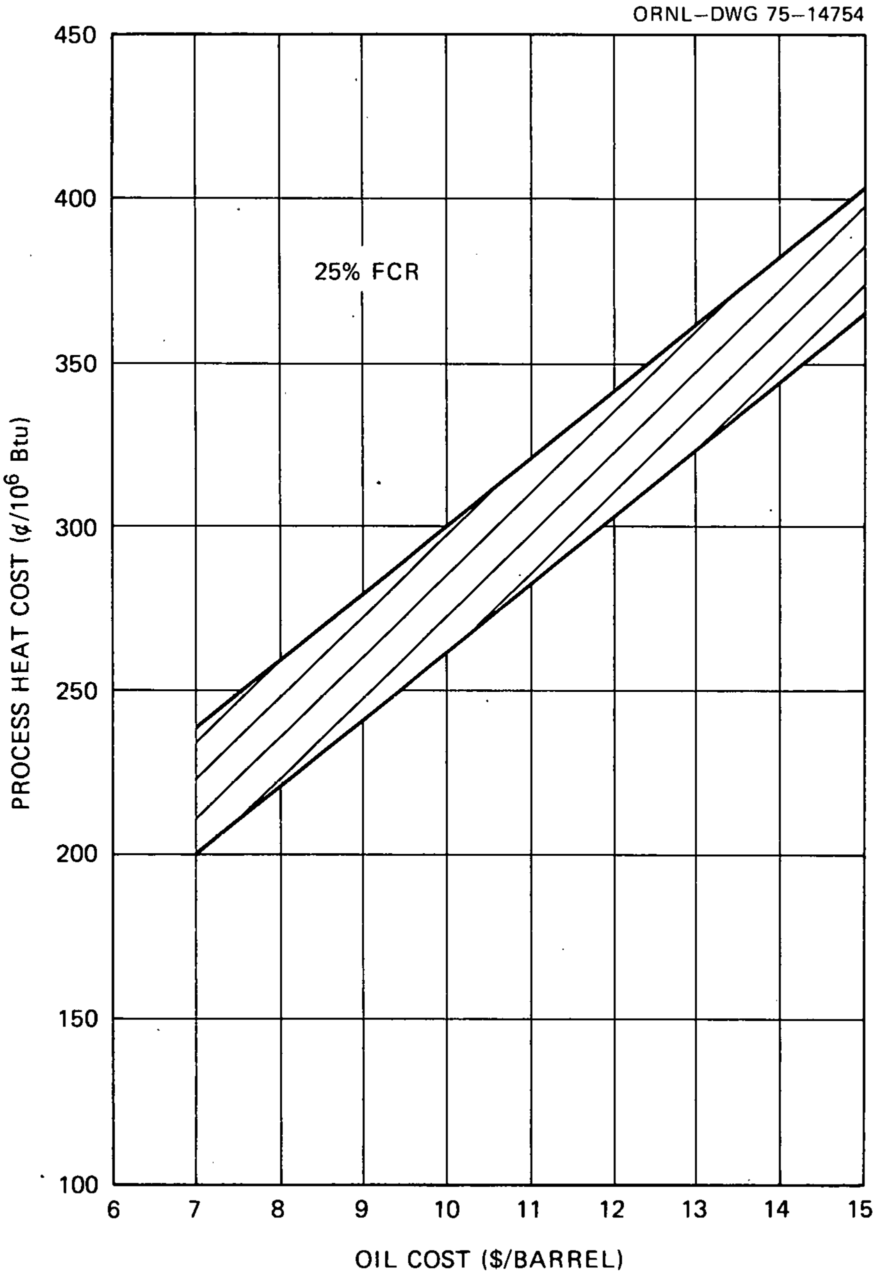

Fig. 17. Cost of process heat from an oil-fired process heater, industrial financing.

Process heat costs from oil-fired process heaters are presented in Figs. 16 and 17. These costs were developed on the same basis as the coal-fired process heater using a range of oil costs from a minimum of \$7/bbl (from *Project Independence*) to a maximum of \$15/bbl.

4.3.3 Fuel cycle considerations

4.3.3.1 The thorium-uranium fuel cycle

The gas-graphite reactor is an efficient converter reactor and is extremely flexible with regard to the use of alternative nuclear fuels. The fuel cycle most commonly proposed by GA and by the German developers of these reactors is the thorium-uranium cycle (Fig. 18). This fuel cycle has the advantages of lowest cost and of higher conversion ratio of fertile thorium to ^{233}U fuel in comparison to the conversion of fertile ^{238}U to plutonium, assuming development of thorium fuel recycle technology. These advantages are due to the superior nuclear characteristics of ^{233}U relative to either ^{235}U or plutonium in the neutron energies typical of gas-graphite reactors.

The problems of ^{235}U and thorium-containing fuel element preparation and design have been thoroughly addressed. Fuel elements have been fabricated by commercial vendors for both HTGR and PBR designs. These elements perform well in reactors. The fabrication of graphite fuels at costs assumed in the economic analysis will require the establishment of large-scale manufacturing facilities, consistent with the deployment of many graphite-fueled reactors.

The reprocessing of spent graphite fuels requires a special head-end process to extract fuel materials and fission products quantitatively and to put them into aqueous solution. This step is followed by a relatively conventional solvent extraction process to separate uranium, thorium, and fission product wastes.

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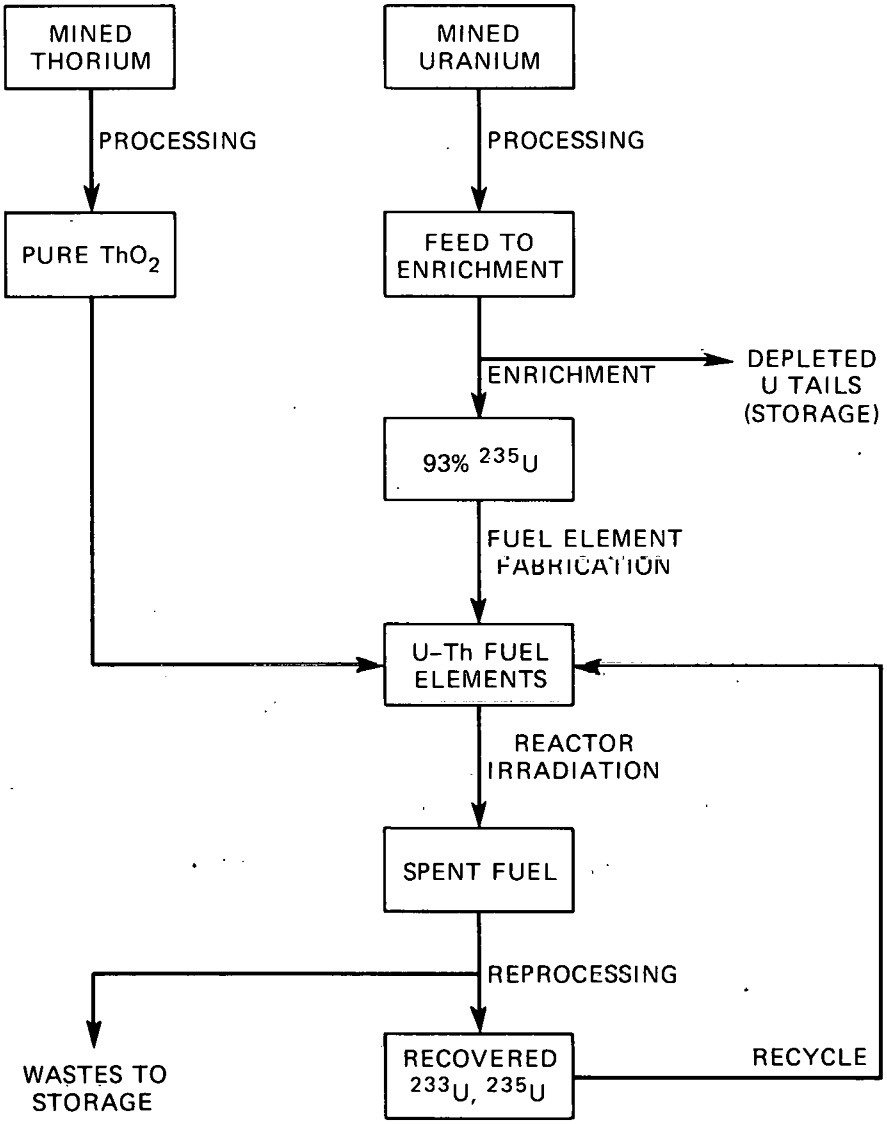

Fig. 18. Thorium-uranium fuel cycle.

The fuel recycle step is a difficult one in that the bred ^{233}U is contaminated with ^{232}U, whose daughters are highly radioactive, requiring remote handling behind shielding. The ERDA has built some applicable laboratory facilities at Oak Ridge and is considering a proposal for the construction of a pilot plant. This part of the fuel cycle will probably be very costly until many graphite-fueled reactors are being operated in the recycle mode.

Ultimate waste disposal from the uranium-thorium cycle would be similar to that from light-water-reactor fuel cycles. There would probably be fewer long-lived actinide isotopes to store. The ERDA currently is speeding up the development of waste disposal facilities for all nuclear fuels.

4.3.3.2 Alternate fuel cycles

Another fuel cycle for the VHTR would involve the use of slightly enriched uranium fuel as proposed by GE.[3] This fuel cycle produces some plutonium in the spent fuel. This approach could make use of some light-water-reactor fuel cycle facilities, but fuel fabrication and spent fuel dissolution facilities would be similar to those of the thorium-uranium cycle. Another option would be indefinite storage of the spent fuel.

The HTGR/VHTR concepts can be made into more efficient users of uranium by taking steps that would raise the conversion ratio and minimize the fissile inventory of the reactor and associated fuel cycle facilities. Such steps include higher thorium loadings, reduced fuel lifetimes, more frequent refuelings, and lower power densities. The initial (startup) demand for U_3O_8 would increase due to a need for higher fissile loadings to compensate for the increased absorptions in the thorium. Less uranium ore will be needed during operation, however, due to the decreased fuel depletion. The overall economics are a balance between reduced fuel depletion costs, higher fuel fabrication, reprocessing, and, possibly, working capital costs. A careful analysis of these higher conversion ratio systems and the associated fuel cycle facilities is needed in an environment of rising uranium prices.

4.3.3.3 Fuel cycle parameters and economics

The gas-graphite reactors are intermediate in fuel economy between light-water reactors and the LMFBR, as shown in Table 16.

Table 16. Typical reactor fueling requirements and costs

Reactor type	Specific inventory [kg fissile/MW(t)]	Conversion ratio	Typical Fuel cycle cost[a] (¢/MBtu)
Light-water reactor	0.85	0.6	40
HTGR — ^{233}U recycle	0.6	0.65	42
HTGR — no recycle	0.7	0.6	44
HTGR — high conversion[b]	0.7-1.0	0.8	40-51
LMFBR	0.80	1.15	15

[a] Based on:
(1) U_3O_8 at \$30/lb — enrichment at \$75/separate work units (SWU); ^{233}U at \$38/g; and $^{239,241}Pu$ at \$27/g.
(2) Fuel fabrication — LWR (\$75/kg); HTGR (\$300/kg); and LMFBR (\$250/kg).
(3) Fuel reprocessing — \$120/kg. (There is considerable uncertainty regarding fuel reprocessing costs. The value of \$120/kg was a ground rule in the vendor studies. Real costs will almost certainly be higher than this.)
(4) Utility finance basis.

[b] The lower values are estimated if refueling frequency can be increased without significant downtime penalty. The higher values are estimated for systems in which the conversion ratio is increased by increasing the thorium loading.

The sensitivity of VHTR fuel cost to uranium cost is shown in Fig. 19.

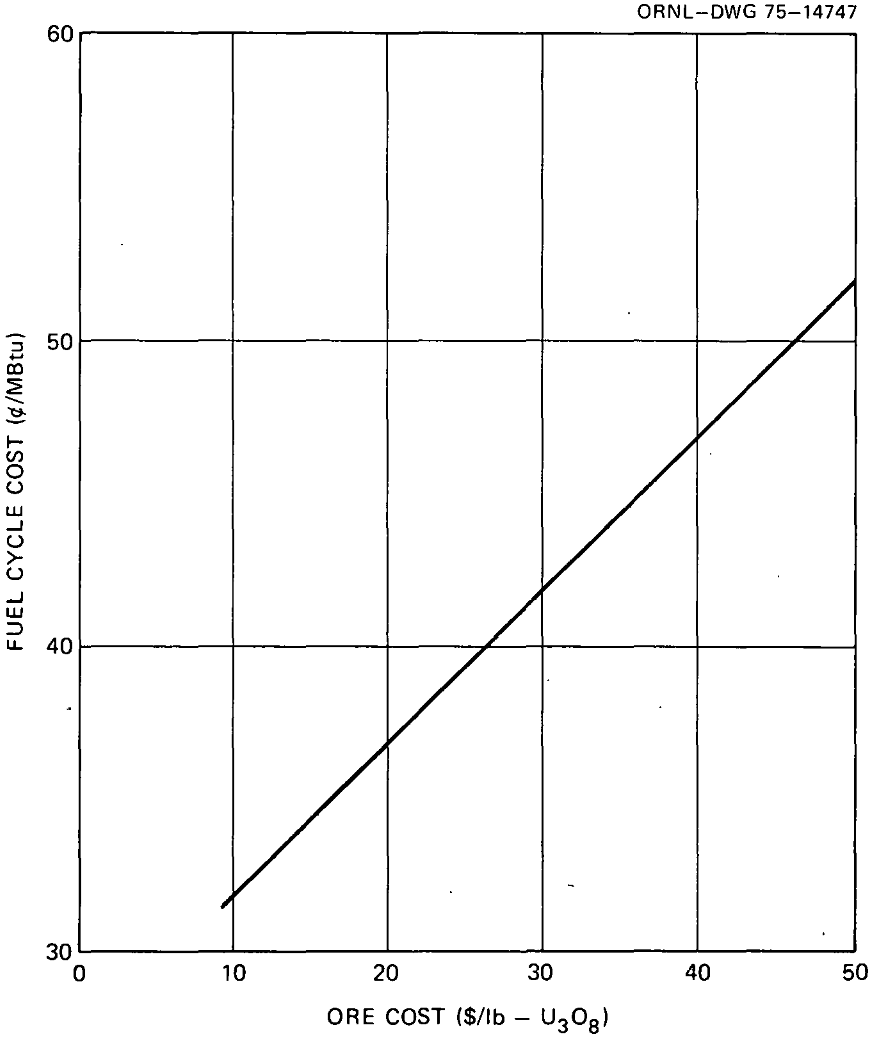

Fig. 19. VHTR fuel cost, thorium-uranium cycle.

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5. SUMMARY OF APPLICABLE PROCESSES

5.1 Steam Reforming of Natural Gas

Catalytic steam reforming of natural gas is the most common method of producing hydrogen or synthesis gas (syngas). Hydrogen and syngas are widely used in the production of ammonia and methanol and in petroleum refining, etc., as discussed in Sect. 30. The commercial process, usually carried out in the neighborhood of 1600°F (871°C) at low pressure inside tubes, is heated by burning natural gas in the shell side of the reformer.

The important chemical reactions are the following:

Steam reforming $CH_4 + H_2O(v) = CO + 3H_2 - 49$ kcal/mole C (1)

Shift $CO + H_2O(v) = CO_2 + H_2 + 9.9$ kcal/mole C. (2)

The nuclear reformer substitutes helium heated in a VHTR for natural-gas combustion. The nuclear reformer will tend to operate at somewhat higher pressures and lower temperatures than conventional systems.

As the temperature is increased and the pressure decreased, the methane reforming reaction goes more strongly toward completion. Table 17 shows the effect of process temperature on the methane conversion. The conversion increases rapidly up to about 1400°F and increases slowly thereafter.

There is a corresponding increase in the reformer heat duty as the process temperature is increased (Table 18). Because the total heat output of the reactor (Table 18) remains constant as the temperature is increased, the heat duty of the steam generator is reduced with increased temperature; heat duty of the reformer and steam generator are equal at about 1500°F maximum process temperature.

The comparison of efficiency of conventional and nuclear steam reformers is shown in Table 19. This table indicates that the efficiency of the nuclear process is considerably better than the efficiency of the all-fossil process. The comparison, however, is not quite as favorable to the nuclear system as it appears (Table 19). The product H_2 contains 10.8% CH_4; if this were removed and recycled to the reformer, efficiency would drop from 84% to about 79%.

Table 17. Methane reformer conversion data

Maximum process temperature (°F)	Entering process temperature (°F)	Steam-gas ratio	Pressure (psia)	Hydrocarbon conversion (%)
1200	1050	4.5:1	300	27.9
1400	1050	4.5:1	300	57.8
1600	1050	3.0:1	400	66.9
1800	1050	1.5:1	500	71.3
2000	1050	1.5:1	600	82.6

Source: *High-Temperature Nuclear Heat Source Study*, Report GA-A13158, General Atomic Company, December 30, 1974.

The technology of steam reforming is highly developed, and very successful tests of a single helium-heated reformer tube (EVA) have been run at KFA Julich.[23] KFA is preparing to build SUPEREVA, a 30-tube reformer test. The AISI Nuclear Steelmaking Subcommittee has published an assessment of nuclear reformers.[16]

Steam reforming of natural gas with nuclear heat is technically the simplest and most attractive process application of the VHTR. Unfortunately, little natural gas is likely to be available after VHTRs are commercially available. Focus is therefore shifted onto other carbon feedstocks for steam-reforming systems. The Japanese nuclear steelmaking scheme uses residual oil as feed, which is partially oxidized to yield lighter hydrocarbons that are steam reformed with nuclear heat. The present evaluation considers coal to be the most likely source of carbon in the United States.

Table 18. Distribution of heat between reformer and steam generator[a]

Maximum process temperature (°F)	Entering process temperature (°F)	Heat duty (10^9 Btu/hr)	
		Reformer	Steam generator
1200	1050	2.50	8.00
1400	1050	4.82	5.68
1600	1050	5.84	4.66
1800	1050	6.38	4.12
2000	1050	7.45	3.05

[a] Core thermal output = 3000 MW(t); pumping power is approximately 80 MW(t) for all cases.

Source: *High-Temperature Nuclear Heat Source Study*, Report GA-A13158, General Atomic Company, December 30, 1974.

5.2 Hydrogasification of Coal

When coal is exposed to hydrogen at elevated temperatures and pressures (1472 to 1562°F — 800 to 850°C, 10 to 100 atm), there is strong exothermic reaction producing methane and other light hydrocarbons. Hydrogen, in turn, can be produced in a methane (light hydrocarbon) steam

Table 19. Efficiency of methane-reforming nuclear and fossil heat

Type of process	Gross heating value GW	 10^9 Btu/hr	Percent of total input
Nuclear process, 1350°F (733°C) reformer			
Feed			
Reformer feed gas (hydrocarbons)	7.19	24.55	70.6
VHTR	3.00	10.24	29.4
	10.19	34.79	100.0
Product			
Hydrogen (88 mole % H_2)	8.49	28.99	83.3
Power	0.07	0.24	0.7
	8.56	29.23	84.0
Fossil heat process			
Feed			
Reformer feed gas (hydrocarbons)	7.19	24.55	63.0
Reformer fuel	4.22	14.41	37.0
	11.41	38.96	100.0
Product			
Hydrogen (88 mole % H_2)	8.49	28.99	74.4

Source: *Studies of the Use of High-Temperature Nuclear Heat from an HTGR for Hydrogen Production,* Report GA-A13391, General Atomic Company, September 30, 1975 (prepared under contract for NASA).

reformer heated by the helium coolant of a VHTR. This highly endothermic reaction is usually carried out at 1050 to 1600°F (565 to 871°C).

The important chemical reactions are the following:

Hydrogasification	$C + 2H_2 = CH_4 + 20.6$ kcal/mole C,	(1)
Steam reforming	$CH_4 + H_2O(v) = CO + 3H_2 - 49$ kcal/mole C,	(2)
Shift	$CO + H_2O(v) = CO_2 + H_2 + 9.9$ kcal/mole C.	(3)

Depending on the desired product, this conversion process can be designed for the net production of methane, syngas (H_2 + CO), or hydrogen.

In the most straightforward version of this process as proposed by the Germans[23,28] (Fig. 20), coal is dried and then gasified with the hydrogen stream produced in the methane steam reformer. The gasified coal is purified (by H_2O, H_2S, and CO_2 removal steps); about one-half becomes product synthetic pipeline gas, and one-half is recycled to the reformer. In this particular configuration, about 40% of the coal heating value remains in residual char, for which an economic use must be found.

Possibilities for the use of the char include steam gasification with nuclear heat or gasification through a partial oxidation process.

The process might also be improved by pretreatment of the coal, such as by the Battelle hydrothermal process.[29] The pretreatment would increase the hydrogasification rate and reduce the amount of char.

Current R&D on the pressurized hydrogasification of coal with simulation of nuclear heat is centered at Rheinische Braunkohlenwerke at Wesseling, Germany. About $10 million has been committed to this program. A 500-kg of coal per hour facility has been in operation for several months. The hydrogasification technology is very similar to that of processes that have been developed in the United States, such as Hydrane or Hygas.

ORNL–DWG 75–14759

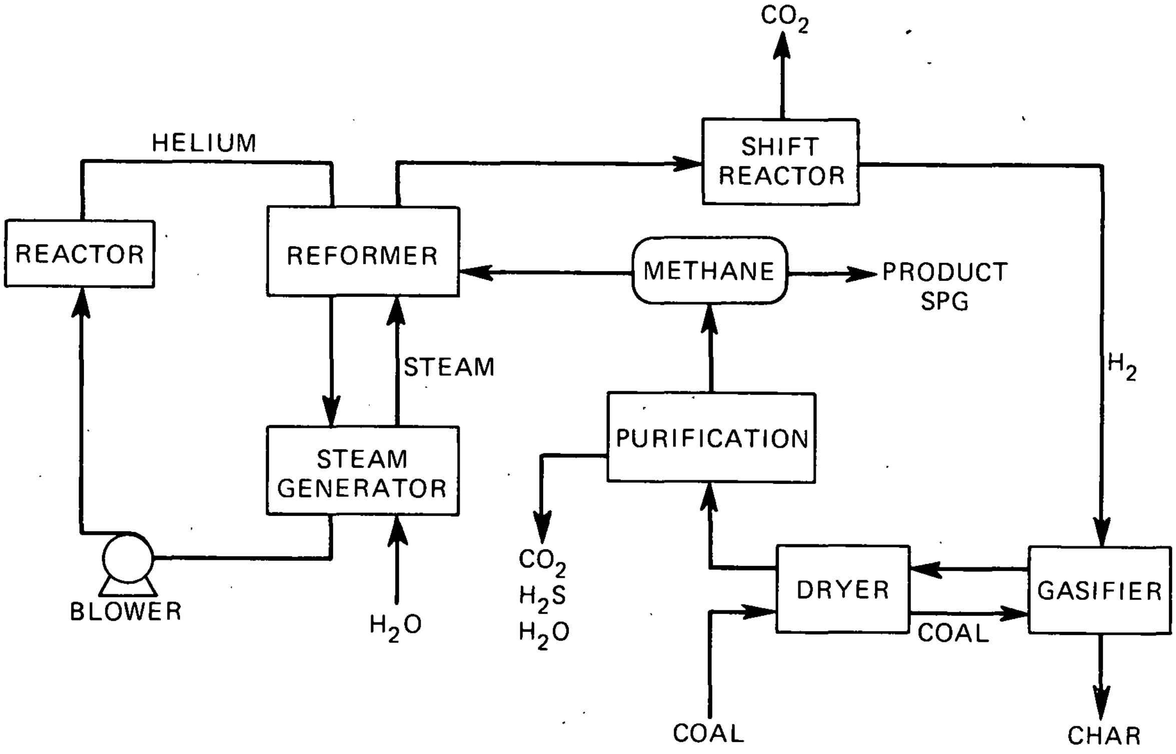

Fig. 20. Hydrogasification of coal using VHTR.

Although lignite or subbituminous coal can be hydrogasified directly, bituminous coal requires pretreatment before gasification. The pretreatment is generally accomplished by burning 3 to 10% of the coal.

5.3 Solution Hydrocracking of Coal

The General Atomic/Stone & Webster (GA/S&W) process[30] (Fig. 21) is a variation of the hydrogasification process where coal is powdered, dried, and dissolved in coal liquids prior to the solution hydrocracking step. The hydrogen for the hydrocracking is obtained, as before, from the helium-heated light hydrocarbon reformer. Depending on the ratio of recycle hydrocarbon to product and the product refining steps, the product mix can be predominately coal liquids, pipeline gas, syngas ($CO+H_2$), or hydrogen.

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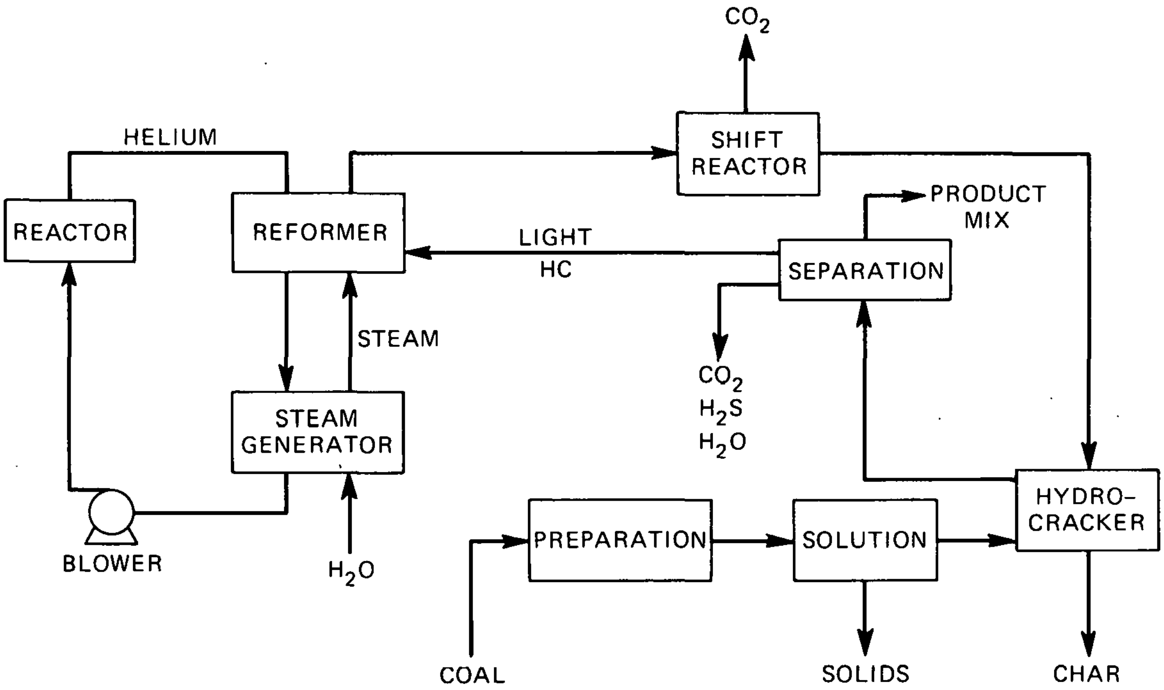

Fig. 21. Solution Hydrocracking of coal using VHTR.

The coal-liquids technology used here is similar to that used for other coal liquefaction systems. It is anticipated that the coal heating value remaining in residual solids will be in the range of 10 to 20% of the original or feed coal heating value.

The process has been developed with support from private sources. Bench-scale test facilities are being operated by Gulf Science and Technology Corporation, Harmerville, Pennsylvania. To date, about $1.5 million have been invested in process development.

5.4 Steam Gasificaton of Coal

Coal reacts with steam at elevated temperatures in a strongly endothermic reaction. The products of the reaction (syngas) can be converted to desired products such as methane or hydrogen. The important chemical reactions are the following:

Gasification $C + H_2O(v) = CO + H_2 - 28.4$ kcal/mole C, (1)

Shift $CO + H_2O(v) = CO_2 + H_2 + 9.9$ kcal/mole C, (2)

Methanation $CO + 3H_2 = CH_4 + H_2O + 49$ kcal/mole C. (3)

The steam-carbon reaction rates (Fig. 22) begin at about 600°C for lignite and 700°C for hard coal. The Germans propose to operate a lignite steam-gasifier at 660°C;[28] this gasifier would be a steam-fluidized bed heated internally with helium tubes. Figure 23 is a schematic of this system.

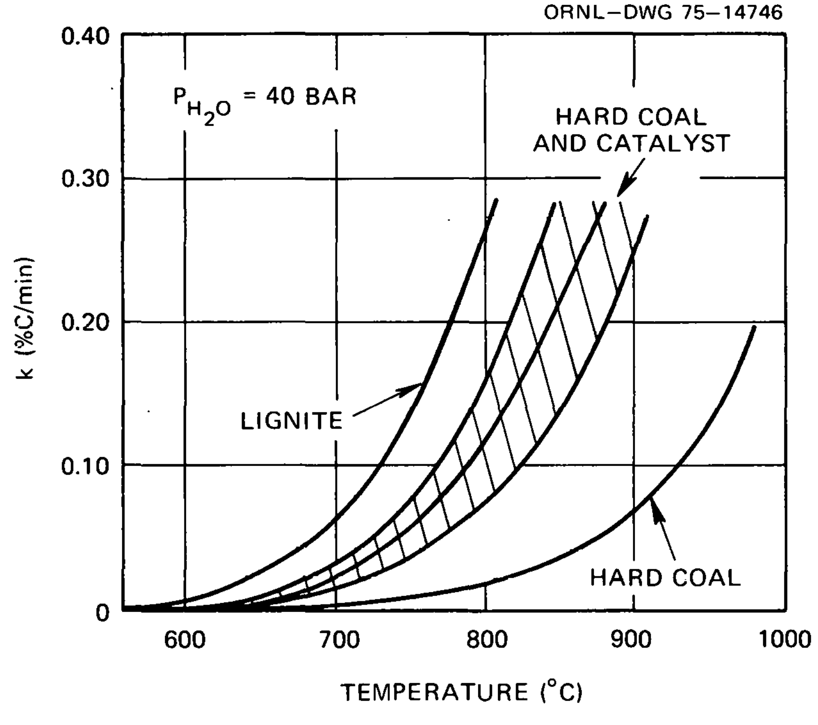

Fig. 22. Steam-carbon reaction rates for lignite, hard coal, and hard coal with catalyst.

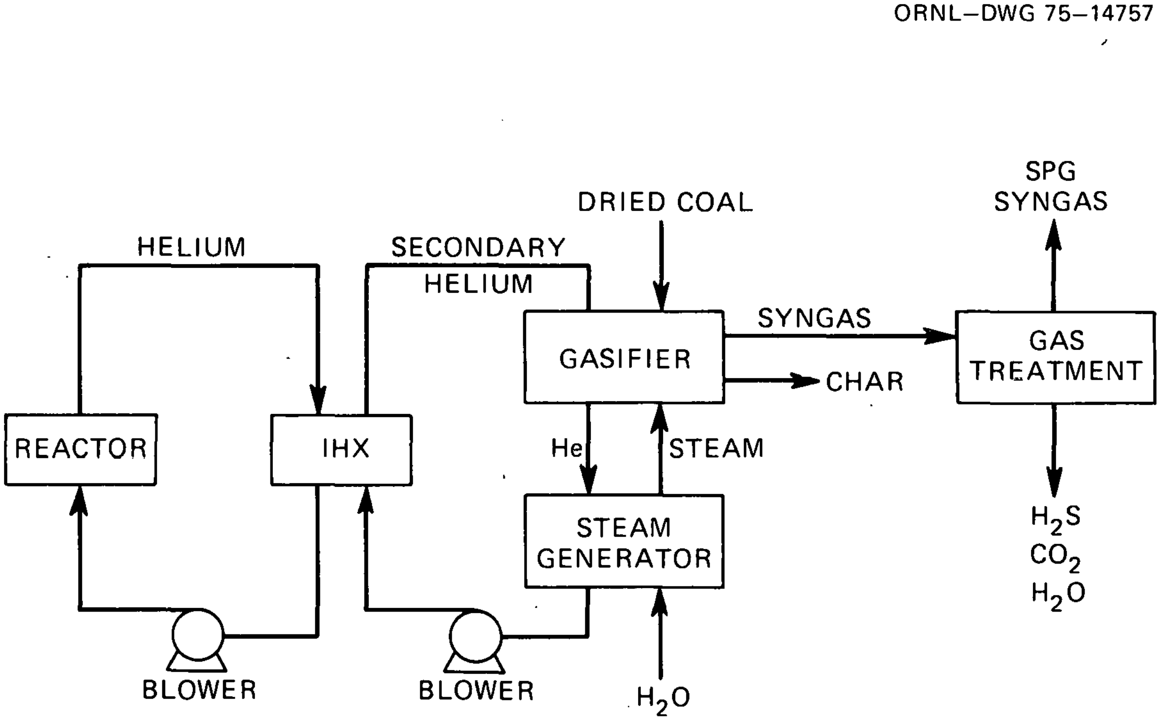

Fig. 23. Lignite-steam gasifier using VHTR.

This system requires an intermediate heat exchanger (IHX) between the reactor and the gasifier because it is not believed practical to provide maintenance for a coal gasifier in the primary coolant circuit. Furthermore, the steam gasification reaction uses a smaller fraction of the VHTR energy output than does the methane reformer of the earlier processes; there is a significant amount of by-product electric power in the German scheme.

The steam gasification process leaves a residue of char, according to United Kingdom (UK) sources;[31] the UK paper cites 750 to 850°C as reasonable temperatures for lignite gasification, with 925°C recommended for "high carbon conversion." The corresponding temperature for hard coal is given as 1050 to 1100°C.

German sources state that the steam gasification reaction rate remains constant as the coal is reacted,[32] that is, that all the coal can be essentially converted to ash and gas.

The Battelle hydrothermal treatment[29] appears to catalyze the steam gasification of bituminous coal. The treatment is reported to reduce the required temperature for good reaction rates to about 700°C.

Steam gasification of coal appears to be a reasonable topping process for a coal hydrogasification system, as shown in Fig. 24. For the "pure" steam gasification process in Fig. 23 to be practical, a very-high-temperature heat source would have to be developed and/or a practical low-temperature coal-steam reaction developed.

ORNL-DWG 76-11105

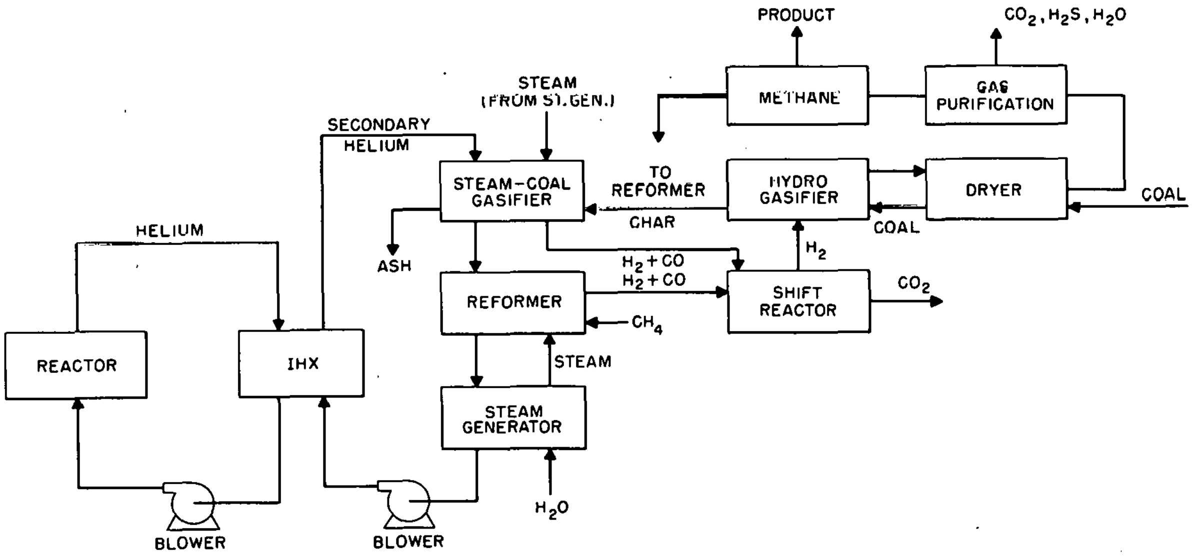

Fig. 24. Hybrid steam and hydrogasification of coal.

The development of the indirectly heated steam gasification process is being carried out under sponsorship of the German government at BergbauForschung, Essen. About $10 million has been committed to the program thus far. A 1-kg/hr apparatus has been in operation since 1973; a 200-kg/hr semitechnical plant is under construction.

5.5 Nuclear Steelmaking

The most viable concept for applying nuclear energy to steelmaking combines two well-known processes: direct reduction in a shaft furnace and refining in an electric furnace.

Although direct reduction of iron ore is a fairly new process, it is well developed and is in commercial use in various parts of the world where low-cost natural gas is available. In this process, iron ore is reduced in the solid condition by a synthesis gas ($CO + H_2$) derived from steam reforming of natural gas to a product known as sponge iron. The reaction required heat addition at high temperatures. Nuclear energy could be used to provide the heat needed to produce the reducing gas for the direct reduction of iron ore and the electricity needed to refine the resulting sponge iron to steel in an electric-arc furnace.

The production of steel by electric-arc furnaces is a long-established commerical technology. Electric-furnace capacity in the United States today is about 30 million tons/year. Almost all of that tonnage is made with scrap as the only ferrous charge, although a number of plants presently use at least some sponge iron in their charges. Sponge iron could be used for a large portion of that charge, if the cost of the sponge were competitive with scrap and provided that the gangue content was low enough. Electric-arc refining uses about 650 kWh/ton of steel.

The impurities or gangue constituents in iron ore (mainly silica and alumina) are not removed in direct-reduction processes as they are when ore is reduced to liquid iron in the blast furnace. Instead, these impurities remain in the sponge iron and increase the amount of slag that must be melted in subsequent refining in the electric-arc furnace. Because this imposes a substantial cost penalty, low-gangue ores are favored for direct-reduction processes.

Processes for direct reduction differ in certain details, but almost all of them use a gas mixture of carbon monoxide and hydrogen at temperatures in the range of 1500-1800°F as a reductant. For the efficient reduction of iron ore, the $CO + H_2$ content of the reducing gas should be above 90%.

Iron ore can also be reduced to sponge iron with hydrogen alone, but there are drawbacks. First, the iron tends to sinter or stick together during hydrogen reduction, and second, there is a strong tendency for the reduced iron product to reoxidize. Both of these problems must be overcome before hydrogen reduction can be utilized commercially on a large scale.

In a steelmaking system involving direct reduction and refining in an electric-arc furnace, nuclear energy can be used to;

(1) Provide high-temperature heat for the production of a gas suitable for the reduction of iron ore to iron. The reducing gas, after removal of sulfur and other impurities, is at moderate temperatures and pressure and can be transported a reasonable distance from the nuclear heat source.

(2) Produce electricity for the operation of electric-arc furnaces to refine the sponge iron. The electricity for this step may be generated in any kind of a nuclear power plant; thus, direct reduction does not necessarily have to be close-coupled with steelmaking.

The American Iron and Steel Institute has studied nuclear steelmaking with syngas produced via steam reforming of natural gas and with syngas produced from coal via the GA/S&W process. A reformer temperature of 1400°F (760°C) was found to be acceptable, although 1500 to 1600°F would be preferred.[15,33] D. J. Blickwede of AISI[12] found nuclear steelmaking to be competitive with conventional blast furnace technology and with the coal gasification-direct reduction process (metallurgical coal assumed at $55/ton and nonmetallurgical coal at $25/ton).

The Japanese nuclear process heat program is concentrating on nuclear steelmaking development. During 1973 to 1978, there is an allocation of about $25 million for this program with the objective of establishing the basis for a prototype. Research and development includes heat exchanger development; high temperature materials, process for converting residual oils to reducing gas via hydrocracking, partial oxidation, and steam reforming of light hydrocarbons; and development of direct reduction equipment.

5.6 The Chemical Heat Pipe System (EVA-ADAM)[34]

The nuclear reactor is a source of primary energy that is economical, potentially abundant, and evironmentally favorable. However, it generally cannot be directly transported, distributed, or utilized by the consumer. Therefore, it is necessary to convert the nuclear heat into a more transportable and usable form of energy, customarily electricity.

The chemical heat pipe is an alternate approach to the transportation of nuclear heat. In this case, the energy is transported in the form of latent chemical energy in a closed-loop system. A reversible chemical reaction is carried out at the heat source and at the point of use. The most established chemical heat pipe system is one involving methane and synthesis gas, because the steps of this cycle involve well-known technology. The basic chemical reaction is as follows:

$$CH_4 + H_2O \rightleftharpoons 3H_2 + CO; \Delta H = +50 \text{ kcal/mole.}$$

The reaction absorbs energy as it proceeds to the right. The reaction products (H_2 + CO) may then be transported (or stored) and later recombined, with the reaction proceeding to the left to yield energy to the remote customer. The equilibrium constants are such that the heat pipe absorbs energy at about 800 to 900°C and releases the energy at about 450°C (the development of new catalysts may extend the latter temperature from 600 to 700°C). It is suggested that for long distance (over 30 to 50 km) transport of nuclear energy, the chemical heat pipe may be more attractive than steam, hot water, or electricity transport. The chemical heat pipe could become an important source of industrial process heat.

5.7 Thermochemical Water-Splitting

It is clear that hydrogen production directly from water via electrolysis or thermochemical processes will ultimately become important as a chemical intermediate and as an energy carrier. Because of this increased importance, the processes for deriving hydrogen from water are receiving considerable support in the United States and in foreign programs. For example, ERDA, the American Gas Association, EPRI, NASA, General Atomic, and Euratom all have sponsored programs related to hydrogen production through at least a dozen institutions. A very large number of chemical cycles are known to be possible, and many have been evaluated in the United States and in foreign programs. Bowman has published a discussion of many of these thermochemical cycles.[35]

Within the VHTR program, attention has been focused on the Westinghouse hydrogen production process, which is a hybrid thermochemical-electrolytic cycle being developed by Westinghouse.[7] The reaction steps are as follows:

Solution	$SO_2 + H_2O \rightarrow H_2SO_3$,
Anode	$H_2SO_3 + H_2O - 2e \rightarrow H_2SO_4 + 2H^+$,
Cathode	$2H^+ + 2e \rightarrow H_2$,
Thermal decomposition	$H_2SO_4 \rightarrow SO_2 + H_2O + 1/2\ O_2$,
Net reaction	$H_2O \rightarrow H_2 + 1/2\ O_2$.

Westinghouse has confirmed the various steps in laboratory tests.

In their assessment of Westinghouse's thermochemical cycle for H_2 production, C. E. Bamberger and J. Braunstein of ORNL concluded that, from a chemical viewpoint, the process appears feasible and attractive. Its advantages include chemical simplicity, use of abundant, low-cost reagents, and no requirement for solids handling. Problems identified included development of suitable separators for the anolyte and catholyte solutions, substitution of electrode materials more suitable than platinized platinum, demonstration of practical construction materials compatible with hot concentrated H_2SO_4, and possible effects of corrosion products transported through the system on other parts of the cycle, especially the electrolytic step.

Although EURATOM has carried out hardware development of thermochemical cycles at Ispra, Italy, the technology is considered to be primarily in the laboratory stage. Many cycles are considered to be potentially attractive and require laboratory investigation. Considerable R&D will be required to develop an economically competitive water-splitting process, but the water-splitting technology can be matured by the time the VHTR is developed.

5.8 Economics of Process Applications

There is unfortunately a lack of definitive data on which to base an economic assessment of many applications of nuclear process heat. Indeed, the same is true of most developing coal conversion processes. This is because most of these processes are in very early stages of development and no economic data have been generated. Therefore, it was necessary to restrict this assessment to processes for which some economic information was available.

We requested United Engineers & Constructors, Inc. (UE&C) to prepare an engineering evaluation of the use of very-high-temperature nuclear reactors (VHTRs) for process heat applications, using as the basis the conceptual design of a coal solution gasification process developed by GA/S&W.[30] The process heat and power for the applications studied would be supplied from a VHTR of 3000 MW(t) capacity. The following is a summary of the United Engineers' report, which is Appendix III (ORNL/TM-5411).

The scope of UE&C work was limited to updating the capital and production (operating) costs of the basic GA/S&W concept for converting coal to synthetic pipline gas (SPG) and to cost-estimate modifications of the GA/S&W concept for the production of synthesis gas, hydrogen, or crude fuel liquids. All estimates included the cost of an intermediate heat exchanger. For comparison with these costs, UE&C updated and developed the costs on a comparable basis for several processes, either commercially available or in a promising development stage. These included the Lurgi and Hygas processes for pipeline gas, the Koppers-Totzek (K-T) processes for synthesis gas or hydrogen, and the H-Coal process for crude fuel liquids production. The Westinghouse water-splitting process combined with the VHTR was evaluated for hydrogen production and compared with K-T and GA/S&W. Another comparison was made of the application of these synthesis gases to direct ore reduction for steelmaking with the conventional blast furnace approach and the more recent direct ore reduction process based on natural-gas reforming.

The GA/S&W SPG process was made the basis for all comparisons. All of the heat from a 3000 MW(t) VHTR, equivalent to 10.2×10^9 Btu/hr, was utilized in a coal conversion process to produce a high Btu gas and a minor amount of a liquid fuel (no coal was consumed as fuel). Modifications to the GA/S&W base process for the production of synthesis gas, hydrogen, or crude liquids also utilized the full 3000 MW(t). The amount of coal input and the point of product withdrawal were varied to obtain the various products. Thus, only the quantity through a processing section of the plant was altered and not the process conditions. Delivery pressures were 1000 psi.

Capacities of the comparable coal-fueled coal conversion processes, chosen from published sources, were adjusted to produce the same quantity of primary products as the GA/S&W versions. For the nuclear/fossil coal liquefaction process comparison, the nuclear plant was sized to use all the heat from a 3000-MW(t) VHTR, whereas the fossil-heated plant was sized to have the same coal feed as the nuclear version. Where another product, steel, was to be made from the synthesis gas, an appropriately sized plant was mated to the synthesis gas plant to suit the feed quantity and composition.

Capital costs of plants and/or sections of plants were updated to July 1974. Interest during construction was taken as 8% of the total plant capital cost per year and then added to obtain the total fixed investment. All chemical plants were assumed to have a four-year construction period and the VHTR an eight-year construction period.

Production costs included the following parametric variations: coal from \$0.50 to \$1.75/10^6 Btu, nuclear fuel from \$0.25 to \$0.60/10^6 Btu, and fixed charge rates (FCR) of 15% or 25% of the total fixed investment. Utilities were adjusted as required to the following bases: electric power at \$1.012/kWhr and raw water at \$0.30/1000 gal. The standard operating year was 330 days. No by-product credits were included; it was assumed that disposal of these would occur at no cost.

The base VHTR capital cost was taken at \$800 x 10^6 and included all direct and indirect charges and interest during construction. The operating and maintenance costs for the VHTR were taken as \$9 x 10^6 per year.

The process-product combinations that were evaluated are shown in Table 20. The capital costs, production cost ranges, and energy conversion efficiencies are tabulated in Tables 21 and 22. In general, the higher ends of the production cost ranges are probably more realistic.

The following conclusions may be derived from the subject study:

1. For production of synthetic pipeline gas, the GA/S&W process, using a nuclear heat source, appears to be competitive with the commercial

Lurgi process. The Hygas process, which is under development, is decidely less expensive on the basis of given estimates.

2. When coal costs are high, a GA/S&W plant modified to produce mainly synthesis gas (H_2 and CO) appears to be competitive with a Koppers-Totzek plant, if compared on the fuel or heating value of the gas.

3. When coal costs are in the medium to high range, a GA/S&W plant modified to produce mainly hydrogen for process use appears to be competitive with a Koppers-Totzek plant.

4. A nuclear-powered coal liquefaction plant is competitive with a fossil heat plant. Additionally, the nuclear version uses less coal, hence there would be a reduced mining impact.

5. On the basis of the UE&C and ORNL work, the Westinghouse hydrogen production process, using VHTR nuclear heat and water splitting, does not appear competitive with nearer-term energy sources based on coal or on hydrogen from nuclear-coal hybrids. (The Westinghouse cost estimates are substantially below the UE&C-ORNL estimates, as explained later.) The Westinghouse process would be of interest for an economy where carbon is very expensive.

Table 20. Process applications studied

Process	Pipeline gas	Crude liquids	H_2	Syngas for steel	Syngas for methanol
General Atomic/ Stone & Webster	X		X	X	X
Lurgi	X				
Hygas	X				
Koppers-Totzek			X	X	X
Coal liquefaction/fossil		X			
Coal liquefaction/nuclear		X			
Westinghouse water-splitting			X		

Table 21. Process products and efficiency

Process	Products	Energy output (10^9 Btu/hr)	Percent (Efficiency)
GA/S&W synthetic pipeline gas	Pipeline gas	24.5	
	Light aromatic liquid	5.0	
	Total	29.5	67
Lurgi synthetic pipeline gas	Pipeline gas	24.4	
	Naptha	0.79	
	Tar	2.82	
	Tar oil	1.54	
	Total	29.55	68
Hygas synthetic pipeline gas	Pipeline gas	26.50	
	Heavy oil	2.35	
	Benzene	0.64	
	Total	29.49	66
GA/S&W synthesis gas	Synthesis gas	15.54	
	Light aromatic liquid	2.76	
	Total	18.30	64
Koppers/Totzek synthesis gas	Synthesis gas	15.48	55
GA/S&W hydrogen	Hydrogen	15.56	
	Light aromatic liquid	2.76	
	Total	18.32	64
Koppers-Totzek hydrogen	Hydrogen	16.97	55
Westinghouse hydrogen	Hydrogen	4.8	45
Coal liquefaction fossil heat	Heavy naphtha	13.92	
	Middistillate	12.42	
	Heavy oil	10.30	
	Heavy gas oil	1.83	
	Total	38.47	65[a]
Coal liquefaction nuclear heat	Heavy naphtha	16.88	
	Middistillate	12.42	
	Heavy oil	11.92	
	Heavy gas oil	1.83	
	Coker gas	2.17	
	Total	45.22	65[a]
Chemical heat pipe (EVA-ADAM)	Synthesis gas	7.1	70[b]

[a] 78% if residual char (heating value 8235 Btu/lb) can be sold.

[b] ORNL estimate.

Table 22. Cost of products derived from nuclear process heat and alternatives[a]

Coal conversion process	Capital cost (millions of $)	Production cost range ($/$10^6$ Btu of product)
GA/S&W SPG	1594	1.87 to 4.12
Lurgi SPG	1089	1.79 to 4.09
Hygas SPG	785	1.47 to 3.68
GA/S&W Syngas	1364	2.22 to 4.63
Koppers-Totzek Syngas	1073	2.34 to 5.47
GA/S&W hydrogen	1466	2.33 to 4.95
Koppers Totzek hydrogen	1180	2.34 to 5.45
Westinghouse hydrogen	1178	5.17 to 8.80
Coal liquefaction/nuclear	1909	1.80 to 4.06
Coal liquefaction/fossil	1241	1.70 to 4.04
Chemical heat pipe	1000	3.70 to 5.97[b]

[a] Basis:

July 1974 Cost Index	
Coal	\$0.50 to 1.75/10^6 Btu
Nuclear fuel	\$0.25 to 0.60/10^6 Btu
FCR	15%, 25%
Plant factor	90%

[b] ORNL estimate.

Electrolytic hydrogen, which can be produced with current or near-term technology, must be considered as yet another source of hydrogen. The Institute of Gas Technology estimates hydrogen costs as about \$8/MBtu with current equipment (electric power at 10 mills/kWhr) and \$5/MBtu with projected equipment.[8]

Figures 25 through 29 show the effect of coal cost on the estimated cost of synthetic pipeline gas, Syngas, hydrogen, crude liquids, and the chemical heat pipe. For systems using nuclear process heat, two estimates are presented. The first is the UE&C estimate based on an $800 million VHTR. However, in studies conducted for NASA,[5,7] GA estimated their VHTR to cost $536 million, without an IHX; Westinghouse estimated theirs to be $447 million, including an IHX. Because of this diversity in VHTR costs, the second process estimate is based on vendor VHTR capital costs.

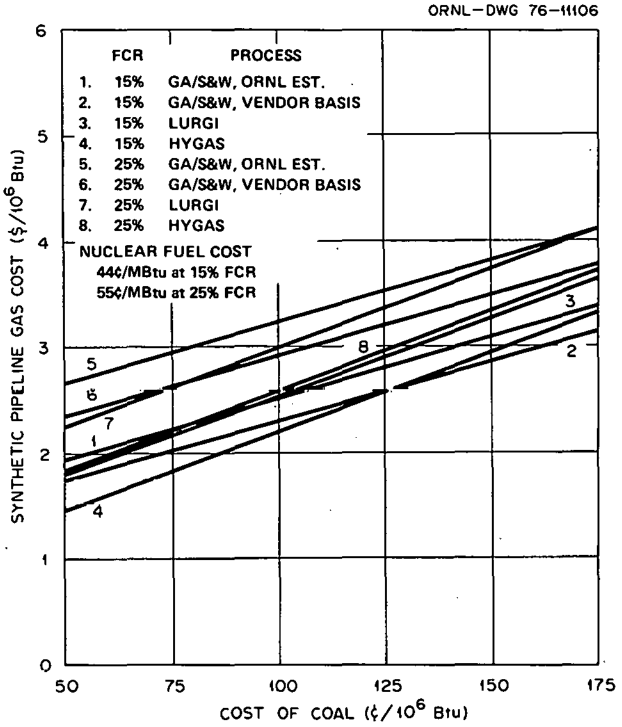

Fig. 25. Synthetic pipeline gas cost vs cost of coal.

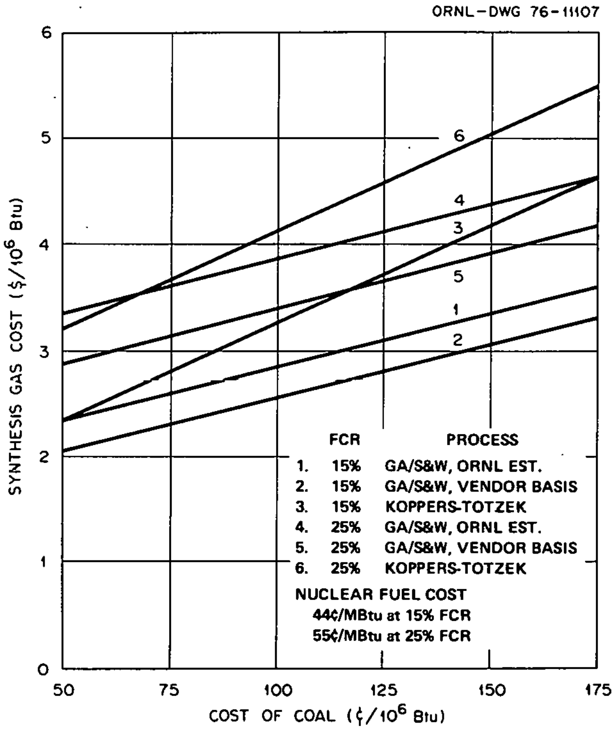

Fig. 26. Synthesis gas cost vs cost of coal.

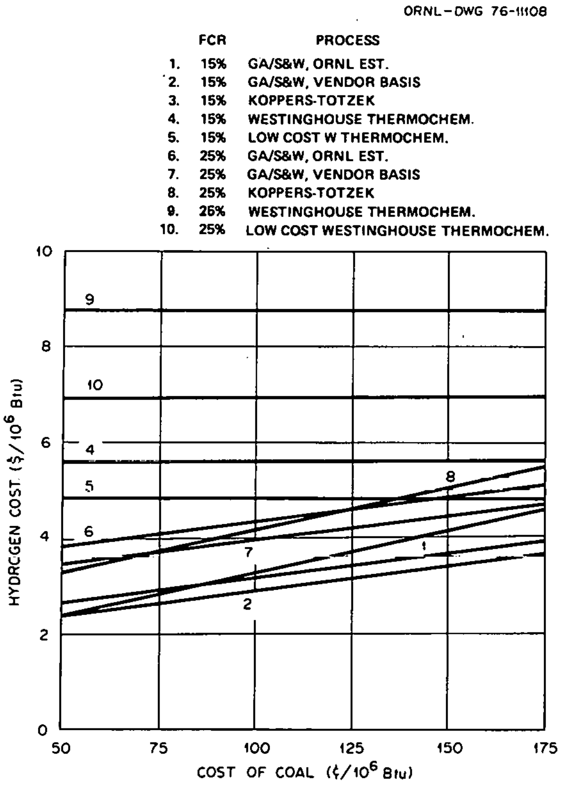

Fig. 27. Hydrogen cost vs cost of coal.

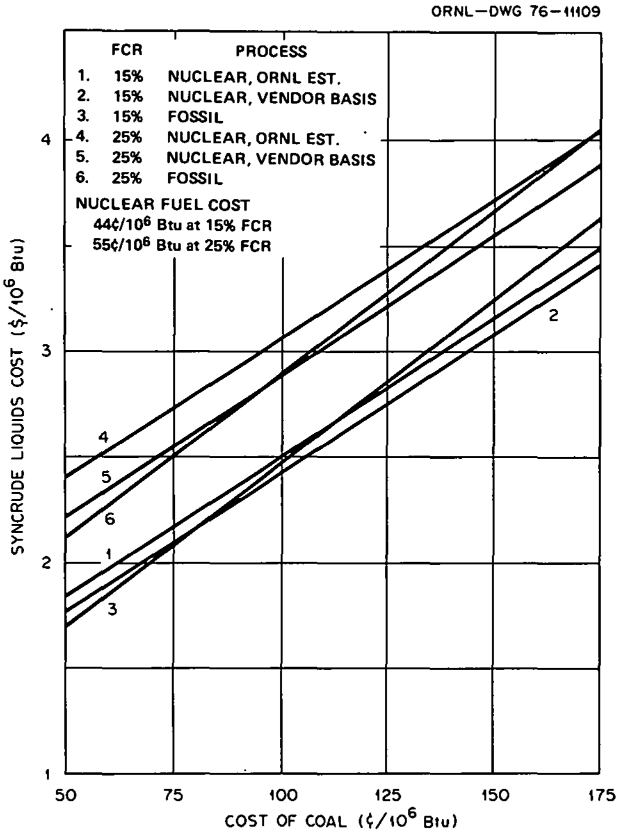

Fig. 28. Synthetic crude liquids cost vs cost of coal.

Figure 29 displays the cost of transported energy as derived in Appendix II (ORNL/TM-5410). The cost presented is that for the production of process steam. This figure suggests that in comparison with other nonfossil energy transportation systems, the EVA-ADAM system is competitive for intermediate distances (less than 250 miles). However, within the present price range of coal, synthetic pipeline gas is more economical for energy transport.

Figure 30 displays the effect of increases in uranium cost on hydrogen cost for selected systems. The impact of increased uranium cost on product cost is less than that of increased coal cost in the fossil or hybrid systems.

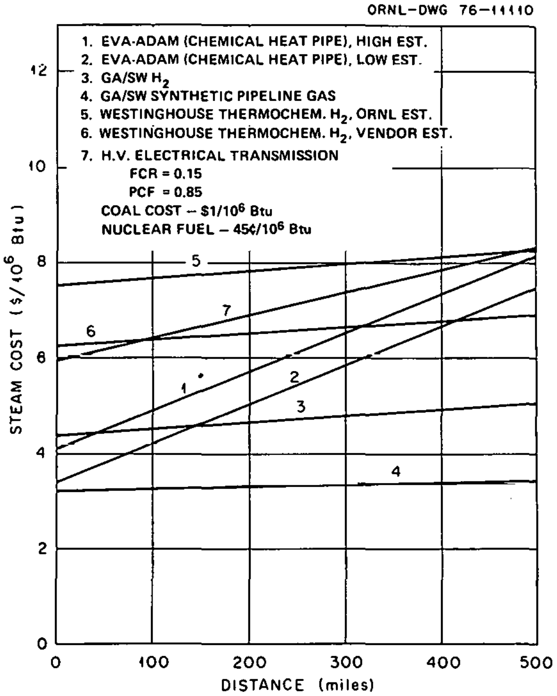

Fig. 29. Cost of steam produced from the chemical heat pipe and other energy transport alternatives.

Figure 31 displays the effect of plant size on hydrogen cost for the nuclear processes. Again, these costs are based on UE&C estimates. Product costs do increase significantly as size is reduced, based on the design concepts studied. The figure does suggest that larger than 3000-MW(t) plants ought ultimately to be considered for thermochemical hydrogen production.

5.9 Oil Shale and Tar Sands

Although nuclear process heat may be able to contribute to oil shale refining and/or in situ mining, these possibilities do not appear to provide immediate incentives for developing the VHTR. Having the VHTR available will not speed up initial development of this resource, but the VHTR could eventually contribute significantly to improving the efficiency of synthetic fuel recovery per unit of shale mined.

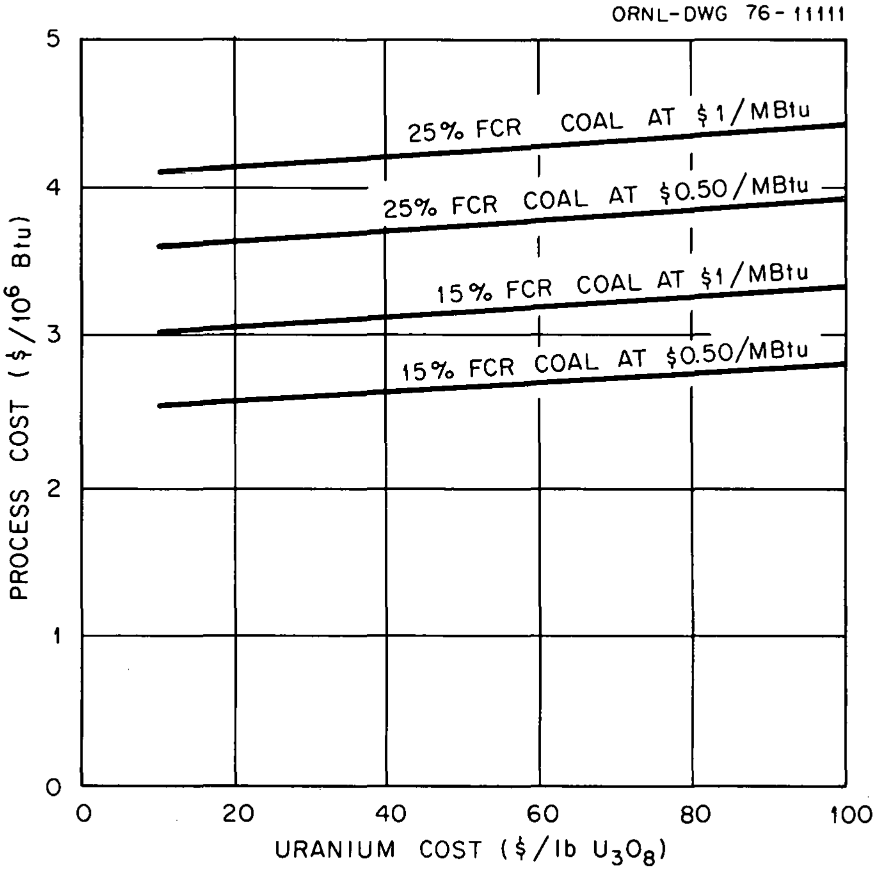

Fig. 30. Effect of uranium cost on cost of hydrogen via the GA/S&W process.

An evaluation of the application of the VHTR to shale oil and tar sands recovery and processing has been completed by the Resource Analysis and Management Group (RAMG) under contract with ORNL.[17]

The principal shale oil resources in the United States are located in the Green River Formation of Colorado, Utah, and Wyoming and in the marine shale deposit in Alaska. A total of 2000 billion barrels constitutes the resource base. Tar sands are a major resource in Canada and Venezuela but total under 30 billion barrels in the United States.

Six different processing concepts were evaluated both with and without the use of the VHTR. The U.S. Bureau of Mines' gas combustion process, with its underground mining operations, was used for a relative comparison of the advantages and disadvantages of the use of a VHTR to process oil shale. The Great Canadian Oil Sands process was taken as a representative scheme to make a relative comparison with the VHTR-modified process for converting, aboveground, tar sand bitumen to a syncrude. The Shell steam injection in situ tar sand process was taken as a basis for comparison in the use of the VHTR for in situ recovery of tar sand bitumen. Where possible, the primary refining step used was the Hydrocarbon Research, Inc., H-Oil hydrogenation unit.

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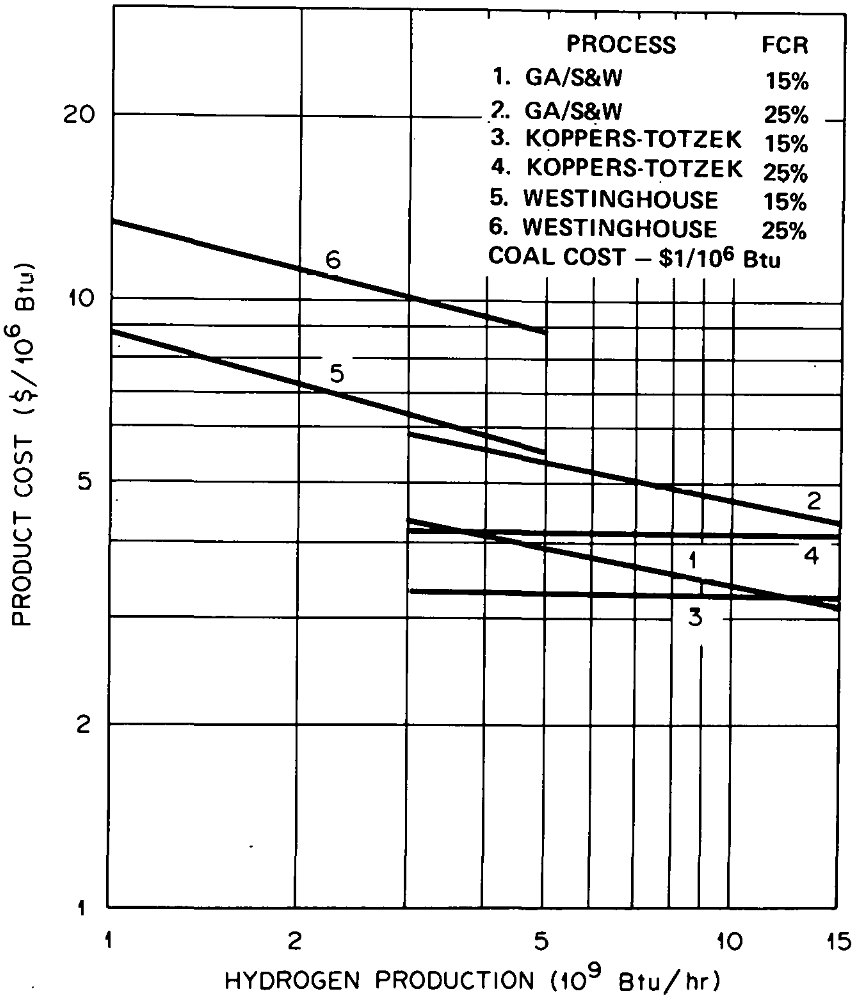

Fig. 31. Effect of size on hydrogen cost.

The evaluation of the use of the VHTR nuclear process heat for tar sand and oil shale recovery and upgrading indicated that:

1. Processing plants are estimated to be built, at least initially, in parallel trains in size increments of 50,000 bbl/day. A 3000-MW(t) VHTR would match several times that capacity.
2. Preliminary evaluations indicate that for shale oil recovery and processing, a VHTR with an output significantly less than 3000 MW(t) may be more attractive.
3. The 3000-MW(t) VHTR coupled with the 100,000 bbl/day tar sand recovery plant using in situ injection is the better match of the processes considered.
4. Estimated benefits of nuclear process heat applications of a VHTR are a 24 to 50% better utilization of the in-place resources, with an attendant lessening of the environmental impact of resource production, and about 20% less water requirement.
5. Product liquid costs from nuclear shale operations might be less than from the conventional approach if mining-reclamation costs are high.

5.10 Petroleum Refining

Previous investigations have indicated that most petroleum refinery process heat applications require process temperatures of 538°C (1000°F) or less. General Atomic Company conducted a refinery evaluation under subcontract to ORNL.[18] The American Oil Company and Shell Oil Company cooperated in providing refinery information and helping with overall guidance of the study.

The objectives of this work area were as follows:

1. Evaluate the use of the VHTR as a heat source for refinery and petrochemical processes requiring process temperatures up to 1000°F and as a hydrogen producer for upgrading hydrocarbon feedstock;
2. Investigate potential heat transfer fluids for transporting heat from reactor site to refinery site;
3. Provide a conceptual design of a secondary helium loop to remove heat from the reactor vessel;
4. Investigate safety aspects of heat transport fluid contamination;
5. Evaluate methods for providing backup in the case of reactor shutdown;
6. Evaluate modifications to the nuclear reactor system;
7. Identify areas where additional R&D is required;
8. Estimate plant availability.

Two basic coupling configurations were investigated. The first is a single reactor with a fossil fuel backup system. The backup system is required to achieve a high availability. The second alternative includes two reactors to increase availability. Refinery steam requirements are generated either at the refinery from energy transported in the heat transport loop or at the reactor site and transported independently. The distance from the reactor site to the refinery boundary is 3500 ft. The total length of the heat transport system is assumed to be 7000 ft, including that portion inside the refinery site.

Table 23 presents a summary of the preliminary engineering design data generated for the different candidate heat transfer fluids. Table

24 presents a summary of the costs generated for the heat transport loop. On the basis of cost, HTS (heat transfer salt) appears to be the clear choice. However, these results are preliminary and other considerations may influence the design choice. For example, compatibility with the refinery fluids in the event of leakage will be an important factor in the ultimate choice.

The cost of heat supplied to the refinery is in the range of $3 to $4/MBtu. Much of the cost is related to the need for backup systems.

Possibly, if the refinery heat supply system were combined with energy storage and the generation of intermediate and peaking power (Sect. 7.3), it would be possible to reduce costs of refinery heat to a more attractive level.

Table 23. Heat transport fluid piping system data[a,b]

Item	Helium	Hydrogen	Nitrogen	Carbon dioxide	Steam	HTS	NaK
Flow rate, lb/hr × 10^6	7.840	2.801	36.719	35,651	17.406	26.275	46.855
Inventory, lb	152,450	48,410	1,269,340	1,540,520	615,380	11,837,000	8,528,850
Supply pipe, OD (ft)	10.07	7.862	11.75	11.23	8.758	3.747	4.746
Return pipe, OD (ft)	9.85	7.199	11.22	10.85	8.299	3.788	4.533
Supply pipe velocity, ft/sec	250	275	135	110	140	11.0	25
Return pipe velocity, ft/sec	150	175	90	70	80	63	17.7
Pump or circulator inlet pressure, psia	622	721	533	438	723	40	40
Pump or circulator outlet pressure, psia	657	767	597	496	805	172	283
Pump or circulator power, MW(t)	108	65.2	122	79.8	71.5	1.93	146
Supply pipe wall thickness, in.	2.58	2.30	2.71	2.15	2.70	0.318	0.648
Return pipe wall thickness, in.	2.38	2.00	2.37	1.89	2.34	0.200	0.201
Piping heat loss, Btu/hr × 10^6	39.6	30.3	46.1	44.4	34.0	10.3	13.4

[a] Transmission of 1364 MW(t) to a 250,000 BPD refinery.

[b] Assumes supply and return pipe length are each 7000 ft.

Table 24. Heat transport fluid piping system cost data (millions of dollars)[a,b]

Cost item	Helium	Hydrogen	Nitrogen	Carbon dioxide	Steam	HTS	NaK
Supply piping	55.379	39.496	67.386	55.985	48.973	6.053	14.415
Return piping (including insulation)	28.883	18.044	32.939	26.180	23.908	2.152	2.607
Pumps or circulators	21.663	13.115	24.476	16.041	14.388	0.387	2.945
Inventory	0.865	0.047	0.027	--	0.004	1.776	13.646
Heat loss	2.311	1.773	2.693	2.595	1.983	0.601	0.783
Unrecovered pump or circulator power loss	2.146	1.299	2.425	1.589	1.425	0.038	0.291
Total piping system cost	111.247	73.774	129.946	102.390	90.681	11.007	34.687

[a] Transmission of 1364 MW(t) to a 250,000 BPD refinery.

[b] Assumes supply and return pipe length are each 7000 ft.

6. POWER GENERATION APPLICATIONS OF THE VHTR

6.1 Base-Load Power Generation

If the VHTR were commercially available, the technology could be applied to novel high-efficiency power cycles. Such cycles would have the advantages of reduced heat rejection to the environment and more efficient utilization of nuclear fuels (up to 50% or more thermal efficiency). These cycles include:

1. Direct cycle gas turbine combined with steam or ammonia bottoming cycles,
2. Direct cycle gas turbine combined with dry cooling tower,
3. Boiling potassium topping cycle for steam cycle plant.

These systems have not been evaluated as part of the present investigation. However, they constitute a significant additional benefit of developing the VHTR.

6.2 Intermediate and Peak Power Generation Using EVA-ADAM Energy Storage

The same reactions used in the chemical heat pipe can be adapted to intermittent power production. The EVA-ADAM peaking power process consists of two sections: the nuclear powered reformer/base power section and the methanator/peaking power section. Figure 32 is a schematic flow diagram of the system.

The peaking power section consists of a catalytic methanator and an intermediate pressure steam cycle. Synthesis gas, which is removed from storage, is passed through a nickel catalyst methanator, where the heat of reaction is transferred to a steam cycle, which, in turn, generates electrical power. The product gas, primarily CH_4 and H_2O, is subsequently cooled through a series of heat exchangers, the water is removed, and then it is sent to storage.

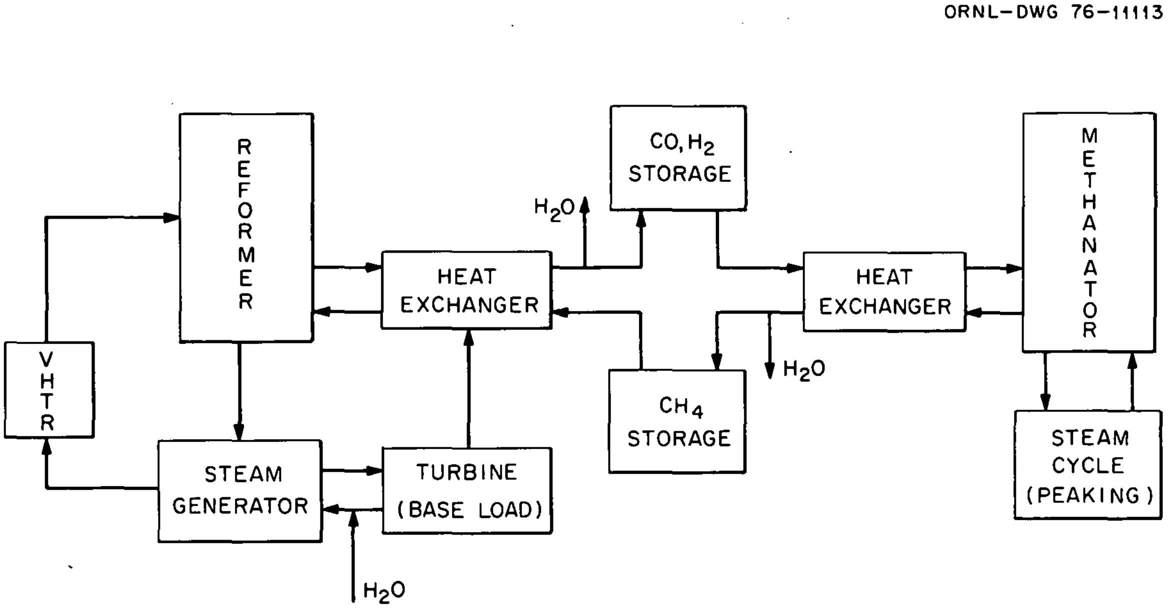

Fig. 32. EVA-ADAM system for peaking power generation.

During low power demand periods, the synthesis gas, which is being produced at a constant rate in the reformer, is stored in the high pressure storage area. When the demand increases, the gas is removed from storage and fed to the intermediate-load and peaking-power plant. The methane produced is stored and retrieved in a similar manner.

Work is in progress to define details of this cycle and to estimate cycle efficiency.

6.3 Intermediate-Load and Peak Power Generation Using Heat Transfer Salt Energy Storage

The technology applicable to supplying refinery heat would also be applicable to the generation of intermediate-load and peaking electricity.

Molten salts are excellent heat transport and storage media. Figure 33 is a schematic diagram of an electric power generating system based on sensible heat storage in heat transfer salt. If the system were used on a daily cycle, it might be assumed that a 3000-MW(t) nuclear island would be coupled to a 3744-MW(e) generation plant operating about 6 hr/day and with a 200-MW(e) base-load capacity.

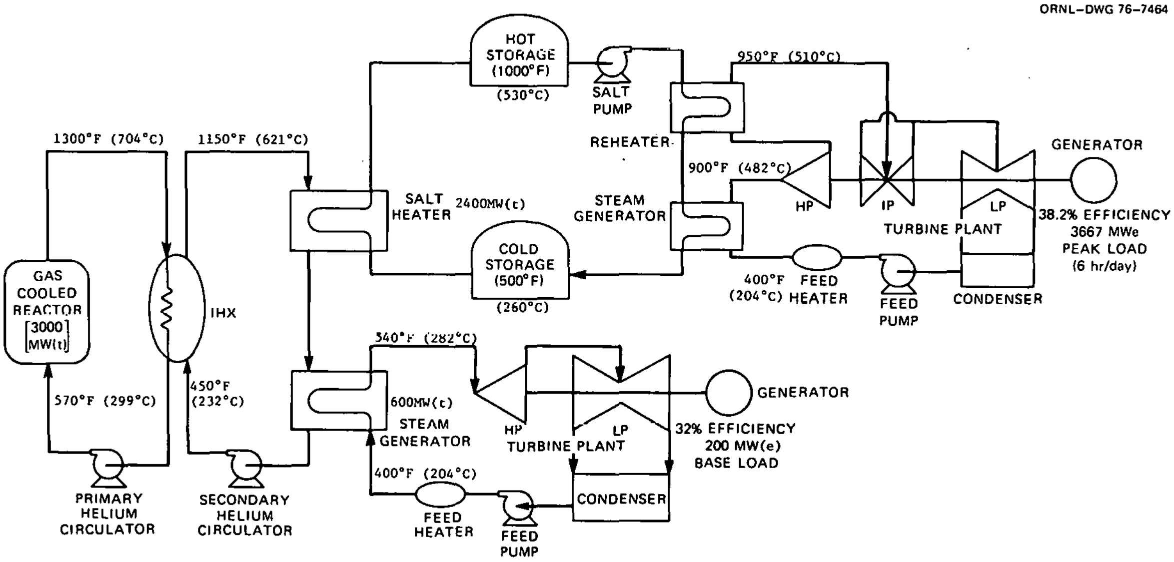

Fig. 33. VHTR peaking power system using HTS storage.

The amount of salt required would be about 7 x 10^8 lb, worth $105 million.

Heat transfer salt (HTS), marketed by Du Pont and others, is limited to about 1000°F because of thermal decomposition. The salt has a freezing point of 288°F and is contained in conventional iron-based alloys. The reactor technology required for molten-salt thermal storage is no more difficult than that for the steam-cycle HTGR. Development of an IHX, however, is required.

Energy storage in HTS may be a useful method of heat recovery from process VHTRs in the temperature range 500 to 1000°F. Intermediate-load and peaking power generated from such a system would probably be much easier to market than continuously generated base-load power.

Conceptual studies of the HTS energy storage system are being continued.

7. ENVIRONMENTAL CONSIDERATIONS

Based on preliminary studies, it appears that many of the environmental effects of the VHTR concept would be the same as those for the current commercial HTGR concept. The exceptional features of the VHTR that would need to be considered include higher temperatures and the specific process applications.

Higher temperature should not lead to any significant changes in the environmental impacts of a developed VHTR. However, in design and development of the concept, one must deal with the possible effects of higher temperature including fission product release, possible chemical reactions due to inleakage enhanced by higher temperature, potential failure modes, etc.

The environmental effects of process applications can be more far reaching. This concept represents a whole new range of applications of nuclear reactor technology. The environmental impacts (both favorable and unfavorable) could be very significant on uranium and fossil-fuel resources and mining, on land and water use, on energy conservation, and on energy self-sufficiency.

Synthetic fuels and commodities produced in VHTR process plants will undoubtedly be closely monitored to ensure that they are free of excessive radioactive contamination. This factor is one which must be considered in the analysis of the need for an IHX.

Several organizations have tried to assess the relative impacts of nuclear and fossil synthetic fuel plants.[6,7,36,37] The results of these evaluations are not always conclusive, but we believe the following to be generally accurate.

7.1 Atmospheric Emissions

SO_2 emissions from a nuclear-coal synthetic fuels plant (540×10^6 ft^3/day of pipeline gas) are expected to be in the range of 1500 tons/year, and NO_x emissions are expected to be an order of magnitude less. A comparable all-fossil plant would emit 3 to 30 times as much SO_2 and NO_x. Major sources of air pollution are steam boilers and process heaters. The potential exists to substantially reduce all of these emissions below the given estimates by process changes. These process changes would increase product costs.

7.2 Solid Waste

Since the nuclear coal conversion systems generally require only about two-thirds as much coal as conventional systems, they have potential for a reduced quantity of solid waste. On the other hand, chars in conventional systems may be used as fuel or for conversion to hydrogen; chars in nuclear systems are an undesirable by-product for which process uses should be found. Solid wastes may logically be returned to the mine for disposal during reclamation.

7.3 Water Use

The consumptive use of water is in the range of 250 to 500 lb/10^6 Btu of product in nuclear process plants or in alternative all-fossil synthetic fuels plants. Water is used as a source of hydrogen and is evaporated to reject heat. Since the thermal efficiency of nuclear and all-fossil processes are in the same range, it is anticipated that there are no major differences in water use.

7.4 Land Use

Nuclear coal conversion plants will somewhat reduce the large impacts of synthetic fuel production plants on land use for mining coal. Extremely large mines will be required, with several feeding into a VHTR coal conversion unit. Table 25 summarizes land-use impacts of selected energy plants.

7.5 Conservation of Fossil Fuels

It would be desirable to reserve fossil fuels for unique and irreplaceable uses such as transportation fuels and clean domestic fuels and feedstocks. The application of the VHTR could eliminate many fossil fuel uses and would make more ideal conservation possible.

7.6 Impacts on Coal Mining and Transportation

Each 3000-MW(t) process VHTR is expected to replace about 120 x 10^{12} Btu/year of coal that would otherwise have to be mined for the synthetic fuels industry (Fig. 34). Significant reductions in demand for coal start about the year 2000; by 2030 the reduction in demand for coal could be 800 million tons/year. Slowing up the rate of growth of coal mining would be expected to have environmental, social, and economic benefits. One important benefit should be a reduction in coal price, which would benefit the entire energy economy. Another benefit would be a reduced need to transport coal.

7.7 Impacts on the Nuclear Fuel Cycle

The use of the VHTR would increase all components of the nuclear industry including uranium and thorium mining, processing, enrichment, fuel reprocessing and recycle, and waste disposal. In particular, about

Table 25. Land-use impacts of selected energy plants[a,b]

Plant	Output	Output in 10^{15} Btu/year	Plant site	Land coal mining	Disturbed, acres Uranium mining & processing	Total
VHTR-coal liquids	180,000 BPD	0.30	2000	56,000	600	58,600
H-coal liquids	180,000 BPD	0.30	2000	66,000	-	68,000
VHTR SPG plant	540 X 10^6 ft^3/day	0.21	2000	36,000	600	38,600
Lurgi SPG plant	610 X 10^6 ft^3/day	0.21	2000	50,000	-	52,000
VHTR-coal hydrogen	900 X 10^6 ft^3/day	0.13	2000	18,750	600	21,350
Koppers-Totzek hydrogen	1250 X 10^6 ft^3/day	0.13	2000	34,000	-	36,000
VHTR thermochemical hydrogen	354 X 10^6 ft^3/day	0.038	500	--	600	1,100
1000-MW(e) HTGR	1000 MW(e)	0.024	100	--	600	700
1000-MW(e) Coal plant	1000 MW(e)	0.024	500	9,000	-	9,500

[a] Thirty-year plant life.

[b] Coal seams 2 m thick.

eighteen 3000-MW(t) VHTRs might be deployed by the year 2000 [vs eight-hundred 1000-MW(e) equivalent units in the electric utility industry], and 132 VHTRs could be justified by the year 2030 [vs twenty-five hundred 1000-MW(e) equivalent units in the electric utility industry]. Nuclear fuel cycle capacity would have to be increased by 2% by the year 2000 and 6% by 2030. The increased enriched fuel demand could be supplied by breeders, by increased mining, or by a combination of the two. Depending on what other reactor types were in use after the year 2000, the VHTR could possibly exert an increased demand for mining uranium much greater than its share of the nuclear market. However, increased costs of nuclear fuels should be much less than the savings in fossil fuels.

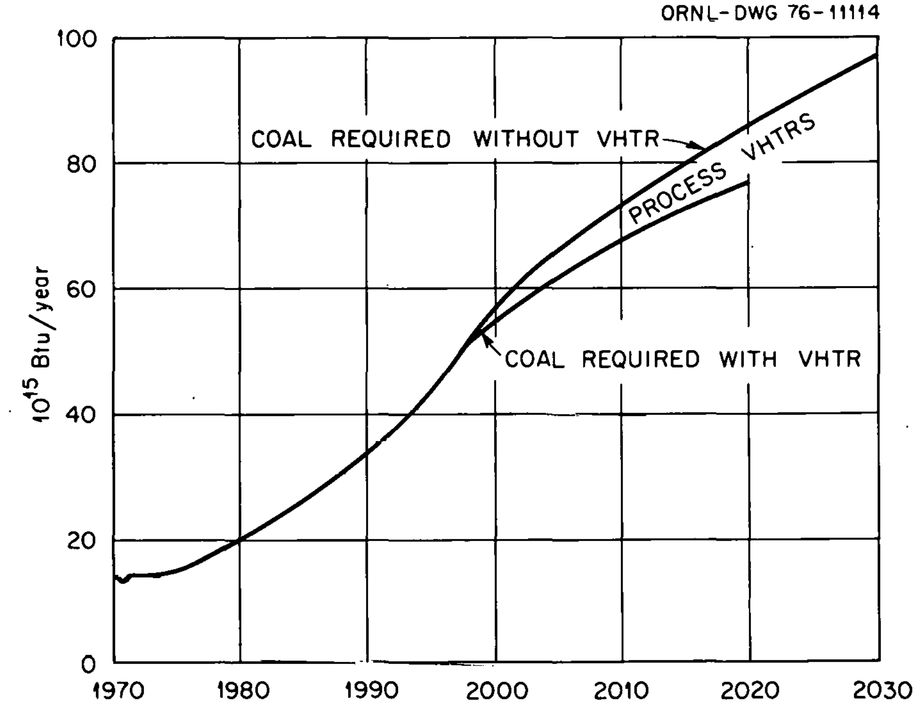

Fig. 34. Impact of VHTR on projected use of coal in the United States.

7.8 Introduction of the Thorium Fuel Cycle

The VHTR would consume thorium as the major raw material for fuel, supplementing the breeder which is based on ^{238}U raw material. The thorium cycle does not produce as many actinides for ultimate nuclear waste storage as does the plutonium-uranium cycle.

7.9 Impacts of EVA-ADAM Chemical Heat Pipe and of Thermochemical Hydrogen Plants

Because these systems appear to have higher product costs than do hybrid nuclear-coal plants, one would expect their introduction into the United States to be delayed until coal prices have increased substantially. Since fossil fuel inputs to these systems are minor, their environmental impacts are much smaller than the impacts of nuclear-coal hybrid plants. Thermochemical hydrogen plants and the "hydrogen economy" are environmentally salubrious and represent a valid long-term goal.

7.10 Atmospheric CO_2

The increased use of fossil fuels has substantially increased the CO_2 level of the atmosphere, thereby increasing solar heating. Other man-caused changes have increased particulates, which have an opposite effect. Climatologists do not currently agree about the importance of these phenomena. It is conceivable that future perceptions about atmospheric CO_2 will bring about limitations in carbon-containing fuels. In that event, the VHTR could play an important role in substituting nuclear for fossil fuels. Water-splitting processes would be preferred.

8. DISCUSSION OF RESEARCH, DEVELOPMENT, AND DEMONSTRATION PROGRAM

8.1 Status of Worldwide Programs on VHTR

The gas-graphite reactor concept has had three highly successful experimental reactor demonstrations: the Dragon Reactor, the AVR Reactor, and the Peach Bottom HTGR. Further, power operation of the Fort St. Vrain HTGR is planned the first part of 1976, and the THTR is scheduled for power operation in 1978. A strong research and development program is being carried out in HTR technology, including areas such as fuels and materials, fuel recycle, chemistry and fission-product behavior, graphite, PCRVs, reactor surveillance, and components testing.

The general applications of HTR technology under consideration have included steam-cycle power reactors, gas turbine (GT) reactors, VHTRs applied to nuclear process heat, and, finally, gas-cooled fast breeders (GCFR). A summary of major program status is as follows:

1. USA. Program has concentrated on steam-cycle HTGRs, with some R&D on the GT and GCFR. Work on VHTR started recently. Recent commercial reverses have brought doubt concerning viability of steam-cycle HTGR.

2. Germany. Strong programs are currently under way on the GT reactor and VHTR. There is a commercial capability for building HTGR steam-cycle reactors.

3. United Kingdom. HTR development has recently been dropped. The related Euratom Dragon project is also being terminated.

4. Japan. Emphasis is being given to the VHTR for application to nuclear steelmaking.

5. France. The program has broad objectives.

Worldwide VHTR activities are summarized in Table 26. The German and Japanese programs are believed to be the most significant.

Currently authorized under the German VHTR program are subtasks totaling 165 million DM (Deutsch Mark) (about $64 million). The major elements are nuclear coal gasification concept development, development of coal-steam gasification and hydrogasification processes, development of EVA-ADAM (chemical heat pipe), and development of a prestressed cast iron reactor vessel. Phase I of a prototype VHTR process plant has been proposed, leading to a detailed reference design and a major project decision in 1980; Phase I will cost about $220 million above what has already been authorized.

Table 26. Worldwide VHTR development activities

	USA	Germany	UK	Japan	France
VHTR concept development	+[a]	++[b]	+	+	+
Commercial reactor supply	++	++			
Component development	++	++		+	++
Nuclear fuel cycle facilities	++	++			
Fuels	++	++	++	+	
Materials	++	++	++	++	+
Methane reformer		++		+	
Matching coal conversion		++			
Nuclear steelmaking	+	+	+	++	

[a] Some research and development reported.

[b] Major program

The Japanese Agency of Industrial Science and Technology has initiated a six-year (1973-1978) program to develop nuclear steelmaking process technology. The budget is 7300 x 10^6 Yen (about $25 million), covering high-temperature heat exchangers, alloys, insulation materials, methane reformers, and direct-reduction systems. The Japanese Atomic Energy Research Institute is planning to build a 50-MW(t) 1000°C reactor to start power operation in 1982. Funds are being expended in the development of fuels, graphite, and reactor component materials; in-pile loop tests at up to 1000°C are expected to start in 1976. There is no indication of actual authorization of the large commitment of funds that would be required for the experimental reactor.

8.2 Status of U.S. Programs on VHTR

Studies of nuclear-coal hybrid systems were started in 1971 by the State of Oklahoma, General Atomic, and Stone & Webster. The Office of Coal Research (OCR) supported a portion of this work, which culminated in the publication of the *Oklahoma Report*,[31] covering the GA/S&W process for the production of pipeline gas from coal. The total cost of this first phase was estimated at $700,000.

A second phase of development of the GA/S&W process has been supported by GA, S&W, Columbia Gas, Transco, and San Diego Gas and Electric Company, covering a period up to April 1976. Hydrogasification tests on coal liquids are under way at Gulf Science and Technology laboratories near Pittsburgh. Conceptual design work is being carried out both on reactors and on process. The cost of this phase is $900,000.

The American Iron and Steel Institute and General Atomic have carried out a group of studies on nuclear steelmaking, which have recently been summarized by D. J. Blickwede.[12] Activities have focused on concepts, economic analysis, reformer technology, and materials.

A number of private R&D programs are being carried out on thermochemical water splitting. The American Gas Association has sponsored such work at the Institute of Gas Technology. Westinghouse states that they have invested over $3 million since 1972 in defining the potential of the VHTR and its applications and in the development of the sulfur-cycle water-splitting process described earlier in this report. General Atomic is also doing analytical and laboratory work under private sponsorship. In addition, NASA has sponsored analytical studies at the University of Kentucky, and ERDA has supported research on water splitting at Los Alamos Scientific Laboratory (LASL) and at ORNL.

The AEC (now ERDA) support of the VHTR was started in FY 1975 at about $1 million. Conceptual studies by GA, GE, and Westinghouse (Fig. 1) were carried out, and LASL undertook development of advanced fuels and system studies. The Office of Coal Research (now a part of ERDA) supported nuclear coal conversion studies at ORNL, which form part of the present evaluation. The National Aeronautics and Space Administration undertook studies of hydrogen production from VHTRs by GA and Westinghouse.

The ERDA support of the reactor studies and development are expected to be about $2.8 million in FY 1976. Programs started in FY 1975 are being continued and a high-temperature materials R&D program was awarded in April 1976.

The present report should focus attention on the needs for the VHTR and should form one basis for a long-range program plan.

8.3 VHTR Program Objectives and Discussion

The major objectives of the VHTR program should be to develop and demonstrate the technology for the generation and use of nuclear process heat. The program should be phased and coordinated with private industry to ensure that proper selection and timing of process applications will take place. The program should seek to solve those technical problems that appear to present the greatest risks for decisions in the private sector. One aspect of the program should be the development of an industrial capability to design and build large HTRs. The program should be balanced between the nuclear technology required and the process technology that would properly exploit the nuclear process heat.

Table 27 presents a matrix of goals for the VHTR and for nuclear process heat that appear to be reasonable for the United States, based on the current study.

Table 27. Goals for the VHTR and for nuclear process heat

Maximum process temperature (°F)	Type of coupling	Applications	Date of lead plant
1400 to 1500	Steam reforming of light hydrocarbons	Hydrogen production, nuclear steelmaking, coal hydrogasification and liquefaction, and chemical heat pipe	1995
	Fluidized-bed process heater	Steam-gasification of lignite and catalyzed char	1995
1600 to 1800	Fluidized-bed process heater	Steam-gasification of coal	2000
	Process heaters	Thermochemical water splitting	2000 or later

Some of the unique features of the VHTR concept that have been proposed by the vendors should be further explored in the development program:

1. An isolation loop appears to be desirable from the standpoint of safety and very likely will be required for most process heat applications. The typical process fluids appear to have the potential for creating hazardous and damaging reactions in the primary reactor loop. An isolation loop would provide an opportunity to clean up contaminants from both the process and the reactor and would avoid the introduction of process fluids into the reactor system and would likewise avoid the potential release of radioactive contaminants. A purification system must be assumed as a part of the isolation loop.

Additional work to look at alternate design approaches for the isolation loop to reduce costs appears worthwhile.

2. The GA fuel concept appears adquate for the 1400 to 1500°F maximum process temperature range, but at some small penalties in fuel cycle cost and/or pumping power as temperatures are increased. Beyond this temperature range, advanced fuel particle development is required.

The pebble-bed fuel concept presented by GE appears capable of higher process temperatures than the GA prismatic fuel concept. The OTTO (once-through-then-out) cycle, however, has not been demonstrated.

The Westinghouse fuel system has the potential for achieving the necessary temperatures. Because this configuration of extruded fuel has never been used in power reactors, it would require substantial development and testing.

3. The prestressed cast iron vessel (PCIV) proposed by Westinghouse could be very worthwhile and is recommended for additional study. This concept could save considerable cost and onsite construction time if remotely fabricated in a factory and assembled on the site. The application of the PCIV is not limited to the VHTR concept; therefore, it is recommended that the PCIV be evaluated as a part of the overall Gas-Cooled Reactor Program.

4. If an isolation loop is required, significant cost savings in PCRV (or PCIV) and containment building costs can be realized if steam generators are located only in the intermediate loop outside the PCRV. Also, this would eliminate the potential for steam ingress if the auxiliary coolant system and other miscellaneous applications of water (steam) were revised. In view of the higher temperature of the graphite moderator, inherent in higher outlet coolant temperature concepts, the elimination of potential steam ingress could be an important advantage in reactor safety.

During the VHTR development program, there exists a need to resolve some of the broad issues that remain uncertain at this date, such as the issues discussed below.

8.3.1 Industrial participation

The VHTR would have major impacts on the energy industries (synthetic fuels production, electric utilities, and coal mining) and the energy-using industries (steel and chemicals). Except for the American Iron and Steel Institute, nuclear process heat assessment seems to be beyond the planning horizon of U.S. companies. There is a need to factor industrial judgment into ERDA's planning for this program.

8.3.2 Commercial supplier of the VHTR

For the development program to be meaningful, ERDA will have to encourage (and possibly provide financial incentives to) those organizations that will build and operate the lead plants, in order for suppliers to establish the VHTR as a commercial product.

8.3.3 Resource availability

On the one hand, a major incentive for the VHTR is the conservation of fossil fuel resources. On the other hand is the question of the availability of sufficient nuclear fuel resources. If the breeder is not widely commercialized, then the VHTR would be competing with current power reactors for a limited nuclear fuel resource. Some analysis of the various aspects of the resource questions is vital. This should include analysis of high-conversion-ratio VHTR designs and the possibilities of minimizing the fissile inventory of the fuel cycle. The present report indicates that VHTR process costs would be in an acceptable range with uranium at \$100/lb. The necessary nuclear fuel resources should be developed in parallel with development of the reactor concept.

8.3.4 Environmental and safety questions

In many respects the results of the analysis of environmental effects could be favorable to the VHTR. However, this cannot be assured, and environmental and safety questions should be the subject of a very thorough investigation early in the development program.

8.3.5 The IHX

The question of whether an intermediate heat exchanger loop is necessary or required is perhaps the most significant issue from the standpoint of VHTR cost and public acceptance. Additional work in this area has already been initiated by ERDA.

8.3.6 Materials difficulty

It appears that suitable materials can be developed for process temperatures of 1400 to 1600°F. However, this cannot be assured until after materials development and code qualification are completed. The materials development program is of crucial importance to the VHTR. Steam power plant cycles over 1000 to 1100°F have apparently been abandoned because of materials problems. Similar difficulties cannot be ruled out in the VHTR development.

8.3.7 Feasibility of appropriate coal conversion applications

The major applications envisioned for the VHTR involve processes that are not yet fully developed. The potential of these applications, and therefore of the VHTR, will remain in doubt until appropriate demonstration of the process feasibility has been carried out.

8.3.8 Development of the thorium fuel cycle

Commercialization of the VHTR would call for development of the thorium fuel cycle. The thorium cycle is a very attractive one for thermal reactors and may be developed independently of HTRs. In any event, the development and commercialization of fuel reprocessing-^{233}U recycle technology will be expensive.

8.3.9 Institutional problems

All process heat applications for the VHTR involve staged temperature utilization. In general, higher temperature energy is used in process heat and lower temperature energy is utilized in steam generation for electric power. Some process applications may be able to use all of this electric power. Many will not. As a result, one can foresee an institutional problem if the products for sale include industrial process heat and electrical power. In the past, utilities have been reluctant to get into the industrial process energy market. If industry operated the plant, they would presumably be required to market the excess power through the local utility.

8.3.10 Availability

Nuclear reactor availability is an important factor in the decision to use nuclear heat for a particular process application. General Atomic indicates[18] that steam-producing HTGRs have a planned availability of 95.6% and believes this is applicable to the process heat plants. A review of British and U.S. power reactors[3] shows that they have had availabilities of 82.4% and 79.8%, respectively. It seems reasonable then that the process heat reactors would have an availability of about 80%, which would increase with time and operating experience to an upper limit of about 90%. Providing for plant outages may be accomplished during the design phase by using multiple units, fossil-fuel backup, and, in some cases, thermal storage. The choice of the particular system design will depend on the process configuration and whether there will be multiple users. It should be noted that many processes may be able to accept some plant outages by stockpiling their products.

8.3.11 Size mismatch

In many cases one 3000-MW(t) VHTR provides much more energy than is normally required for a single industrial plant or process application. Thus, some applications may involve multiple customers for a single reactor or reactor site. The development of 1000- to 2000-MW(t) economic units would be very desirable.

8.4 Program Options

The HTR technology is a very attractive one and its technical feasibility for large units appears to be assured. Thus far it has not succeeded commercially because the margin of potential superiority over other energy sources (light-water reactors) has not been decisive in any application or in any country. All future applications of the HTR (including the VHTR) would benefit enormously from the early introduction and commercial success of the gas-graphite reactor in any one application. The prospects for commercialization which appear to us be most likely are the following:

(1) Steam-cycle HTGR. General Atomic Corporation has indicated that it is making a strong effort to develop a competitive design. The first commercial plant could be started about 1987 if support is found for this program.

(2) German VHTR. German hard-coal prices are now just under \$2/MBtu, and their major source of fuel is imported oil at about the same price level. In view of the large German investment in HTR technology and the high price and scarcity of fossil fuels, prospects appear bright for a VHTR prototype by 1990 and commercialization by 1995.

(3) Japanese VHTR. Steelmaking, based on imported coal, constitutes 20% of the Japanese demand for energy. Coal has recently increased greatly in price, and the coal supply has become less reliable. Japan has very strong incentives to deploy the VHTR and is likely to be interested in a cooperative VHTR program.

(4) Peaking HTR. If this system were developed, an economic size prototype [1000 to 2000 MW(t)] could probably be deployed by 1990.

A number of sequences of VHTR introduction have been suggested, including;

1. HTGR → VHTR,
2. HTGR → HTGR-direct cycle gas turbine (GT) → VHTR,
3. HTGR-GT → VHTR,
4. VHTR directly.

Because all variations of the HTR share technology and fuel cycle facilities, it is highly desirable that HTGR power reactors be commercialized and deployed prior to the buildup of VHTRs. This strategy would reduce the costs and risks of VHTR development, and, therefore, improve benefit-cost assessments pertaining to the VHTR. Sequence 1 above is therefore preferred, assuming that the competitive power producer can be developed. If not, sequence 4 would appear to be the next best choice.

Other considerations are the risk-benefit analysis of each major step and the willingness of private industry to assume risks. Criteria favoring strong private participation would include:

1. perception of possibilities of increased profits and/or reduced costs,

2. technological simplicity,
3. environmental attractiveness,
4. high probability of success, and
5. strong commercial sponsorship and warranties.

The steam cycle HTGR appeared to satisfy these criteria until recently. Recent deficiencies have appeared in the economic projections, and difficulties with the Fort St. Vrain reactor have raised doubts in some quarters about the probability of solving the detail design problems inherent in the concept. Assuming that Fort St. Vrain is soon brought effectively on line, the best possibility for early industry participation would still appear to be the HTGR.

The intermediate-load and peaking HTR via heat transfer salt thermal storage appears to have characteristics that may lead to a favorable risk-benefit analysis for early deployment. If the HTGR cannot be made viable, this system might be a practical target for the commercial introduction of the HTR in the United States.

There do not appear to be the necessary strong economic incentives to balance the technological risks of early deployment of the HTGR-GT or the process VHTR in the United States. These concepts should preferably be preceded by technologically simpler HTRs in the United States and/or by foreign VHTR prototypes.

A number of nuclear process-heat program options appear to be available for consideration by ERDA;

1. Full-scale ERDA program leading to a U.S. VHTR process plant prototype at the earliest possible date (about 1991).
2. An international cooperative program, to which ERDA would make

substantial contributions, leading to the capability for a process VHTR lead plant in the U.S. to start up about 1995. Foreign prototypes would be possible by about 1990 if foreign investments were made.

3. An R&D program emphasizing key problem areas.
4. No program.

It is recommended that the second alternative be accepted. A cooperative international program would be effective in two ways. First, it would minimize duplicate effort on the part of the participants and would allow the United States to profit from the development work of others. Second, this cooperative effort would reduce the funding required from any particular participant and would accelerate the development of a viable VHTR system. The U.S. contribution to the program should emphasize key technology areas carried out in the United States and should develop U.S. vendor capabilities to supply a lead plant.

8.5 VHTR R&D Program Elements and Costs

The VHTR technology is based on the extrapolation of HTR steam cycle technology as typified by the Fort St. Vrain or the THTR pebble-bed reactor. If additional HTGRs are built, the HTGR Base Program costs will be chargeable to those plants. If HTGRs are not built, most of the base technology will still be needed if VHTR process plants are to be built. (HTGR-GT plants also use much of the same base technology.) The scope of the HTGR base program is assumed to cover the following major elements:

1. Reactor core design;
2. Component development and testing;
3. Fuel materials and fabrication development;
4. Materials development for 1400°F helium outlet temperature (metals, graphite, insulation);
5. HTGR chemistry; and
6. In-service inspection and instrumentation.

The HTGR base R&D program cost, starting in FY 1977 and culminating in the construction of a lead HTGR (or VHTR) plant, is estimated to be about $130 million (in 1975 dollars). In the event that ERDA decides to go directly to the VHTR, bypassing HTGR and HTGR-GT, the base program must be restructured in scope and timing.

Each VHTR vendor study[2-4] presented an R&D study required for the concept. The elements have been reviewed and modified by ORNL staff, and other elements have been added to present a complete program concept.

A five- to eight-year VHTR program-definition phase is recommended, leading to a decision on whether to support development and construction of a lead VHTR process plant. The reactor development program must be reinforced by an applications-evaluation and process-development program that provides process data required for the decision to build a lead VHTR process plant. The cost of these programs, through the decision point, is expected to be $110 million and $60 million for the reactor and process programs, respectively. The ERDA's share of these costs could be reduced by suitable international program sharing.

The scope of VHTR development is assumed to cover the following major elements:

1. Overall system conceptual design and costs,
2. High-temperature materials development,
3. High-temperature design methods,
4. Intermediate heat exchanger development,
5. Methane steam reformer development,
6. High-temperature fuel and core components,
7. Component development,
8. High-temperature chemistry, and
9. Safety.

Additional details are given in Section 8.6.

The scope of applications evaluation and process R&D is assumed to cover the following major elements:

1. Development of processes for producing hydrogen from coal and heavy liquids via nuclear-heated steam–light hydrocarbon reforming;
2. Development of nuclear coal-conversion processes for producing synthetic pipeline gas and liquids;
3. Nuclear shale-oil processing;
4. R&D on thermochemical water-splitting;
5. Evaluation of EVA–ADAM chemical heat pipe; and
6. Development of molten salt thermal storage, transport, and energy conversion technology.

Additional details are given in Sect. 8.7.

The HTR technology program must be supported by a graphite fuel reprocessing and recycle program. The ERDA has been considering support of reprocessing-recycle facilities that would serve early commercial steam-cycle HTGRs. Because the HTGRs are now not being built on the original schedule and may not be built at all, the fuel reprocessing-recycle program can obviously be stretched out. If the national program on HTRs proceeds directly to the VHTR with a lead plant to be operated in 1995, only laboratory-scale R&D should be supported during the program definition phase. A minimal five- to eight-year expenditure in the range of $50 million would perhaps be justified. This program could benefit from international agreements.

The fuel reprocessing-recycle program is assumed to include: (1) fuel handling development, (2) reprocessing development, (3) refabrication development, (4) waste treatment development, and (5) fuels irradiation testing and evaluation.

Following a decision to build a lead process VHTR, the above R&D programs would be continued. Some effort would be expended on increasing the temperature capabilities. Lead plant design and detail development would be authorized, including the following items: (1) detail design of nuclear and process plants, (2) verification tests of key components, (3) preliminary and final safety analysis reports, and (4) environment report.

The total R&D program cost is summarized in Table 28. The commitment to a VHTR process program is $170 million prior to a decision to build the lead plant. Additional costs of $110 million are incurred for supporting programs. The ERDA's share of all of these costs may be reduced through international agreements, which are recommended.

Table 28. Summary of R&D program elements required for lead VHTR process plant[a,b]

Element	Budget (millions of 1975 dollars		
	Program definition (phase 5-8 years)	Construction phase	Total
VHTR process program			
VHTR development	110	110	220
Applications evaluation and process R&D	60	60	120
Lead plant design and detail development		120	120
Subtotal, VHTR process program	170	290	460
Supporting programs			
HTGR base program	60	70	130
Fuel reprocessing-recycle	50	100	150
Subtotal, supporting programs	110	170	280
Total	280	460	740

[a] Estimate does not include the construction cost of the lead VHTR process plant

[b] Estimate assumes HTGR-steam cycle and HTGR-gas turbine plants are not developed, so that costs of the supporting programs are chargeable to VHTR.

8.6 VHTR Development Details

The following is an outline of priority tasks that should be undertaken during the five- to eight-year program-definition phase.

1. Overall lead plant conceptual design — $35 million. The system to be designed should have a process temperature of 1400 to 1500°F, assuming that the coupling component will be a steam—methane reformer. Important initial design choices that must be made are IHX vs duplex-tube PHX vs no IHX, and pod-type PCRV vs nonintegrated PCRV. This phase should include analyzing cycle conditions — identifying component design requirements, determining maintenance criteria, and developing a specific

conceptual design that forms the basis of a decision whether to build the lead process plant. One aspect of the design program relates to the proper choice of size; sizes in the range of 1000 to 2000 MW(t) would probably be preferred if economical.

2. Materials development program — $15 million. This program includes materials selection for the 1400 to 1500°F lead process plant, physical tests in the appropriate environments and at temperatures up to 1850°F, welding, corrosion tests, tests of compatibility with fission products, materials qualification, and alloy development. A convincing case must be developed that these materials will perform reliably and be licensable. Additional qualification and alloy development would be carried out during the later detail design-construction phase, increasing the total materials-development cost to $25 to $30 million. About 10% of this program should be directed at materials for the 1600 to 1800°F process plants.

3. High-temperature design methods — $5 million. New structural design technology will be required for equipment operating at temperatures far above current standards. This program will develop information on material responses to applied loads, mathematical descriptions of materials behavior or constitutive equations, structural analysis methods, and design rules and criteria.

4. Intermediate heat exchanger — $10 million. Development of the IHX should be initiated as a high-priority item under the assumption it will be required in the lead plant. If the conceptual design task and subsequent licensing action indicates the IHX will not be needed in the lead plant, there could be a slow-down in IHX development after the

program-definition phase. The IHX would be needed, in any case, for later process plants (such as for steam-coal gasification or for thermochemical watersplitting).

5. Steam reformer — $5 million. This is a key component; hopefully a great deal of relevant information will be obtained from the German program. The reformer should be optimized for the process conditions selected. If the reformer will be inside the PCRV, it may be desired to develop a smaller-diameter tube than the conventional reformer tube. If analysis shows it to be desirable, a duplex-tube should be developed.

6. Fuel and core components — $10 million. Development should focus on higher-performance kernels, more retentive coatings, better thermal transfer between fuel particles and coolant, and irradiation testing. High conversion ratio concepts and components should be developed.

7. Component development — $15 million. At this stage, efforts should be focused on a 2-MW electrically heated component test loop such as proposed by D. L. Hanson and M. E. Muller.[38] Experiments would cover high-temperature ducts, insulation, IHX modules, reformer tube, etc. Practical experience should be gained in long-term operation at VHTR temperature levels (1400 to 1600°F process) and simulated chemical conditions.

8. Chemistry — $5 million. Accurate predictions are needed of tritium behavior, fission product transport and interactions, reactions of graphite with helium impurities, etc. This program is an extrapolation of HTGR base program work to the temperature levels characteristic of process VHTRs.

9. Safety — $10 million. This program should be closely coordinated with the HTGR safety program, and relates primarily to safety implications of the higher VHTR temperatures and the possibilities of process-reactor interactions. Work should be started on the PSAR of the lead VHTR process plant, and licensing needs of the lead plant should be considered.

The above program should be considered for either the "full-scale ERDA program" option or for the "international program" option. The major differences between these two cases are the number of years scheduled for the program definition phase and the possibility of some cost-sharing with other countries.

If ERDA chooses a "technology" program, the high-temperature materials work should be carried out as proposed above, concept development should be pursued at a reduced level, and some fuel work and component development should take place. International technology-sharing should be an important part of such a program.

Table 29 presents a breakdown of the anticipated VHTR development cost.

Table 29. Estimate of VHTR development detail costs (millions of dollars)

Development step	Program definition phase	Construction phase
Conceptual design	35	
Materials development	15	15
High-temperature design methods	5	5
IHX	10	15
Steam reformer	5	20
Fuel and core components	10	8
Components and PCRV	15	15
Chemistry	5	5
Safety	10	10
Contingency		17
	110	110

8.7 Applications Evaluation and Process R&D

The following is an outline of applications tasks that should be undertaken during the five- to eight-year program definition phase. It should be recognized that inputs into this part of the report were much more limited than into the VHTR R&D needs. Therefore, if ERDA decides to support a significant nuclear process-heat program, it will be imperative to better define process research, development, and demonstration priorities at an early date.

1. Development of processes for producing hydrogen from coal and heavy liquids via nuclear-heated steam-light hydrocarbon reforming — $20 million. The application envisioned here is the secondary energy depot of Fig. 10. It resembles the Japanese approach to nuclear steelmaking. The AISI Task Force on Nuclear Steelmaking has also suggested this approach.[14] Program tasks are expected to be definition of carbon feedstocks, definition of appropriate commercial or near-commercial process elements, identification of missing process links, laboratory and pilot-plant scale R&D on needed process elements, R&D relating to use of chars, R&D relating to standards for the hydrocarbon feed to the reformer (for example, maximum acceptable impurity levels from corrosion point of view), and development of an overall system concept. This task should have the participation of industries that represent potential sponsors or customers of such a plant. If the program definition phase resulted in a decision to build the lead VHTR process plant, it seems likely that this process concept would be adopted.

2. Development of nuclear coal-conversion processes for producing synthetic pipeline gas and liquids — $15 million. Program tasks are

expected to include definition of appropriate commercial or near-commercial process elements, definition of missing process links, R&D on steam-coal and steam-char indirectly heated processes, and development of preferred overall system concepts for the production of liquids and SPG. Key objectives are to evolve simple coal conversion systems if possible, to minimize char production, and to find the proper balance between maximum nuclear process-heat temperature and process efficiency. During the program definition phase, it would be desirable to narrow development to one liquids process and one SPG process. A decision should then be made, with industrial participation, as to the rate at which this technology should be developed further and deployed. A great deal of technology will be developed in nuclear coal-conversion process in Germany; it would be desirable to gain access to the results of that work.

3. <u>Nuclear shale-oil processing — low budget</u>. While nuclear process heat might eventually make an important contribution to shale-oil extraction and refining, it is not likely to be an important element in initial shale-oil ventures. Work in this field should be limited to evaluations until such time that greater possibilities are apparent.

4. <u>Thermochemical water splitting — $10 million</u>. Applications for thermochemical water splitting in the United States are likely to be after the year 2000. This type of process is expected ultimately to become so important that R&D is justified now. Los Alamos Scientific Laboratory[39] and Westinghouse[7] have proposed R&D programs. Recommended R&D program steps should include laboratory investigation of the kinetics of key process steps, thermodynamic measurements, thermodynamic analysis

of alternative cycles to make best use of practical process steps, and limited engineering-scale tests. An ERDA long-range plan for development of thermochemical water splitting would be desirable.

5. Evaluation of chemical heat pipe — low budget. Because, in our evaluation, this system does not appear likely to compete with synthetic pipeline gas in the United States prior to 2000, the program should be limited to exploratory evaluations at the present time. If a cost-effective concept is evolved, an appropriate R&D budget should then be made available. Germany is making a major effort on the EVA-ADAM system. The results of that program should be followed closely and factored into ERDA programmatic decisions.

6. Development of heat-transfer salt thermal storage, transport, and energy conversion technology — $15 million. Because this technology can be used with HTRs operating at current temperature levels, it may be applied sooner than the VHTR technology for process heating or for power generation. The major problems foreseen are in developing technology for stabilizing and containing the salt at the upper end of its temperature range and for developing components such as HTS steam generators.

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