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Technical Assessment of the Office of Industrial Programs' Advanced Heat Exchanger Program

February 1987

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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TECHNICAL ASSESSMENT OF THE OFFICE OF INDUSTRIAL PROGRAMS' ADVANCED HEAT EXCHANGER PROGRAM

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EXECUTIVE SUMMARY

In support of the Office of Industrial Programs (OIP), U.S. Department of Energy (DOE), a panel of industry experts was convened to review the current technical status of OIP's Advanced Heat Exchanger (AHX) Program and make recommendations regarding the future program structure.

The AHX Program is a part of the OIP's industrial energy conservation strategy to support heat exchanger research and development (R&D) projects that are long-term, high-payoff, and high-risk. This represents a significant redirection from OIP's very successful near-term approach of the 1970s. The near-term technology sponsored by the DOE was estimated to have saved 116.3×10^{12} Btu (DOE 1984). In terms of dollar leverage, $12.25 were saved for each $1.00 expended by the federal government on completed OIP technologies. Now that the near-term, high-impact conservation efforts are in place, the transition to a long-term high-risk program is considered to be a proper role for federally supported industrial R&D. Federal support is considered essential to ensure continued progress in developing competitive, energy-efficient industrial processes and practices.

The panel was convened in Washington, D.C. on January 30, 1986, and charged by OIP to review and evaluate the AHX Program's technical substance and to comment on aspects of the program that should be continued, changed, and discontinued.

In response to the first charge, the panel recommended that the following programs and projects should be continued:

1. development of cost-effective, monolithic ceramic material production and fabrication techniques
2. development of cost-effective, composite ceramic material fabrication and coating techniques
3. development of nondestructive evaluation (NDE) techniques for ceramic materials
4. development of novel, fluid-bed heat exchangers, including the tubular distributor grid configuration.

In response to the second charge, the panel recommends that the following programs and projects be changed:

1. shift R&D emphasis from rapidly declining, heavy industries to emerging high-technology, high-temperature (HTHT) industries having a broad range of temperature, pressure, and corrosion requirements

2. accelerate the developmental work on enhanced heat transfer techniques, including both convective and radiant heat exchanger processes, and combine with advances in three dimensional woven coated fabric composites and extruded monolithic shapes

3. redirect the waste energy stream diagnostic work to define new opportunities for waste heat recovery

4. expand corrosion-resistant materials' and coatings' projects to include heat exchanger applications ranging from 1000°F to 1600°F

5. include industrial user field testing and the value of factual field performance data for examination by prospective users as integral proof of the AHX Program

6. consider ways to better use the talent and facilities of the national energy laboratories and universities

7. concentrate contact with the technology user community through furnace, boiler and recuperator manufacturers to identify generic heat transfer technology needs and to gain support for field testing and commercialization

8. study program selection and management strategy to assure that progress toward objectives is maintained.

In response to the third charge, the panel recommends that the following projects be discontinued:

1. AiResearch's and Babcock & Wilcox's high-temperature burner duct recuperator (HTBDR) project

2. Thermo Electron's fluid-bed waste-heat recuperator (FBWHR)

3. high-temperature heat pipe technology
4. development of a fouling probe.

GLOSSARY OF ABBREVIATIONS

AHX	advanced heat exchanger
CVD	chemical vapor deposition
DOE	Department of Energy
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
FBWHR	fluid-bed waste-heat recuperator
GRI	Gas Research Institute
HIP	hot isostatic pressing
HTBDR	high-temperature burner duct recuperator
HTGR	high-temperature gas-cooled reactor
HTHT	high-technology high-temperature
MHD	magnetohydrodynamic
NDE	nondestructive evaluation
OIP	Office of Industrial Programs
ORNL	Oak Ridge National Laboratory
PNL	Pacific Northwest Laboratory

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1.0 INTRODUCTION

The DOE's AHX Program is an integral part of the OIP's Waste Heat Recovery Program. The programmatic goals of the OIP are to 1) increase the end-use energy efficiency of industry and agricultural operations, and 2) expand the energy options for manufacturing processes by providing technologies which use various fuels including coal, renewables, oil, and natural gas. To achieve these goals, the OIP has established the following objectives:

- perform R&D of selected high-risk conservation technologies on a cost-shared basis with private industry
- capitalize on energy conservation R&D opportunities identified in the private industrial sector which, for a variety of reasons, are not being pursued
- encourage, through information dissemination, the implementation of energy-conserving technologies by the private sector once they are developed
- conduct the Industrial Energy Efficiency Improvement Program as mandated by the Energy Conservation and Policy Act.

The overall intent of the OIP's Waste Heat Recovery Program is to

> ". . . establish a strong technology base to address current deficiencies which prohibit timely development of ceramic heat recuperators and heat pump technology for a wide range of industrial waste heat sources."

The AHX program is a major activity within OIP for high-temperature waste heat recovery. It is recognized that heat recuperator technology is potentially subject to severe performance degradation because recuperators operate in high-temperature, corrosive and surface-fouling environments. Thus, over the past ten years, the AHX program has supported a number of projects which have not only significantly advanced hardware development and field testing but also supported related technological improvements. In many cases, the AHX Program helped to advance the state of the art in materials, instrumentation and operation.

Within the context of these goals and objectives, the OIP, acting through Pacific Northwest Laboratory (PNL),[a] has convened a panel of industry experts to conduct a technical assessment of OIP's AHX Program. This report documents the results of the panel's assessment. The panel's evaluation occurred during a period when the spot price for oil dropped from $27 to $13 per barrel. It helped to focus the panel's attention to the market forces which can affect technology development and utilization and the risks involved.

This report is a composite of contributions by each panel member. The panel based its evaluation on information provided by the OIP at a meeting on January 30, 1986, in Washington, D.C. Subsequently, OIP, PNL, and others provided supplemental information on topics that included the characterization of industrial waste and input heat flows, and detailed technical information on completed and ongoing projects sponsored by OIP in advanced heat exchanger development.

To consolidate the material from the individual panel members, three panel meetings were convened: the first in Washington on January 30 and two in Chicago on February 18 and April 1, 1986. A common outline was developed and the following individuals contributed in assigned subject areas:

Chairman:	Franklin G. Rinker, P.E. Industry Consultant
Panel Members:	James Batman Industry Consultant
	Arthur Ed Bergles, Ph.D., P.E. Professor of Mechanical Engineering Industry Consultant
	Thomas J. Marciniak, Ph.D., PE President, Enerteq Sciences

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute.

The panel's conclusions were arrived at independently and the report documents the consensus of the group. Results include analysis of business conditions in the industrial heat exchanger marketplace and analysis of the program portfolio and its fit with industry trends as the panel views them.

This report summarizes the opinions of the panel members and is intended to assist OIP in structuring the AHX Program. In preparing this report, the panel used the present program structure as a basis for its recommendations for the future of the AHX Program.

2.0 MARKET ASSESSMENT

The key to continued success of OIP's AHX Program is a continued awareness and evaluation of both current and emerging markets for industrial heat exchangers in the United States. The panel's approach in defining these market needs was to evaluate both existing target industries and emerging industries, as identified by the panel. Each is discussed in more detail in the following sections.

2.1 ANALYSIS OF TARGET INDUSTRIES

For the past several years, the AHX Program has concentrated on the research, development, and demonstration of high-temperature (>1600°F) recuperators. The reason for this is quite simple. The heat exchanger manufacturing industry is mature, and a vast array of economical equipment is available for applications at temperatures below 1000°F. It is widely recognized that as high temperatures are encountered, especially in corrosive and fouling environments, materials are severely structurally and chemically degraded. Figure 2.1 shows the temperature distribution of industrial waste heat streams based on data compiled by PNL (Wikoff et al. 1983).

At temperatures exceeding 1000°F, the total amount of renewable industrial waste heat is approximately 0.7 quad (1.0 quad = 10^{15} Btu). Although this represents only 10% of the 6 to 7 quad of industrial waste heat streams, it is present in industries that can benefit most from improved process efficiency and lower operating costs--the primary metals and glass industries. Based on this assessment, the energy-intensive industries targeted by DOE for AHX development included the following processes:

- steel mill soaking pits
- steel mill reheat furnaces
- aluminum reheat furnaces
- glass melting furnaces
- direct-fired, high-temperature furnaces.

The economic value of recovering the heat above 1000°F that is now wasted could have a displaced fuel value of $1.6 billion based on an average energy cost of

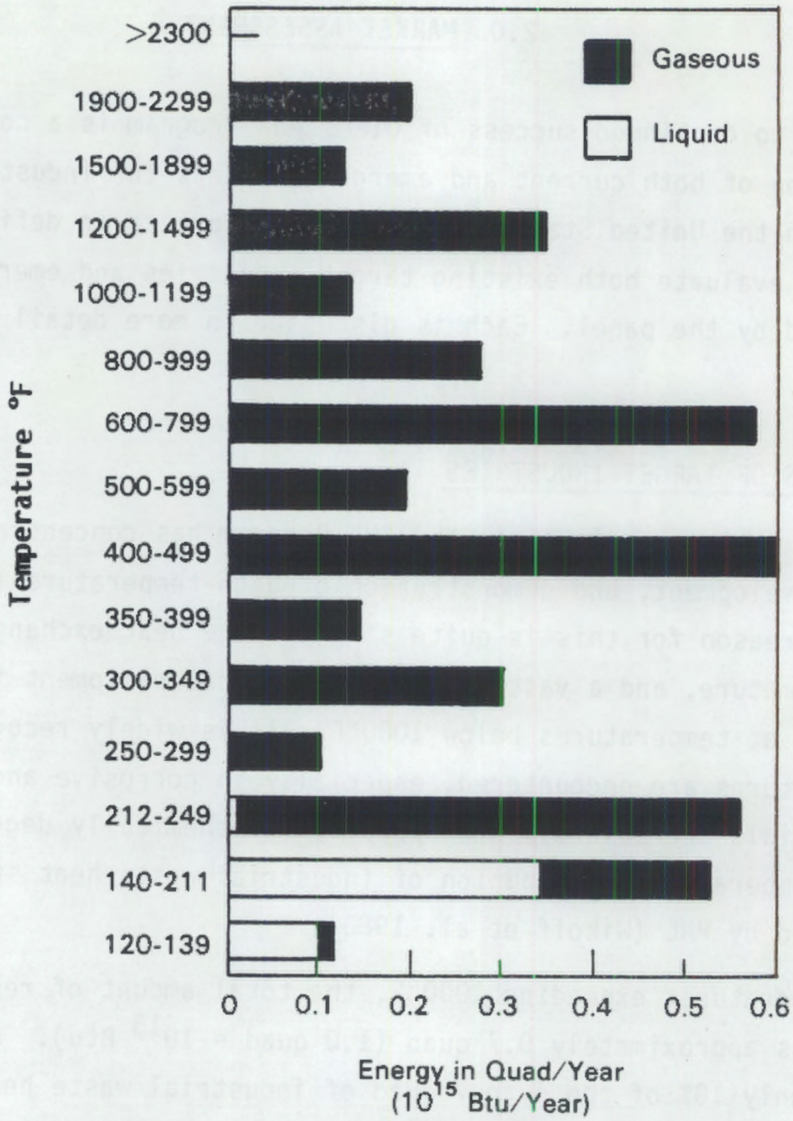

FIGURE 2.1. Industrial Waste Heat Streams

\$4/MMBtu and a furnace efficiency of 80%. In other words, development of new heat exchanger technology to address this market can significantly benefit the country as a whole.

In earlier DOE-sponsored studies, specific industries were targeted for recuperator R&D support on the basis of their 1) yearly energy consumption, 2) energy savings potential, and 3) high flue gas temperatures. These studies resulted in the initiation of a high-effectiveness recuperator R&D program for application on direct-fired clean flue gas furnaces. An estimated \$36 million

(DOE 1984) in fuel cost savings have been realized to date as a consequence of the DOE-initiated recuperator research programs performed by GTE[(a)] and AiResearch. The results of this research have been the development of recuperators that are compact and have high heat-rate effectiveness. Ceramic recuperators have been developed for 0.5 to 1.5 MMBtu/hr (1 MMBtu/hr = 10^6 Btu/hr) operation. In addition, recuperators combining both ceramic and metallic design have been developed in this research. The energy savings, along with the productivity gains resulting from more efficient heat recovery, have benefited the heat treating and forging industries with cost savings approaching nearly 40%.

To extend the success with lower-temperature heat exchangers to the target industries, DOE initiated its present AHX Program. The program focused on the R&D of high-effectiveness recuperators in high-volume, high-temperature, dirty, corrosive flue-gas environments. Initially, the AHX Program launched four development efforts covering fluid-bed waste heat recuperators (FBWHRs) and high-temperature burner duct recuperators (HTBDRs) for the target industries.

During the development period of the FBWHRs and the HTBDRs, several major events occurred in the target industries. The initial criteria of high-temperature flue gases and high energy consumption no longer served as the only criteria justifying development programs. U.S. industry has shifted emphasis from integrated plants to the selective manufacture of semifinished and finished high value-added goods. Domestic facilities are now employing modern fabrication techniques and are committed to expend the required capital to maintain a competitive edge. This trend is evident in both the U.S. aluminum and steel industries. Aluminum, high value-added, finished goods shipments continue at record-setting levels, while primary aluminum smelters are being closed because they cannot compete with foreign-based ingot suppliers. The steel industry reached its employment peak in 1953 with over 500,000 workers, but by 1985 the estimated hourly paid work force had been reduced to 156,000.

(a) GTE Products Corporation. 1983 (Draft). Technology Acceleration Program for the GTE Ceramic High-Temperature Recuperator. GTE Products Corporation, Towanda, Pennsylvania.

The most drastic change occurred during the recession of the early 1980s where, prior to its start, the steel industry's average number of hourly paid workers was 453,000.

High labor and fuel costs, foreign trade practices, and high interest rates all contributed to the move away from production of domestic primary metals to importing of aluminum and steel ingot or billet forms. Primary metals production is down by over one-third since 1979 and as technology improvements such as continuous casting are introduced, soaking pits and reheat furnaces are becoming obsolete and unused. New reheat furnaces, for example, are designed for greater thermal effectiveness. The result is a substantial reduction in both flue gas temperatures from 2100°F to 1600°F[a] and the need for high-temperature recuperators.

Future trends indicate increased foreign competition in the primary metals industry and a continued decrease in fossil fuel prices. This will result in a trend towards fabrication-type manufacturing and to new, emerging high-technology industries.

2.2 EMERGING HIGH-TECHNOLOGY INDUSTRIES

The key to future, effective AHX programs is to take advantage of the advanced ceramic materials and composites developed by DOE contractors and couple them with the new industrial trends and developments. This section introduces several new, emerging industrial process needs.

2.2.1 High-Temperature, High-Technology Processes

1973 through 1985 was a transitional period for U.S. industry. The traditional "smokestack" industries such as steel and aluminum were moving from basic commodity manufacturing to fabrication of specialty products. The steel mill soaking pit is disappearing, and continuous casting is expected to handle 60% of carbon steel production by 1988 (Labee 1986). The aluminum industry is

(a) Information obtained in a private communication with T. Otti, Thermal Transfer, Inc., Pittsburgh, Pennsylvania, February 28, 1986.

moving away from primary metal production to concentration on fabrication and high value-added products. Foreign suppliers are more competitive sources for primary steel and aluminum.

The old heavy industries are being replaced by new high technology industries. A list of furnace types being purchased today include the following:

- fluid-bed coal combustors
- toxic waste incinerators
- hot isostatic presses
- ion nitriding furnaces
- plasma carburizing furnaces
- induction hardening furnaces
- vacuum sintering furnaces
- chemical vapor deposition (CVD) furnaces
- fume and solid waste incinerators.

Conversations with individuals in the furnace and recuperator industries indicate that there is a shift to these newer, high-technology fields. The panel believes that the AHX Program should examine new opportunities in these emerging industries. These industries and applications tend to be in smaller furnaces having a broader temperature range, and in many cases, a wider range of corrosive gases are found to exist.

High-temperature combustion air preheaters are a basic component of both open- and closed-cycle magnetohydrodynamic (MHD) power plants. This is another technology being developed primarily overseas, particularly in the Soviet Union. The problems are formidable, since the combustion air is heated up to 2000°C (3632°F) and exhaust gases cannot drop below about 1200°C (2192°F) in order to prevent slagging. Much experience has been gained with regenerative ceramic matrix heaters of the type used in blast furnaces. Recuperators have also been considered. Again, this experience should be monitored--for the benefit of the recuperator program and for possible application to the U.S. MHD program.

Active programs for developing large-scale high-temperature gas-cooled reactors (HTGRs) are under way in the Federal Republic of Germany, Japan, and the Soviet Union. Recuperation of both production and process heat is an objective of the programs. For example, in Japan R&D have been directed toward nuclear-steel-making technology using high-temperature reducing gas produced by nuclear energy. Other applications include advanced coal gasification and new hydrogen production technologies. A reactor outlet temperature of 905°C (1742°F) to 1000°C (1832°F) is presumed.

A critical component of such systems is a metallic recuperator between the primary and secondary helium circuits. Much effort has gone into the design of this recuperator, and the test experience should be of interest to the present U.S. DOE recuperator program. Also, if the U.S. resumes an active interest in HTGRs, much information will be available. It is significant that these development efforts involve enhancement of both convective and radiative heat transfer.

The Electric Power Research Institute (EPRI) has recently formed an international consortium to draw together the best in fossil fuel plant technology. The intention is to speed the creation and development of improved components and materials leading to advanced power plant designs. Included in the R&D program is improved superheater/reheater materials for increased resistance to coal ash corrosion, tube exfoliation, and hard-particle erosion. It would seem that this project would be of considerable interest to the DOE on materials activities, particularly ceramics. This will require a stronger liaison with EPRI program personnel.

2.2.2 Redirection of OIP's Targets

The objective of OIP's programs, as the panel views it, is to combine the newer high-technology, high-risk generic technology being developed with the AHX Program with the emerging high-technology, high-temperature industries in the United States. In some cases, these new applications are also found in lower-temperature processes where the demands are challenging in terms of pressure, corrosion or fouling. Many of the high-temperature applications will be challenging in terms of cost. Enhanced heat transfer and high-strength properties will be required to ensure technological dominance in these areas.

Projects sponsored by the AHX Program should be directed to benefit the user community in terms of:

- enhanced heat transfer
- cost effectiveness
- corrosion resistance
- high-temperature strength for high-pressure and vacuum applications.

The program should be balanced with regard to both ceramic composites and monolithics. Some attention should be given to high-performance stainless steels. The projects should be selected to produce generic hardware and comparative data for prospective users. Projects should be directed to generate information and experience for the prospective user community, i.e., the furnace, boiler, and recuperator manufacturers.

The panel suggests that there is a much wider market for the results from the DOE-supported AHX projects. In general, product needs in the year 2000 should be determined. This input should be the overriding factor in selecting future projects for DOE support. Some forecasters anticipate that the continued expansion and evolution of high-performance ceramics and stainless steels will be seriously curtailed with oil prices falling to $13/barrel, even though it is clear that prices may well climb to over $20/barrel in the not-too-distant future. This is the precise timing for government to encourage the continuation of the strongest of the advanced heat exchange projects to bring them to maturity.

The Japanese have mastered the art of government-supported technology development in order to lead to world market domination in selected areas. Cameras and machine tools are examples of the results of this strategy. They started years ago with the idea of world dominance in the machine tool industry, and fostered programs and disciplined themselves to select the best for government support. They were extremely successful in moving in on their selected targets. The United States now has an opportunity to establish a worldwide leadership role in marketing high-performance heat exchangers. Therefore, the United States should concentrate on heat exchangers for corrosive and pressure conditions ranging from 1000°F to 4000°F and focus on key growth areas such as the following:

- clean combustion of coal
- combustion of wastes and garbage

- ceramics manufacturing
- production of high-performance specialty metals
- near net shape forming and sintering
- vacuum metallurgical processing.

In summary, the panel recommends that the AHX Program emphasize emerging industries, support emerging technology, and make program findings available for new applications in a generic sense. The panel believes that the program should remain primarily in high-temperature applications but expand the temperature range both upward to 4000°F and downward to 1000°F. Within this range, the targets should be further identified within an expanded outline of growth industries in the United States. Programs and projects should be selected to include generic, broadly defined, heat exchanger technology development.

3.0 OIP PROGRAMS

3.1 HISTORY

The DOE's AHX Program originated in earlier programs of the Energy Research and Development Administration (ERDA), precursor to the DOE, in 1976. ERDA's intent was:

> "to develop heat exchangers with performance capabilities greater than could be obtained from heat exchangers that were commercially available" (DOE 1985a).

The projects funded by ERDA emphasized the accelerated demonstration of existing technologies in moderate-risk, high-temperature, clean gas stream environments in industries in which a high economic impact could be expected. The ERDA work resulted in three heat exchanger improvements:

- a metallic plate-fin recuperator
- a ceramic matrix recuperator
- a ceramic tubular recuperator.

Development and field testing of these recuperators highlighted a number of serious problems relating to heat transfer surface contamination and degradation in heat recovery systems. These formed the basis for a series of projects undertaken in 1981. The goal at that time was to design, test and evaluate advanced systems for high-temperature, dirty waste heat stream environments using technologies that were available or close to being available to the market. Four projects were funded:

- a silicon carbide, high-temperature burner-duct recuperator (HTBDR) made by Babcock & Wilcox
- a combination silicon carbide and metallic HTBDR made by AiResearch Manufacturing
- a fluidized bed waste heat recovery system (FBWHRS) made by Aerojet
- an FBWHRS using two fluid beds made by Thermo-Electron.

The work on these projects, initiated in 1981/1982, is nearing completion.

The current goal of DOE's AHX Program is:

"to advance the technology for designing, fabricating, and using heat exchangers for waste heat recovery and process heat exchange in U.S. industry" (DOE 1985a).

The projects initiated to support this goal are somewhat more generic than the earlier ERDA and DOE demonstration projects. The focus is more on advancing the basic technology base than on the applied engineering of the earlier programs. The new AHX Program is relative to both high-temperature waste heat recovery and fouling environments. The program is divided into three areas:

- configurations
- materials
- support technologies.

The configurations area includes the demonstration programs described above, which started in 1981. In addition, this area includes advanced configurations that will improve the technology and will develop test modules to evaluate proposed concepts. There are six projects in this advanced configurations area:

- two high-temperature heat pipes (AiResearch and Thermo Electron)
- two advanced fluid beds (Southwest Research Institute and United Technologies Research Center)
- two composite materials heat exchangers (Babcock & Wilcox and Thermo Electron).

The materials' area of the program includes the national laboratory support (failure analysis, post-test examination, etc.) for the program, and some specific materials technology development projects, including the following:

- development of a low-cost SiC powder synthesis method
- a summary of all ceramic and metal coupon exposure tests
- an assessment of protective ceramic coatings
- development of a new corrosion-resistant material

- summarization of a ceramic recuperator's fouling and corrosion experience
- development of a tube fabrication process for toughened oxide ceramics.

The mission of the support technologies' part of the current program is to address the technology shortcomings identified in the other two parts of the program. This currently includes lifetime prediction methodology development including 1) nondestructive evaluation 2) development of an in-situ-stressed material sample test, and 3) assessment of fracture mechanics in ceramic components.

Table 3.1[a] shows the funding breakdown according to the programmatic subareas outlined above. Also indicated is the amount of industrial financial participation in each of these areas. Overall, financial participation by industry in DOE-funded projects seems to be heading in the right direction--as the risk of failure is reduced, industrial participation has a tendency to increase. It would appear, then, that the AHX Program is fulfilling the general OIP goal of funding high-risk technology development.

3.2 RESULTS

With the exception of GTE's program for ceramic high-temperature recuperators, the panel could not assess the technical or commercial success of the AHX projects that either have been completed or are in progress. The three recuperator designs that evolved from the 1976 programs have been described as technically successful through the sponsored demonstration phase of the development. However, they have not been commercially successful.

The final report of the GTE project[b] identified some of the heat exchanger systems and the fouling issues that led to the 1981 generation of

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(a) Information obtained in private communication between R. S. Richlen and T. J. Marciniak, February 1986.

(b) GTE Products Corporation. 1983 (Draft). Technology Acceleration Program for the GTE Ceramic High-Temperature Recuperator. GTE Products Corporation, Towanda, Pennsylvania.

TABLE 3.1. AHX Program Funding Levels: DOE/Industry

	1985				1986			
Program/Project Area	DOE	Industry	Total	% DOE	DOE	Industry	Total	% DOE
HTBDR	$ 0	$ 0	$ 0	0	$ 0	$ 0	$ 0	0
FBWHR	759,000	559,000	1,318,000	58	280,000	139,000	419,000	67
Ceramic Composite	1,000,000	203,000	1,203,000	83	970,000	196,000	1,166,000	83
Nondestructive Eval.	100,000	0	100,000	100	410,000	78,000	488,000	84
Ceramics Development	400,000	0	400,000	100	650,000	0	650,000	100
Related Research	143,500	11,600	155,100	93	165,000	18,000	183,000	90
Program Support	200,000	0	200,000	100	200,000	0	200,000	100
FY Total (actual)	$2,602,500	$773,600	$3,376,100	77	$2,675,000	$431,000	$3,106,000	86

projects. The report also summarized the economics of the installations and identified an attractive overall 2.2 year simple payback for those installations reporting fuel savings.

The impact of the DOE high-temperature recuperator demonstration programs was apparent to the panel on a more qualitative basis. The acceptance of the new furnace recuperators by industry is prima facie evidence that these programs have contributed to the acceptance of the new recuperator technology by the normally conservative primary metals industry.

3.3 ISSUES

Several issues can influence the wide-range application of high-temperature ceramic heat exchangers in U.S. industry: technical, environmental, DOE's relation to industry, and cost and design. It is recommended that OIP address these issues in the planning and structuring of future programs.

3.3.1 Technical Issues

The primary technical issues that need to be addressed are:

- characteristics of today's ceramics
  - high cost
  - brittle
  - limited property data available and limited options in shapes.
- joining and sealing techniques
  - how to make mechanically reliable and gas tight joints between ceramics and metals
- corrosion and fouling
  - techniques needed to mitigate the effects of corrosive and fouling atmospheres on the mechanical and heat transfer performance of ceramic heat exchangers.

3.3.2 Environmental Issues

The success of the search for high-temperature heat exchanger materials will be indicated by their application in a high-temperature heat recovery process. However, the wide spread use of this equipment could be prohibited in some parts of the United States because a burner with the higher inlet air temperature is likely to emit NO_x in excess of that allowed by air quality standards. The technology to solve this problem exists in U.S. industry. However, it may not be readily available in the companies that make today's industrial furnace burners. It should be a goal of the AHX program to insure that there are low NO_x burners or conversion devices when the high-temperature recuperators are ready to go to market.

3.3.3 DOE's Relation to Industry

Information transfer is a prerequisite to technology transfer. In the panel's opinion, the results of some DIP-sponsored research are not being adequately disseminated. Part of the problem may be due to complications on cost-shared projects where contractor proprietary interests are at stake. To effectively discharge its mission in high-temperature heat recovery, the OIP should increase its efforts for contact (site visits, workshops, etc.) with potential users. Undoubtedly there will be resistance to adoption of some of the technology even though it has been shown to be highly effective. Personal contact could lower this barrier. There is a precedent in regard to development of sensors where industry working groups were effective in promoting the technology transfer process, identifying needs for national laboratory research and communicating the results to the needy manufacturing establishment.

The relevance and the acceptance of the OIP work would benefit from improved two-way communication with the industrial user community. The goal of the recommended program is to establish a means of shortening the communication link between the real needs and concerns of the heat exchanger market and the OIP sponsoring work for the benefit of these industries. The purpose of establishing this link is to give the industrial community an effective and convenient vehicle to communicate their heat exchanger requirements to the OIP and at the same time give the OIP a means of communicating the progress of their programs to the potential users. The result of this program would be that the DIP-sponsored work would be more pertinent to the needs of the industry. In addition, the technology would be more rapidly absorbed by an industry that has followed and participated in the progress of the development work. The panel suggests the following organization of the work:

- Establish an effective two-way communication program with industrial users and heat exchanger manufacturers.
- Establish an OIP newsletter directed to the membership lists of the user organizations in the industries that would use advanced heat recovery equipment. The newsletter would publicize the OIP work in progress, solicit input on user needs and concerns, and publicize OIP-sponsored workshops.
- Establish direct involvement with user organization committees.
- Work in conjunction with the user organizations to set up workshops involving users, suppliers and the OIP.

3.3.4 Cost and Design

Cost and design are the two areas which will ultimately determine the commercial success of high-temperature (ceramic) materials in heat exchanger applications. Ceramic manufacturing problems, for example, were recognized as a major contributor to high-temperature heat exchanger costs during the Gas Research Institute's (GRI's) High Temperature Ceramics Workshop in 1983 (GRI 1983).

Excessive material costs will either keep the high-temperature heat exchanger out of the market place with a noncompetitive product cost or will quickly get it out of the marketplace with an unacceptable profit margin. For a material to have a chance to reach commercial application, the cost, manufacturability and material properties must all meet the needs of the heat exchanger designer.

The panel suggests that the AHX Program focus on high-temperature ceramic materials and the cost to manufacture a heat exchanger surface using these materials. High-temperature ceramic material candidates should be evaluated based on their dollar/heat-transfer capability. The high risk, as far as industry is concerned, is associated with developmental efforts not reaching the goal of cost-effective, high-temperature heat exchangers. The high payoff, from a national strategic and environmental standpoint, would be in terms of energy savings and increased manufacturing efficiency. The concept of ceramic materials development fits in well with DOE's stated goals and objectives.

The composite material program currently funded by OIP is a major step in developing a commercially viable ceramic material for heat exchangers. The program not only has the potential to reduce material cost, but it can dramatically reduce the cost of heat exchanger surfaces. It is suggested that the OIP solicit additional work with the objective of developing lower-cost ceramic heat exchanger surfaces.

Another materials' issue that must be resolved is that of determining and achieving physical properties. Although properties and cost are recognized as "chicken and egg" issues, it is the panel's position that the cost issue must be resolved in order to assume eventual commercial success. As cost-effective processes and materials are developed, the materials must be evaluated to assure that they have acceptable properties, and eventually, complete design data must be developed. As a matter of interest, problems associated with inadequate materials data are not limited to ceramics. In heat exchanger applications, such as a gas-fired forging furnace using high-temperature alloys, designers sometimes have inadequate data on high-temperature stress, rupture and creep.

3.4 PROGRAMS NEEDED

The relatively small annual budget for the AHX Program makes it particularly important to focus the funded effort on a few well-chosen goals to make the desired impact in an acceptable time. The added threat of budget cuts imposed by the Gramm-Rudman legislation further emphasizes the need to direct the funding to the best areas in order to get something accomplished.

One panel member observed that the technology demonstration programs tend to do little to actually advance the state of the art of heat exchangers. The strong desire to be successful, limited time, and limited funds all push the contractor in the direction of novel application of existing technologies rather than a contribution of new knowledge. Attractive materials economics and adequate materials data most likely will get a new technology to market with very little additional OIP funding.

For those reasons, the panel endorses the move away from technology demonstration to the more generic research. It is the panel's view that the state-of-the-art opportunities lie in the areas of:

- high-temperature materials
- corrosion and fouling control
- enhanced heat transfer using advanced material concepts.

The OIP programs to date have focused on the high-temperature and fouling issues. Although the energy rejected in temperatures ranging from 80°F to 119°F is 37.4% of the estimated 6.75 quad discarded by U.S. industry annually (Wilfert et al. 1984), development of the technology to make this heat useful departs from the traditional emphasis of the AHX Program. In the interest of continuity and focus, it is suggested that work on low-temperature heat recovery not be undertaken at this time.

3.4.1 Goals

Connecting the stated objective of the program to the current AHX Program is difficult. It is suggested that the AHX Program Manager establish one or two specific goals and organize the funded work to logically support these goals. The panel suggests the following goals:

- Establish an effective two-way communication program with industrial users.
- Develop cost-effective, high-temperature structural materials for applications with heat exchanger output temperatures above 1600°F.
- Investigate corrosion conditions in new situations with waste streams above 1000°F and provide recuperator manufacturers with data on materials and coatings.
- Accelerate the development of enhanced heat transfer techniques using extruded monolithic or woven composite ceramic exchanger surfaces.
- Clearly define the high-temperature area for programs and the associated waste heat streams and their energy conservation potential.

- Find ways to use the talent and facilities available in the national laboratories and universities.

- Ensure that the technology is available to the user community without delay and/or proprietary restrictions.

3.4.2 Program Plans

Table 3.2[a] shows the projected funding levels for the various activities in the AHX Program. These projections, which form the basis for the funding levels outlined in the Multi-Year Plan (DOE 1985a) for the AHX Program through 1991, also indicate the future direction of the program. For example, the HTBDR effort will end, while the FBWHR program will receive funding through FY 1988. This only includes the development of an advanced distributor plate for fluidized bed applications. AHX Program funding is earmarked to support technological development in areas such as:

- advanced ceramic composites
- nondestructive evaluation of composites
- ceramic fabrication, coatings and corrosion/erosion research
- high-temperature fouling
- initiation and support of a program on enhanced heat exchanger performance.

It is clear that the program has been well thought out and coordinated not only with industrial needs but with complementary developmental work sponsored by others, such as the GRI.

With regard to the future direction of the AHX Program, the panel believes that the emphasis should be shifted to take into account the changing market for industrial heat recuperators and to take advantage of certain high-risk, high-payoff opportunities. Therefore, the following changes are recommended:

(a) Information obtained in private communication between R. S. Richlen and T. J. Marciniak, February 1986.

TABLE 3.2. AHX Program's Program/Project Funding Percentages

Program/Project Area	Fiscal Year 1985	1986	1987	1988	1989	1990	1991	Cumulative
HT8DR	.0	.0	.0	.0	.0	.0	.0	.0
FBWHR	29.2	10.5	8.0	37.5	.0	.0	.0	13.7
Ceramic Composite	38.4	36.3	28.0	22.5	16.0	12.9	.0	21.9
Nondestructive Eval.	3.8	15.3	20.0	12.5	20.0	.0	.0	10.1
Ceramics Development	15.4	24.3	20.0	12.5	20.0	16.1	15.4	17.3
Related Research	5.5	6.2	8.0	5.0	20.0	32.3	38.5	16.1
Program Support	7.7	7.5	8.0	5.0	8.0	6.5	7.7	7.0
Enhanced Performance	.0	.0	8.0	5.0	16.0	32.3	38.5	14.0
FY Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1. Materials, coatings and fabrication techniques now available can be combined to attain new high-temperature/pressure levels. Coatings are continually emerging to extend metal or fabric applications into hot corrosive applications. Advanced high-performance ceramics can be considered for high-pressure or vacuum chambers or exchanger designs not previously possible. The program should provide a creative climate where synergistic combinations will result with high payoff products.

2. The necessary condition in high-temperature waste heat recovery is to build heat exchangers that withstand hostile environments. Thermal performance is important, but the recuperator must retain its structural integrity, exhibit tolerable wastage due to corrosion and erosion, and not be subject to inordinate fouling. Current OIP programs and the AHX Multi-Year Plan (DOE 1985a) stress these issues. In addition, however, a case can be made for developing high-performance surfaces in the interests of compactness and cost reduction. The current, plain surface recuperators can be regarded as "first-generation" heat transfer technology while the advanced, enhanced surfaces are regarded as "second generation" technology. Efforts were made to document this technology in a recent ECUT program. Enhanced heat transfer apparently shows up as "Enhanced Performance" in the Multi-Year Plan (DOE 1985a); however, there is no evidence that the subject is being pursued, even though a program was recommended in FY 85.

   Beyond the internally finned ceramic (carborundum) tube for the AiResearch HTBDR, there is little evidence that enhanced surfaces are being considered for ceramic heat exchangers. The panel is convinced that enhanced surfaces can become the key to using the expensive ceramic materials in a cost-effective heat exchanger apparatus. The combination of advancing the heat transfer performance by a substantial amount will offset the high initial costs. The answer and the reason for R&D emphasis in the area are to raise the performance, making these materials cost effective. This is analogous to the trend in space framing of automobiles, using fewer pounds of high-strength low-alloy materials as a cost-effective design solution.

3. The diagnostic work for waste streams historically has addressed steel, aluminum and glass furnace flue-gas streams. Many interesting flue-gas streams, such as hazardous waste incineration, are uncharted from a high-temperature heat transfer/corrosion point of view. The nature of streams is more diverse but important, and work needs to be performed to assist industry in new areas.

4. The trend in the planned programs is to follow the HTBDR programs with the composite exchanger developments, addressing a temperature range over 1600°F. Recuperator manufacturers are expressing an interest in temperatures ranging from 1000°F to 1600°F where stainless steel is commonly used. The need for corrosion resistance and coatings' evaluation in this temperature range is important and should not be overlooked.

Some panel members contacted industry personnel to develop outside relevant data on ceramics, composites, and corrosion and fouling. Chapter 4.0, "Ceramics and Composites," and Chapter 5.0, "Corrosion and Fouling," cover this work.

3.5 MANAGEMENT

An overview of the AHX Program management strategy for future programs was presented in a January 30 meeting with OIP in Washington, D.C. The overview indicated program funding plans for work extending into 1980 and through 1990. In addition, eight reports were made available to the panel members on March 10 (Aerojet 1985; AiResearch 1986; Babcock & Wilcox 1985, 1986; Cole, DeSaro and Patch 1984; Cole et al. 1985; DOE 1985b).[a] These reports were used by the panel to gain insight into completed program management issues and performance results.

(a) Also Schaffer, P. (Draft.) Development of a Process for the Production of Inexpensive, Reproducible, Microcrystalline Beta Silicon Carbide Powder. Advanced Refractories Technologies, Buffalo, New York.

The panel supports the OIP concept of funding more than one contractor for phased work in a given technology area. The competitive aspect of this dual funding gives the contractor an incentive to produce the desired results and increases the overall creative thinking brought to bear on the technology. The OIP funding of follow-up work based on the initial results and the promise of future success are further incentives to the contractor to produce and give OIP the flexibility to apply their limited budget in the most productive areas. The panel urges the OIP to continue this method of program management.

It is difficult for someone who has not been involved in the evolution of the AHX Program to follow the path from the OIP's overall goal to the individual programs that are currently active. Without the interconnecting logic, the program appears to be fragmented and not focused on defined objectives that support the OIP goal. In the interest of focus and organizational clarity, the panel suggests that the OIP establish intermediate goals that support the overall program (Section 3.4.1). Any new work should support one or more of the intermediate goals to be considered for funding.

The reports provided for the panel's review show some very competent work by the contractors:

- The panel was very favorably impressed with the analytical work reported on the FBWHRs (Cole, DeSaro and Patch 1984) and on the ceramic fiber composite heat exchanger (Babcock & Wilcox 1985). Both of the designs seem to be backed by adequate analysis to improve their probability of success.
- The CVD composites heat exchanger (Cole et al. 1985) has benefited from a systems approach to the heat recovery problem in eliminating a dilution air requirement. This concept also appears to offer good economics for the producer and the user.

Some less favorable results were also reported, which suggest that a change in the management and review of these programs might improve the results:

- An after-the-fact performance/economic tradeoff showed that the original design had gone beyond the point of diminishing economic returns.
- Erosion tests failed to yield useful results because the test did not simulate the application.
- The contractor was negotiating with a test site operator to install needed instrumentation after the installation was complete.
- A field-test program suffered months of delay at the test site while the contractor resolved quality and design problems that should have been resolved by more rigorous design and fabrication efforts.

The panel suggests that the OIP periodically conduct critical program reviews where the contractor would present to qualified, disinterested experts the scope and results of his design and analysis work and solicit suggestions for additional work. In addition, these reviews should question the logic of the program planning to insure the desired results can be achieved.

3.6 FIELD TESTS

Based on the results of the field tests and demonstrations of high-temperature metallic recuperators, HTBDRs, and FBWHRs, the AHX Program Managers recognized the need to sponsor R&D in ceramics and fouling environment controls under high-temperature conditions. The direction that the program has taken, which was highly commended by the ten industry representatives who were contacted during this assessment, would not have been possible without DOE participation in "field tests." Thus, it is disconcerting to the panel that both DOE policy and funding levels will eliminate direct AHX Program participation in technology field tests. Close cooperation with the GRI, which can and does sponsor technology demonstrations, can help to delineate future program directions.

4.0 CERAMICS AND COMPOSITES

The energy conservation technology explosion that resulted from R&D projects after the price of energy increased in 1973 is well known. This span of 13 years represents a fruitful period for materials' developments. Many of these new materials and applications were developed to meet high-temperature advanced heat exchanger requirements.

In an effort to assess the acceptance of materials' development within the AHX Program, representatives of firms engaged in developing high-temperature heat exchanger and ceramic materials were surveyed. These included firms that either are participating in the AHX Program or are funded by GRI. It also included one firm that is not participating in either but is working on ceramic development with a defense-oriented national laboratory.

The survey indicated unanimous support for the AHX Program, mainly because the work generally would not be done by industry because of the risk and expense involved. However, there are areas which could be improved.

During a conversation with one manufacturer, concern was expressed that in the high-performance ceramics industry, R&D funding will become increasingly difficult to obtain in view of the drop in world oil prices and the resulting de-emphasis of industrial conservation activities. The continued presence of OIP in the development of advanced ceramics is a matter of great importance in industry. Without government support, most industrially sponsored R&D may be discontinued at a time when it appears to be on the threshold of success. The negative impact may be more than unacceptable from a national perspective. The panel suggests that a comprehensive evaluation of the future for advanced ceramics be undertaken by OIP. R&D of advanced ceramics and composites funded by OIP, and others such as GRI, have helped to accelerate progress in the industrial sector, on which the panel concentrated its thoughts and comments.

The March 1986 issue of Industrial Heating indicated that many materials that were unknown or relatively unknown in the marketplace in 1973 are now commonplace. Some of these include:

- vacuum-formed ceramic fiber
- fiber-reinforced refractories
- Kevlar®[a]
- Fiberfrax®[b] sprayable ceramic fiber insulation
- zirconium tubes
- Nextel 312 fabric woven shapes
- high-performance ceramics
- Zircarr refractory alumina sheets.

It is clear that despite the introduction of many new high-performance ceramics, the development of heat exchangers using these materials has not achieved widespread use in the marketplace. Only recently has the idea of three-dimensional heat exchanger component fabrication, using coated composite woven shapes, emerged. The economic demands of the energy crisis have precipitated the introduction of new technology, much of which resulted from DOE-supported energy conservation technology programs.

(a) Registered trademark of duPont, Wilmington, Delaware.
(b) Registered trademark of Sohio Engineered Materials Company, Niagara Falls, New York.

5.0 CORROSION AND FOULING

The emphasis on fouling in the AHX Program is appropriate; however, the Multi-Year Plan (DOE 1985a) is loose with the word "solve." As long as the waste heat streams remain dirty, the fouling problem is not going to be "solved." Heat exchange surfaces will continue to foul and require periodic cleaning. The panel does not believe that additional stream characterization is required, considering the work already done in this area.

Fouling-resistant heat exchangers can and should be pursued, but the goal should be realistic to avoid raising false expectations. Properly designed surfaces may have lower fouling rates so that cleaning is required less frequently. In certain cases, it may be possible to live with a fouled surface if moderate equilibrium fouling resistance is attained. This type of research activity was not identified in the Multi-Year Plan (DOE 1985a).

The panel feels that a strong case cannot be made for the gas-side fouling monitor. With the kinds of industrial waste heat streams under consideration, the buildup of a fouling layer is readily indicated by increases in pressure drop or decreases in heat exchanger efficiency. Alternatively, the approach and discharge temperatures can be monitored for deterioration in effectiveness. These overall measurements should suffice since local fouling rates are not considered to be critical.

In connection with the development of surfaces that minimize fouling, advanced cleaning techniques or fouling resistant surfaces should be studied. Perhaps new ways can be developed to clean with high-pressure air or steam. One particularly intriguing approach is the acoustic techniques (sonic horns) that have been developed in Europe.

6.0 SUMMARY AND RECOMMENDATIONS

6.1 SUMMARY

Heat exchanger technology for conventional or target industries has advanced as a result of OIP's direction and initiatives in waste heat recovery. An estimated 95% of reheat furnaces in the steel industry now have recuperation units (Bugysis and Taylor 1985). The newer recuperators are guaranteed for 85% effectiveness with 1600°F flue gas and 1300°F air preheat (Lukasiewicz 1985). Container glass furnaces have reduced energy consumption by more than 20% over the past 10 years (Denniston 1985). The list of industry achievements in energy conservation is extensive. Mature industries have embraced OIP's energy conservation technology program, and competitive heat exchanger products are available today largely as a result of the OIP program. DOE's cooperative participation with industry has been both a stimulus and a vehicle for the adoption of this technology.

Initially, the justification for government support of advanced industrial heat exchanger R&D was based on the anticipated rapid adoption and implementation of new industrial exchangers. The industry base of 1973 represented huge quantities of high-temperature waste heat, and the opportunities for attractive investments were widespread. Now that heat exchanger installations in these mature industries are less attractive, the emphasis must shift to those industries where the quantities of waste heat are less and the technical problems are more severe, i.e., corrosion, pressure, and high installation costs.

The results will be hard to measure since they will be found in what is called "embodied energy" savings. New, improved hot isostatic pressing (HIP) technology will produce super-alloy turbine blades for jet aircraft. Because of higher turbine inlet temperatures, these engines will be more efficient and the energy savings will be spectacular. The energy saved at the furnace may be small in comparison. In the final analysis, energy conservation is achieved and American workers have jobs building HIP furnaces and advanced jet aircraft engines.

The panel believes that AHX Program opportunities exist in developing technology for new growth industries. In general, U.S. industry is adopting a future competitive course that is directed towards less energy-intensive, high valued-added manufacturing operations. Although many of these operations have less severe flue-gas conditions, many have yet to be charted and exploited from an energy conservation standpoint. The role for OIP becomes even more vital because the R&D risks are higher than those that heat recovery equipment manufacturers would likely undertake. The results in terms of materials performance, corrosion resistance and heat transfer rates needed present a real challenge, especially in today's competitive world marketplace.

Foreign competitors of U.S. industry, specifically the Japanese, have mounted a strong effort to develop ceramic materials for high-temperature applications. However, unlike the current effort in the United States, and that sponsored by AHX Program, Japanese firms are emphasizing the development of monolithic ceramics. The Japanese are looking closely at business opportunities related to the sale of boilers and heat exchangers to the U.S. power industry, anticipating an opportunity as the industry shifts to solve "acid rain" problems associated with burning high sulfur coal. It is time to adjust the program emphasis to a broader range of temperatures and pressures, keying on corrosion-control, cost effectiveness and enhanced heat transfer performance.

Overall, the AHX Program, as presently constituted, appears to meet the OIP's overall goals and objectives. The current and future programmatic emphasis on high-risk, technological R&D is balanced, is coordinated with the needs of the industry (at least with industries involved in developing economically viable high-temperature heat exchangers), is perceived as needed, and has performed quite well in the past.

The panel feels that the general goals of the AHX Program are commendable. The emphasis on high-temperature waste heat recovery is appropriate. The positive impact of the program is being felt by industry, even if the DOE role is, more often than not, explicitly acknowledged. The cost of this program is minimal, considering the potential return--a modest effort to enhance the competitiveness of U.S. basic industry. Furthermore, the investment made now promises to provide heat exchange technology for future high-temperature applications.

With the new emphasis on "small-scale" laboratory work, there is danger that the technology will not be fully developed. Full-scale testing on actual process streams must be done. If the technology appears to be very promising (albeit high risk), and industry is generally unwilling to participate except on a limited cost-shared basis, then DOE should properly take the lead--perhaps through one of the national laboratories.

6.2 RECOMMENDATIONS

The small annual budget for the AHX Program area makes it particularly important to focus the funded effort on a few, well-chosen projects. In recognition of this need and considering the options available to OIP, the panel advances the following recommendations.

6.2.1 High-Temperature Burner Duct Recuperator

The anticipated HTBDR program through 1991 shows that this area will not be supported. The panel agrees that these projects have achieved their goals, and based on the declining trend in the U.S. heavy industries, concurs with the plan. Although the two projects are nearly completed and likely will not be commercialized without further DOE assistance, the panel recommends no further action by OIP on behalf of these projects. The panel hoped that the results of these projects would be used in further high-temperature systems. The panel would also point out that the combination of recuperator, burner and burner ducting as a system is important for future program planning considerations.

6.2.2 Fluid-Bed Waste-Heat Recuperator

From 1985 to 1991, about 14% of the AHX Program budget has been earmarked for this area. Most of this support will go to distributor plate development. The panel agrees that continued support of this development program is necessary. The distributor plate concept is innovative and where the development has been completed, it promises to be an attractive heat exchanger component for dirty gas streams having a wide range of temperature, pressure and corrosive conditions. The development of a successful distributor plate for dirty gases will, in the panel's opinion, find applications in other than industrial furnaces and therefore, should be funded to completion. The panel would like to point out the need for additional flexibility in the proposed design to avoid undesirable distortion of critical distributor components.

6.2.3 Ceramic Composites

For the 1985 to 1991 time frame, 22% of AHX program support is anticipated to go to developing the ceramic composite heat exchanger. This project area will receive the largest portion of future funding, and the panel is definitely in agreement. However, the panel believes that this area should be combined with enhanced performance to achieve cost effectiveness.

The panel believes that this work is the most important and potentially the most promising of the work under way. In addition, it is important to ensure that the results attained be applicable to the new high-temperature processes discussed in Section 3.0. Ceramic composite heat exchanger work should be accelerated to achieve a competitive technological edge in international markets. In any event, ceramic composite heat exchanger work is a high priority and should be supported accordingly.

6.2.4 Nondestructive Evaluation

An estimated one-tenth of program funding will be directed to develop NDE technology for use in the refractory materials development programs. This is important and is a good point for OIP to inject funds to support all of the commercial interests working in ceramic development. The panel endorses this work.

6.2.5 Ceramics Development

Program planning for the 1985 to 1991 time period stresses the importance of ceramics development with the second largest portion of funding, 17% of the total for the period. The emphasis is on fabrication, coatings and corrosion for the first 3 years. The last 4 years are open to pursue additional, as yet undefined, projects.

The panel considers continuing efforts in the development of cost-effective monolithic ceramic materials to be important. Work should be continued with new projects aimed at developing reliable components, reducing cost and enhancing performance of monolithic ceramic materials. The emphasis should be placed on high-pressure and corrosive conditions at high temperatures. The panel anticipates consideration of generic development of heat exchanger components and high performance in terms of heat transfer rates, high pressures and corrosive gas atmospheres. The work on ceramic recuperators at Hague International and GTE is considered to be forerunners of current products development. The field of high-performance ceramics needs design ideas in order to initiate new product applications. The success of the GTE and Hague work heavily depended on innovative design approaches. Design innovation will be the key to future monolithic ceramic development for heat exchangers. This continuing program area should emphasize innovative design approaches.

6.2.6 Related Research

Related research will receive an estimated one-sixth of the total AHX Program funding with heavy commitments in the last 4 years of the planning period. The fouling probe work ends in 1986 and the panel agrees that it should be terminated.

Waste stream diagnostics are important as a tool to evaluate new situations. Substantial data are available for industrial processes related to the steel, glass and aluminum industries. Very little data are available for hazardous waste incineration or sintering metal powders. The emphasis should also be placed on higher-pressure situations with flue gases from coal combustion on the dirty gas side. In summary, funding should emphasize data acquisition from new situations to establish corrosion and fouling data for the composites' and ceramic materials' development programs. An immediate need was identified in the 1000°F to 1600°F temperature range where various stainless steels qualify based on strength characteristics. However, the corrosion resistance of these steels is uncertain. Heat exchanger manufacturers require comparative data for high-temperature, corrosive atmosphere conditions using existing stainless steels and combinations of emerging corrosion-resistant coatings. Clearly in the related research area, an effort should be included to consider the development of a data base in the 1000°F to 1600°F temperature range for metals.

6.2.7 Program Support

The Multi-Year Plan (DOE 1985a) includes program support in materials earmarked specifically for Oak Ridge National Laboratory (ORNL). The panel agrees with this work and believes that support from industry for the national laboratories would be desirable. In general, the panel favors programs and projects which can effectively use the talent and facilities of the national laboratories and universities.

6.2.8 Enhanced Performance

Of the total funds, 14% is earmarked for future work in the area of enhanced performance. This work should include both convective and radiant heat transfer modes. Enhanced heat transfer work is not currently supported. The internally fired ceramic (carborundum) tube for the AiResearch HTBDR is the only evidence available to indicate that enhanced heat transfer mechanisms are being considered for ceramic heat exchangers.

In view of the high costs for ceramic exchanger components, the idea of increasing heat exchanger performance in order to become competitive, i.e., using less ceramic material and being more efficient, has merit. With the development of three-dimensional woven, coated composites, an excellent opportunity for enhanced heat transfer exists. The panel feels that this combination is an area that may provide a breakthrough in the development of efficient, low-cost ceramic heat exchangers.

6.2.9 Other

The panel believes that other areas also should be considered for inclusion in the AHX Program along with an effort to ensure that the program continues to be relevant:

- The current emphasis in the AHX Program on the development of ceramic composites is well-placed. However, given the continued R&D on monolithic ceramic materials elsewhere, it would be prudent to re-assess the technological requirements and R&D needs of this material. It may be that insufficient effort is being expended in this area by industry (including GRI), and that further support is needed from the AHX Program.

- To date the AHX Program has emphasized the development of high-temperature, low-pressure heat exchangers for use with flue gases and preheated combustion air. However, in some cases a better use for high-temperature air could be mechanical or electrical power production using either open- or closed-cycle gas turbines. This application would fit with other areas of OIP's programs (heat pumps and industrial cogeneration), but it would require the development of high-temperature, <u>high-pressure</u> heat exchangers.
- In addition to the National Research Council Advisory Board review, some form of industry peer group technical overview should be instituted for the AHX program. These individuals should 1) not be directly funded by the program (i.e., be impartial), 2) have a good understanding of the technical and economic issues involved, and 3) have high standing in the technical community. They should represent heat exchanger manufacturers and users, the R&D community and the academic community. Service in the group should be rotated and limited to, perhaps, three years in order to both preserve continuity and inject new ideas.
- A better industrial and economic data base appears to be needed to support the planning and evaluation of the AHX Program.

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