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ADVANCED GAS COOLED NUCLEAR REACTOR MATERIALS EVALUATION AND DEVELOPMENT PROGRAM

**PROGRESS REPORT
FOR PERIOD**

SEPTEMBER 23, 1976 — DECEMBER 31, 1976

**BY
PROJECT STAFF**

**GENERAL ELECTRIC
ENERGY SYSTEMS PROGRAMS DEPARTMENT
SCHENECTADY, NEW YORK 12345**

JANUARY 1977

**Prepared for
THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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FORWARD

The Advanced Gas Cooled Nuclear Reactor Materials Evaluation and Development Program is being conducted for the Division of Nuclear Research and Applications, U.S. Energy Research and Development Administration by the Energy Systems Programs Department, General Electric Company, Schenectady, New York, 12345. The Program is under the direction of Mr. J.E. Fox, ERDA Program Manager, and is being managed for the General Electric Company by Mr. R.G. Frank, Manager, Materials Technology. The Principal Investigator for the Program is Dr. O.F. Kimball, Manager, Gas Reactor Materials with responsibility for overall technical coordination. Other major contributors to the Program are:

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ABSTRACT

This report presents the results of work performed from September 23, 1976 through December 31, 1976 on the Advanced Gas Cooled Nuclear Reactor Materials Evaluation and Development Program. The objectives of this program are to evaluate candidate alloys for Very High Temperature Reactor (VHTR) Process Heat and Direct Cycle Helium Turbine (DCHT) applications, in terms of the affect of simulated reactor primary coolant (impure Helium), high temperatures, and long time exposures, on the mechanical properties and structural and surface stability of selected candidate alloys. A second objective is to select and recommend materials for future test facilities and more extensive qualification programs.

Work covered in this report includes progress to date on alloy selection for VHTR Nuclear Process Heat (NPH) applications and for DCHT applications. The present status on the simulated reactor helium loop design and on designs for the testing and analysis facilities and equipment is discussed.

Section 1.0

INTRODUCTION

ADVANCED GAS COOLED NUCLEAR REACTOR
MATERIALS EVALUATION AND DEVELOPMENT PROGRAM

1.0 INTRODUCTION

The Very High Temperature Reactor (VHTR) Process Heat and the Direct Cycle Helium Turbine (DCHT) Systems are being developed to provide an expanded nuclear power capability. In both cases the use of high temperature helium-cooled reactors will require a knowledge of the long term properties of reactor fluid containment materials and of the materials used in constructing related hardware. Because of the very high temperatures required for process heat and DCHT applications, the need is evident for materials testing in the proper helium environment in the temperature range from 1400° to 2000°F on those alloys which might serve as materials of construction for heat exchangers, ducting liners, turbine buckets and vanes and other high temperature structural components.

The objectives of the Advanced Gas Cooled Nuclear Reactor Materials Evaluation and Development Program are to:

1. Evaluate candidate alloys for Very High Temperature Reactor (VHTR) Process Heat and Direct Cycle Helium Turbine (DCHT) applications, in terms of the effect of the primary coolant exposure and thermal exposure on:
 - o Surface stability (corrosion resistance) in 10,000 hours.
 - o Structural stability in 10,000 hours - changes in microstructure and tensile, impact and fatigue properties.
 - o Creep properties in 15,000 hours
 - o Stress rupture properties in 10,000 hours
 - o Fatigue properties
 - Low cycle 10^3 to 10^5 cycle
 - High cycle 10^5 to 10^7 cycle
2. Select and recommend materials for future test facilities and more extensive qualification programs.

The data base will permit the selection of materials of construction and should provide a reliable level of design data for the construction of various items of development hardware leading to the successful development of VHTR and DCHT systems. The present lack of an accurate measure of materials capabilities under these high temperature helium environments is a factor which is currently limiting the development of the VHTR/DCHT systems. This program is intended to provide such initial information.

Section 2.0

PROGRAM STATUS

2.0 PROGRAM STATUS

The Advanced Gas Cooled Reactor Materials Evaluation and Development Program is organized into nine (9) tasks which are designed to accomplish the program objectives listed in section 1.0 of this report.

The task structure (Program Work Breakdown Structure) is reported under Task 9, Data Analysis and Reporting, on page 16 and a brief description of each task can be found in the Program Work Statement included as Appendix A.

During the first quarter of the program, work was initiated on Task 1 (Selection of Candidate Alloys), Task 3 (Testing and Analysis Facilities and Equipment), Task 4 (Simulated Reactor Helium Environment Facilities and Equipment) and Task 9 (Data Analysis, Reporting and Program Management).

2.1 TASK 1 - SELECTION OF CANDIDATE ALLOYS

The basic objective of this task is to select the alloys for the test program. These alloys should be the leading candidates for potential application as components in the primary circuit of the Direct Cycle Helium Turbine (DCHT) systems and Very High Temperature Reactor/Nuclear Process Heat (VHTR/NPH) systems. A list of leading candidate alloys for each system and materials property data supporting and justifying the selection is being prepared by the General Electric Company. These data and supporting information will be provided to the Materials Selection Group, organized and staffed by the Nuclear Research and Application Division of ERDA. The Materials Selection Group will have final approval of the list of recommended candidate alloys to be evaluated in the program.

Up to 12 alloys, 2 weldments, and 3 surface coating systems will be selected for DCHT applications. Attention will be given in the selection of the alloys to insure that the needs of the various DCHT components (turbine vanes, buckets, and ducts) are adequately represented over the temperature range of 1400° to 2000° F. A list of leading candidate alloys is given in Table 1. The alloys listed in Table 1 have been evaluated further and subject to additional G.E. review and ERDA review and approval, the following alloys have been recommended for evaluation in subsequent tasks of the program.

TABLE 1

TYPICAL CHEMICAL COMPOSITION OF CANDIDATE
TURBINE BUCKET, VANE, AND DUCTING ALLOYS FOR DCHT

Alloy	Ni	Co	Cr	Fe	Chemical Composition, W/O				Cb	Ta	C	Other
					Al	Ti	Mo	W				
<u>Cast Nickel and Cobalt Base Alloys</u>												
M-21	Bal	--	5.7	--	6.0	--	2.0	11.0	1.5	--	0.08	--
Rene' 100	Bal	15.0	9.5	--	5.5	4.2	3.0	--	--	--	0.18	1.0 V
INCO-713LC	Bal	--	12.0	--	5.9	0.5	4.5	--	2.0	--	0.05	--
MM-004	Bal	--	12.0	--	5.9	0.6	4.5	--	2.0	--	0.05	1.3 Hf
Rene' 77	Bal	15.0	14.6	--	4.6	3.4	4.2	--	--	--	0.07	--
MM-247	Bal	10.0	8.3	--	5.5	1.0	0.7	10.0	--	3.0	0.16	1.5 Hf
IN-738	Bal	8.5	16.0	--	3.5	3.4	1.8	2.6	0.9	1.8	0.12	--
TRW VIA (DS)	Bal	7.5	6.0	--	5.4	1.0	2.0	6.0	0.5	9.0	0.1	0.43 Hf 0.5 Re
Rene' 80	Bal	9.5	14.0	--	3.0	5.0	4.0	4.0	--	--	0.17	--
X-40 ^(a)	10.5	Bal	25.0	--	--	--	--	7.5	--	--	0.5	1.0 Mn, 1.0 Si, 2.0 Fe
MM-509 ^(a)	10.0	Bal	23.5	--	--	0.2	--	7.0	--	3.5	0.6	0.5 Zr, 1.5 Fe, 0.4 Si

(a) Not candidates for DCHT cycle because of high Co content; could be considered for indirect cycle.

Note: Most of the Ni-base alloys also contain B and Zr.

TABLE 1 (CONTINUED)

Alloy	Chemical Composition, W/O											
	Ni	Co	Cr	Fe	Al	Ti	Mo	W	Cb	Ta	C	Other
<u>O.D.S. Alloys</u>												
YD-Ni	Bal	--	--	---	---	---	---	---	---	---	---	2.0 Y ₂ O ₃
MA-754	Bal	---	20.0	1.5	0.4	0.4	---	---	---	---	0.06	1.0 Y ₂ O ₃
MA-755	Bal	---	15.0	--	4.5	3.0	3.0	5.5	---	2.5	0.07	1.0 Y ₂ O ₃
HD 8077	Bal	---	16.0	---	4.0	---	---	---	---	---	---	1.5 Y ₂ O ₃
YD-NiCrAl	Bal	---	16.0	---	4.5	---	---	---	---	---	---	1.2 Y ₂ O ₃
MA-956	---	---	21.0	Bal	5.0	---	---	---	---	---	---	1.5 Y ₂ O ₃
<u>Wrought Molybdenum</u>												
<u>Base Alloy</u>												
Mo-TZM	---	---	---	---	---	0.45	Bal	---	---	---	0.015	0.09 Zr
<u>Wrought Nickel</u>												
<u>Base Alloys</u>												
Incoloy 800H	32.5	--	21.0	Bal	0.4	0.4	---	---	---	---	0.08	
Hastelloy X	Bal	1.5	22.0	---	---	---	9.0	0.6	---	---	0.1	
Inconel 617	Bal	12.5	22.0	18.0	1.0	---	9.0	---	---	---	0.07	

<u>Cast Nickel Base Alloys</u>	<u>ODS Alloys (a)</u>	<u>Wrought Molybdenum Base Alloys</u>	<u>Wrought Nickel Base Alloys</u>
INCO-713LC	MA-754	Mo-TZM	Inconel 617
MM-004	HD-8077		Hastelloy X
M-21	YD-Ni		
Rene' 80	YD-NiCrAl		
Rene' 100			
MM-247			
TRW VIA (DS)			

(a) A minimum of one alloy.

The two candidate alloys for hot gas ducting applications will be evaluated with respect to weldments as well as the base metal; the rest of the alloys are recommended for their potential as bucket and/or vane materials. Also, it is planned at this time to recommend that the effect of directional solidification (DS) on a cast alloy be evaluated at least in terms of environmental effects and NASA/TRW VIA is considered an attractive candidate. Further data are being gathered to assist in this alloy/process selection and recommendation.

Mechanical and physical property data are being compiled for each of the alloys recommended and this process is about 75% complete. The availability of data in the open literature or in General Electric specifications and materials handbooks is obviously quite varied and in some cases very little data are available. Also, as would be expected, the majority of the data available relate to the properties of the alloys in oxidizing (air breathing) environments and, with few exceptions, the effect of a gas reactor helium environment is not recorded. The available literature from U.S., Japanese and European projects related to the current program have been obtained and are being reviewed for pertinent alloy data.

Coating systems have been reviewed and it is tentatively proposed that a simple aluminide coating and a pre-oxidation procedure be the two protective systems for evaluation. Other, more sophisticated coating techniques are being considered further, but are not being recommended for review at this time. Weldments for the ducting alloys have not been finalized.

Up to 15 alloys, 12 weldments and 6 surface coating systems will be selected for VHTR/NPH applications. Again, attention will be given in the selection of alloys so that the various components in the primary circuit of the VHTR/NPH Systems are represented. A list of the leading candidate alloys along with their typical chemical compositions is presented in Table 2.

This list of about 30 alloys is the basis for a detailed analysis which will lead to the final selection of recommended alloys. Data on physical properties and mechanical properties (e.g. stress for rupture and stress for 1% creep in 10^3 , 10^4 , 10^5

TABLE 2

TYPICAL CHEMICAL COMPOSITIONS OF CANDIDATE
ALLOYS FOR VHTR/NPH APPLICATIONS

Alloy	Chemical Composition, W/O										
	C	Ni	Co	Cr	Fe	Al	Ti	Mo	W	Cb	Other
<u>Wrought Iron-Base Alloys</u>											
Incoloy 800H	0.08	32.5	--	21.0	Bal	0.4	0.4	--	--	--	
Incoloy 802	0.35	32.5	--	21.0	"	0.6	0.75	--	--	--	
Incoloy 807	0.08	40.0	8.0	20.5	"	0.35	0.45	--	5.0	1.0	
Incoloy DS	0.05	37.0	--	18.0	"	--	--	--	--	--	2.3 Si
Sanicro 32X	0.07	31.0	--	21.0	"	0.35	0.35	--	3.0	--	
HD-556	0.10	20.0	20.0	22.0	"	0.3	--	3.0	2.5	0.1	1.5 Mn, 0.9 Ta
<u>Cast Iron Base Alloys</u>											
IN-519	0.30	24.0	--	24.0	Bal	--	--	--	--	1.5	1.0 Si
HK-40	0.40	20.0	--	24.0	"	--	--	--	--	--	1.8 Si
Manaurite 36X	0.40	34.0	--	25.0	"	--	--	--	--	1.5	1.5 Si
Manaurite 900	0.15	32.0	--	21.0	"	--	--	0.3	--	1.5	1.0 Si
<u>Wrought Nickel Base Alloys</u>											
Hastelloy X	0.10	Bal	1.5	22.0	18.0	--	--	9.0	0.6	--	1.0 Si
Hastelloy S	0.02	"	--	15.5	1.0	0.2	--	15.0	--	--	0.1 La
Nimonic 75	0.15	"	--	19.5	2.0	--	0.4	--	--	--	

(TABLE 2 CONTINUED)

Alloy	Chemical Composition, W/O										Other
	C	Ni	Co	Cr	Fe	Al	Ti	Mo	W	Cb	
<u>Wrought Nickel</u>											
<u>Base Alloys</u>											
Nimonic 80A	0.06	Bal	1.0	20.5	--	1.4	0.05	--	--	--	
Nimonic 90	0.09	"	16.5	19.5	--	1.4	2.35	--	--	--	
IN-586	0.05	"	--	25.0	--	--	--	10.0	--	--	0.3 Ce
Inconel 600	0.04	"	--	15.8	7.2	--	--	--	--	--	
Inconel 601	0.05	"	--	23.0	14.0	1.4	--	--	--	--	
Inconel 617	0.07	"	12.5	22.0	--	1.0	--	9.0	--	--	
Inconel 625	0.05	"	--	22.0	3.0	0.2	0.2	9.0	--	4.0	
<u>Cast Nickel</u>											
<u>Base Alloys</u>											
IN-638	0.5	Bal	15.0	26.0	--	--	--	--	5.0	1.0	
IN-643	0.5	"	12.0	25.0	3.0	--	--	0.5	9.0	2.0	
<u>Cast Nickel</u>											
<u>Base Alloys</u>											
Supertherm	0.5	Bal	15.0	26.0	17.0	--	--	--	5.0	--	1.6 Si
<u>ODS Alloys</u>											
HD-8077	0.5	Bal	--	16.0	--	4.0	--	--	--	--	1.5 Y ₂ O ₃
MA-956	--	--	--	21.0	Bal	5.0	--	--	--	--	1.5 Y ₂ O ₃
MA-754	0.06	Bal	--	20.0	1.5	0.4	0.4	--	--	--	1.0 Y ₂ O ₃
MA-755	0.07	"	--	15.0	--	4.5	3.0	3.0	5.5	--	2.5 Ta 1.0 Y ₂ O ₃

(TABLE 2 CONTINUED)

TYPICAL CHEMICAL COMPOSITIONS OF CANDIDATE
ALLOYS FOR VHTR/NPH APPLICATIONS

Chemical Composition, W/O

Alloy	C	Ni	Co	Cr	Fe	Al	Ti	Mo	W	Cb	Other
<u>Molybdenum Base</u>											
<u>Alloys</u>											
Mo	--	--	--	--	--	--	--	Ba1	-	--	--
Mo-TZM	0.015	--	--	--	--	--	0.45	Ba1	-	--	0.09 Zr

hours at 1400°, 1600°, 1800° and 2000°F), corrosion resistance in impure helium and structural stability are being compiled.

Upon completion of the data compilation, the selection of the candidate alloys to be recommended for each component will be based upon availability, cost, strength, stability, fabricability, and behavior in HTR helium.

Work on this portion of Task 1 will be completed during the next quarterly reporting period with a complete recommendation and substantiation of the selected alloys for the meeting of the ERDA Alloy Selection Group in March, 1977.

2.2 TASK 3: TESTING AND ANALYSIS FACILITIES AND EQUIPMENT

The objective of this task is to establish the laboratory facility and the testing equipment to be used for the program, particularly the equipment required for the simulated reactor helium environments.

Drawings of a number of laboratory layouts of the simulated reactor helium test facility have been prepared and evaluated. The goal is to obtain the best balance between installation/start up costs and long term operating costs. The final laboratory layout has been selected (Fig. 1); detailed construction drawings are now being made.

Specifications for the single specimen creep-rupture test stands to be purchased by General Electric have been completed. Vendor bids to supply the equipment to the G.E. specifications have been received and evaluated. The award of the construction contract will be made during the next report period.

Specifications for the screening test equipment also have been completed. Vendor bids from U.S. suppliers have been evaluated. A request for bids has been sent to Flight Refueling, Ltd., England and their proposal is expected in January 1977. A vendor will be selected and a contract award made in the next report period.

Preliminary discussions have been held on the retort design for the fatigue/tensile stands. Retorts currently in operation and/or commercially available are being examined prior to writing detailed specifications.

Design and preparation of specifications for the aging and corrosion/stability stands are in progress.

2.3 TASK 4: SIMULATED REACTOR HELIUM ENVIRONMENT FACILITIES AND EQUIPMENT

The purpose of this task is the design, construction, installation, and checkout of two simulated reactor helium gas test retorts. Conceptual design of the helium loops have been prepared and reviewed. Preliminary layouts of the general arrangement of pumping, purification, and gas chemistry measurement packages have been completed and flow rates, impurity addition methods, purification methods, and analysis methods have been finalized. Detailed design of the purification system components, pumps, piping, etc. is in progress.

Figure 1. Laboratory Layout for Simulated Reactor Helium Test Facilities

A skematic of the addition and purification sections of the loop is given in Figure 2. This type of system was selected because it was felt that the addition or removal of specific gas impurities was desirable; the system indicated approaches that goal.

The addition system can add any of the desired impurities H_2 , CO , CO_2 and CH_4 from tanks containing 10% of each individual impurity in helium (bottled 100% impurity gas could be used, if that should prove to be desired). Water is to be added by passing a controlled amount of helium over hydrated oxalic acid.

The purification system will be able to selectively remove CO_2 [Ascarite (NaOH)] and H_2O [Magnesium perchlorate, $(Mg (CO_4)_2)$]; oxygen (O_2) is removed by Cu at $\sim 500^\circ C$, which also removes minute quantities of CO . Hydrogen (H_2) is removed by CuO at $\sim 150^\circ C$, which also removes CO . Methane (CH_4) is removed by the use of a molecular (mole) sieve, which will be kept at room temperature to decrease the possibility of release of impurities due to accidental warming of a cooled mole sieve. Of course, the mole sieve also will remove CO_2 , H_2O , and CO . Nitrogen (N_2) will be removed by a liquid nitrogen cooled activated charcoal trap, which will be used only when nitrogen levels are too high. This should occur primarily during initial start up of the system. The trap will be designed to require refilling once or twice a week. In addition to N_2 , the liquid nitrogen trap also will remove CH_4 , CO_2 , CO , and H_2O .

Adjustment to compensate for removal of impurities other than the desired species can be done with the specific gas species addition system.

The system as designed has considerable versatility; the series/parallel arrangement allows removal of CO (with CuO , molecular sieve, or liquid N_2 trap), CH_4 (molecular sieve or liquid N_2 trap), CO_2 (NaOH, molecular sieve, or liquid N_2 trap), H_2O (magnesium perchlorate, molecular sieve, or liquid N_2 trap) in either major purification "leg". This allows considerable latitude in operating the loop and allows easy replacement (or regeneration) of any depleted (saturated) component. The primary purification method for any impurity will be as discussed in the preceeding paragraphs and as summarized in Table 3.

The gas analysis will be done by a dewpoint meter for H_2O , solid ceramic electrolytic cell for O_2 , and a gas chromatograph for CO_2 , CH_4 , CO , H_2 , and N_2 . The system will be capable of analyzing for all controlled impurities at individual retort exits as well as in the main loop on the inlet and outlet sides with respect to the retorts.

Figure 2. Schematic of Proposed "Helium Loop" Purification & Addition System

TABLE 3

SUMMARY OF PURIFICATION METHODS AND REACTIONS

PRIMARY IMPURITY REMOVED	PURIFICATION METHODS (a)	PURIFICATION "REACTION"	OTHER IMPURITIES REMOVED
O ₂	Copper "Bed" at 500°C (followed by NaOH to remove CO ₂ , Mg(ClO ₄) ₂ to remove H ₂ O, or molecular sieve to remove both)	$\text{H}_2 + \frac{1}{2}\text{O}_2 \xrightarrow{\text{Cu}} \text{H}_2\text{O}$ $2\text{Cu} + \text{O}_2 \longrightarrow \text{Cu}_2\text{O}$	CO: $\text{CO} + \frac{1}{2}\text{O}_2 \xrightarrow{\text{Cu}} \text{CO}_2$
H ₂	CuO "Bed" at 150°C (followed by NaOH to remove CO ₂ , Mg(ClO ₄) ₂ to remove H ₂ O or molecular sieve to remove both)	$\text{CuO} + \text{H}_2 \rightleftharpoons \text{Cu} + \text{H}_2\text{O}$	CO: $\text{CuO} + \text{CO} \rightleftharpoons \text{Cu} + \text{CO}_2$
CO	CuO "Bed" at 150°C (See above)	$\text{CuO} + \text{CO} \rightleftharpoons \text{Cu} + \text{CO}_2$	H ₂ : $\text{CuO} + \text{H}_2 \rightleftharpoons \text{Cu} + \text{H}_2\text{O}$
H ₂ O	Magnesium Perchlorate [Mg(ClO ₄) ₂] or molecular sieve	$\text{Mg}(\text{ClO}_4)_2 + x \text{H}_2\text{O} \rightarrow \text{Mg}(\text{ClO}_4)_2 \cdot x\text{H}_2\text{O}$	None
CO ₂	Ascarite (NaOH) followed by Mg(ClO ₄) ₂ to remove H ₂ O)	$2\text{NaOH} + \text{CO}_2 \rightarrow \text{Na}_2\text{CO}_3 + \text{H}_2\text{O}$	None
CH ₄	Molecular sieve (at room temperature)	Adsorption	CO ₂ , H ₂ O, CO
N ₂	Liquid Nitrogen Cooled Activated Charcoal	Adsorption	CH ₄ , CO ₂ , CO, H ₂ O

(a) First Method Listed is the Primary Method.

The helium flow rate in the main loop will be ~ 225 liters/min.; the flow rates in the small single specimen retorts will be ~ 2 liters/minute and in the large, multiple specimen retorts ~ 10 liters/minute. The loop will have a minimum excess flow capacity of 50% of the flow required for the retorts (≈ 150 liters/min.); all retort flow rates are given at room temperature).

The primary reason for the relatively high flow rates is to decrease depletion of impurity species in the hot retorts. Significant impurity depletion (greater than 25% to 50% depletion of any controlled impurity) remains a primary concern, particularly for test temperatures of 1800°F and 2000°F . Further increases in loop flow rate are not practical due to limitations of pumping capacity. Therefore, other solutions to the impurity depletion problem must be found. Possible solutions to the problem include pre-test conditioning of the metallic retorts or use of ceramic retorts, at least for the high temperature tests. For the multi-specimen retorts (which contain ~ 90 specimens, holders, pull-rods, etc.), even with pre-conditioned or ceramic retorts, significant depletion may still occur. This would require a special design for the helium distribution system.

It is quite likely that experimental work to study the extent of depletion and the effectiveness of solutions for the problem will be necessary.

The design of the simulated reactor helium supply system will be completed and construction initiated during the next reporting period.

2.4 TASK 9: DATA ANALYSIS AND REPORTING, PROGRAM MANAGEMENT

The nine major tasks that comprise the Advanced Gas Cooled Reactor Materials Program are allocated to four General Electric Company operations:

- o Energy Systems Programs Department, Schenectady, N.Y.
- o Materials and Process Laboratory, Large Steam Turbine-Generator Operation, Schenectady, N.Y.
- o Corporate Research and Development Center, Schenectady, N.Y.
- o Material and Process Technology Laboratory, Aircraft Engine Business Group, Evendale, Ohio

The Program organization and work distribution within these organizations is depicted in Figure 3.

A top level Work Breakdown Structure (WBS) has been prepared in accordance with the general format of the Statement of Work of the Advanced Gas Cooled Reactor Materials Program, Contract No. EY-76-C-02-2975.A002 (Appendix A), and is shown in Figure 4. At this level, the WBS depicts the nine major tasks (Level 1) plus the next lower level (Level 2) work elements required to fulfill the contractual commitments of the Program. In order to more effectively manage and control the resources committed and expended during the course of the program, portions of the WBS have been expanded to the next level of detail (Level 3), but are not shown in Figure 4.

The advanced Gas Cooled Reactor Materials Program master schedule has been directly keyed to the major work elements identified in the top level Work Breakdown Structure. The Program Schedule is shown in Fig. 5. The master schedule highlights the milestone completion dates needing ERDA approval.

The first milestone identified as "ERDA Approval", denotes the start of the Advanced Gas Cooled Reactor Materials Program. The second milestone establishes the selection of the alloys to be evaluated in the screening test program to be completed by March 30, 1977. The major output of this, is a report summarizing the data, data analysis and rationalization supporting the recommendations of the selected alloys for the Direct Cycle Helium Turbine (DCHT) and the Very High Temperature Reactor/Nuclear Process Heat (VHTR/NPH) materials evaluation test programs. At this point the Alloy Procurement/Characterization task will begin.

The third and fourth ERDA controlled milestones represent the Helium Test Equipment and Helium Gas Supply System Design Reviews to be held on the sixth month of the program.

An indepth review and evaluation of the available data from past and existing related programs on the behavior of the materials in gas cooled environments will commence in the twenty-second month of the program resulting in a report recommending modifications in chemical composition of commercial alloys and/or new and optional alloy development programs to enhance the corrosion resistance of materials to DCHT and VHTR/NPH helium environments.

The final ERDA controlled milestones are topical reports covering specific phases of the program (to be established by ERDA) including a final report with alloy recommendations for each major critical component of the DCHT and VHTR/NPH systems for further in-depth evaluation and initiation of ASME code design data.

Detailed work plans have been prepared by each contributing G.E. component involved in the program; these are being integrated into the overall Program Work Plan.

A trip to High Temperature Materials Program (Wimborne, England) and Kernforschungsanlage (Jülich, West German) was made by Project Staff Personnel from Energy Systems Programs Department, Advanced Energy Programs and Corporate Research and Development Center on December 13-17, 1976.

Details of loop design and operating experience and experimental gas reactor materials programs were discussed. Helium loop designs utilized by the Dragon Program at CIIR (Oslo, Norway) and Fiat (Turin, Italy) were reviewed with people at HTMP. Test facilities at the KFA, including Helium loops and creep-rupture equipment were inspected and discussed at length with design and operating personnel.

HTMP and KFA personnel were very helpful and informative; considerable technical information was exchanged and is summarized in a detailed trip report prepared for the ERDA Program Manager.

Members of the G.E. Advanced Gas Cooled Reactor Materials Program Advisory Review Board have been selected; all have agreed to serve. The function of this Board, composed of qualified and nationally recognized individuals in areas of technical specialization appropriate to the program, is to review plans and progress of the program at selected critical times and to provide advice, recommendations and overall assessment of the program to the G.E. Program Manager and to ERDA.

The members of the board, their affiliations and areas of expertise, are:

GE ADVANCED GAS COOLED REACTOR MATERIALS PROGRAM
ADVISORY REVIEW BOARD

<u>Name</u>		
Mr. L.P. Jahnke	Consultant	High Temp. Alloys, Program Management
Dr. L.F. Coffin	GE CRDC	Fatigue/Creep, and effects of environment on properties
Mr. C.T. Sims	GE GTPD	Superalloys, Refractory Alloys, Surface Stability
Mr. G.M. Slaughter	ORNL	HTGR (U.S.) Materials Program, Component Fabrication
Prof. Per Kofsted	U. of Oslo	Surface Stability, Materials Testing, CIIR (Oslo) Program
Dr. L.W. Graham	HTMP, Wimborne	HTGR, DCHT environment Materials Testing, Dragon Project and GA (European) Materials Testing Programs
Prof. H. Nickel	KFA, Julich	Director, Institute for Reactor Materials, German HHT, (DCHT), PNP (VHTR/NPH) Materials Programs

An informal program integration review meeting was held with the ERDA Program Manager on November 4, 1976.

Figure 3. Program Functional Organization

Figure 4. Advanced Gas Cooled Reactor Materials Evaluation and Development Program -- Work Breakdown Structure.

Figure 5. Advanced Gas Cooled Nuclear Materials Evaluation and Development Program

Section 3.0

WORK TO BE COMPLETED DURING THE NEXT QUARTER

3.0 WORK TO BE COMPLETED DURING THE NEXT QUARTER

1. Task 1 - Selection of candidate alloys
2. Task 3 - Design of screening creep equipment
Design of creep/rupture equipment
Design of thermal stability and helium exposure equipment
3. Task 4 - Design of simulated reactor helium gas supply systems
4. Task 9 - Work Plan
Program Management Plan
Financial Management Plan

Appendix A

Appendix A

ADVANCED GAS COOLED NUCLEAR REACTOR MATERIALS EVALUATION AND DEVELOPMENT PROGRAM

STATEMENT OF WORK

1. INTRODUCTION

The Very High Temperature Reactor (VHTR) Process Heat Program and the Direct Cycle Helium Turbine (DCHT) Program, both sponsored by ERDA, will provide an expanded nuclear power capability. This will be accomplished through the development of a source of high temperature process heat, through the conversion of power at higher, more thermally efficient, temperature levels using closed cycle gas turbines and through the incorporation of energy conversion and energy conservation systems such as conventional temperature steam turbine systems, recuperators and pre-heaters which minimize rejection of waste heat. In both cases the use of high temperature helium-cooled reactors will require a knowledge of the long term properties of reactor fluid containment materials and of the materials used in constructing related hardware. The technology of the Nuclear Process Heat reactors can be applied in several ways including:

1. hydrocarbon reforming at 1400° - 1600° F for nuclear steel-making, energy transmission and storage, hydro-gasification and liquefaction of coal, petroleum refining and ammonia production;
2. steam-carbon gasification of coal at approximately 1800° F for producing synthetic pipeline gas and synthetic liquid fuels; and
3. thermochemical water splitting at 1500° - 2000° F for merchant hydrogen production without use of fossil fuels.

Because of the very high temperatures required for process heat applications, the need is evident for materials testing in the proper helium environment in the temperature range from 1400° to 2000° F on those alloys which might serve as materials of construction for heat exchangers, ducting, liners and other high temperature structural components.

The Direct Cycle Helium Turbine (DCHT) technology will require similar material evaluations from 1400° to 1800° F, the temperature range in which long life, high reliability closed cycle gas turbine technology can most readily be developed.

The development of an adequate data base concerning the characteristics of materials for the above applications is necessary. The data base must

permit the selection of materials of construction and should provide a reliable level of design data for the construction of various items of development hardware leading to the successful development of VHTR and DCHT systems. The present lack of an accurate measure of materials capabilities under these high temperature helium environments is a factor which is currently limiting the development of the VHTR/DCHT systems; the proposed program is intended to provide such initial information.

2. PROGRAM OBJECTIVES

The objectives of this materials evaluation and development program are:

1. to evaluate prospective candidate alloys for VHTR and DCHT applications with regard to their mechanical properties, structural stability and corrosion resistance in simulated reactor helium environments.
2. to use the resulting data to make recommendations of alloys for gas reactor project commitments including:
 - a. high temperature materials and components test loops, and
 - b. high temperature materials and components prooftesting.
3. to use the resulting data to make recommendations of commercial and experimental alloys for continued evaluation in a subsequent, more extensive, qualification program for demonstration plant reference alloys.

3. SCOPE OF WORK

The contractor shall provide and/or provide for, the necessary personnel, facilities, services, equipment, and materials to conduct the evaluation test programs and to do all things necessary for, or incident to, completion of the program described in this section.

3.1 TASK 1 - SELECTION OF CANDIDATE ALLOYS

The contractor shall submit to ERDA a list of potential candidate alloys, coatings and surface treatments for VHTR and DCHT applications. The contractor shall serve, at the request of ERDA, on a materials selection group organized and staffed by the action of the Nuclear Research and Application (NRA) Division of ERDA. This materials selection group, with the support of the contractor, shall review the pertinent literature and shall prepare a list of recommended candidate alloys. The group shall be guided in their final selection of candidate alloys by detailed sets of materials selection criteria (minimum property requirements) which

will be provided through NRA for the VHTR and DCHT reactor systems. As many as 15 alloys, 12 alloy weldments and up to 6 coating systems shall be selected for VHTR applications and up to 12 alloys, 2 weldments and 3 coating systems shall be selected for DCHT applications (or a total of up to 25 alloys, 12 weldments and 6 coatings will be selected for a combined evaluation program). The selection of alloys shall be accomplished to insure that the needs of the various components (such as ducts, valves, heat exchangers, thermal barriers and turbine blades and vanes) are adequately represented. All final selections will require ERDA approval.

The materials selection group, at the discretion of ERDA, shall meet at subsequent times of review test results and render further recommendations regarding commitment of new alloys or deletion of certain alloys from the test program.

Based on evaluation of the results of the screening studies (creep, thermal stability and corrosion), the contractor shall recommend to ERDA the selection of materials for more intensive engineering studies in specific VHTR/DCHT atmospheres. As many as 6 alloys, 4 weldments and 2 coating or surface treatments shall be selected for more intensive precision studies for the VHTR applications and up to 4 alloys, 1 weldment and 2 coatings shall be selected for the DCHT applications (or a total of up to 10 alloys, 5 weldments and 4 coatings will be selected for a combined evaluation program).

3.2 TASK 2 - PROCUREMENT AND CHARACTERIZATION

The contractor shall procure the approved alloys in the forms and quantities required for the test program; procurement of materials shall be to nationally recognized specifications or to commercial specifications which have proven acceptable for either industrial or aircraft gas turbine application. Characterization testing of the alloys shall be performed to verify conformance to specification test requirements. Where no specification may exist, as for certain developmental alloys, the heat of material being tested shall be characterized by chemical composition, by room temperature tensile properties and by grain size and microstructure. All materials shall be non-destructively tested by radiographic inspection and fluorescent penetrant inspection for cast alloys and by fluorescent penetrant inspection and immersed ultrasonic inspection for wrought alloys in mill product form. Where weldability information is not available, the weldability of applicable plate alloys shall be determined by weld restraint patch weld tests and the relative weldability of the alloy shall be rated in relation to competing alloys in the program. A limited number of weld specimens shall be prepared for environmental testing.

3.3 TASK 3 - TESTING AND ANALYSIS FACILITIES AND EQUIPMENT

The contractor shall provide all of the conventional and special testing and analysis facilities and equipment required to successfully execute the proposed program. These shall include the conventional materials laboratory support facilities and equipment, such as those for materials inspection, chemical analysis, metallographic examination and determination of room and elevated temperature mechanical properties in air (e.g., tensile, impact, stress-rupture and creep) and the specific facilities and equipment required for the screening and precision engineering tests in VHTR/DCHT environments, which are identified in the remaining tasks. The latter facilities and equipment will be located in a contractor laboratory in Schenectady, New York and will include the following:

1. Up to 6 multiple-specimen screening creep testing units,
2. Up to 8 thermal stability/corrosion exposure units,
3. Up to 10 stress-rupture/creep-rupture testing units,
4. Up to 35 precision creep testing units.
5. Two combined stress (low and high cycle) fatigue testing units, and
6. One tensile testing unit (to be incorporated with one of the combined stress fatigue testing units).

3.4 TASK 4 - SIMULATED REACTOR HELIUM ENVIRONMENT FACILITIES AND EQUIPMENT

The contractor shall provide the facilities and equipment required to prepare, distribute, monitor and control helium atmospheres simulating those of typical VHTR and DCHT systems. Representative impurity levels for these systems are the following:

<u>System</u>	<u>Impurity Content, microatmosphere (μAtmo)</u>						
	<u>H₂</u>	<u>CO</u>	<u>CH₄</u>	<u>H₂O</u>	<u>N₂</u>	<u>CO₂</u>	<u>O₂</u>
DCHT	200-700	40-120	40-80	0.5-3	<20	<5	<10 ⁻¹⁴
VHTR	600-1200	20-100	30-70	0.5-50	<20	<5	<10 ⁻¹⁴

(Separate recirculating master loops shall be provided for the VHTR and the DCHT simulated reactor atmospheres.) Each master loop shall supply controlled-impurity helium to half of the screening creep, thermal

stability/corrosion, stress-rupture and precision creep testing units. The loops shall feature automatic flow control which will permit the addition or removal of test units to or from the loops without any detrimental effects on the other units. The loops will also be designed to permit limited changes in the number of different types of testing units being supplied by either master loop. In this regard, the pumping capacity of each master loop must be sufficient to adequately supply the following combination of test units: 4 screening creep, 5 thermal stability/corrosion, 10 stress-rupture and 20 precision creep. The flow of simulated reactor helium through each test unit must be sufficient at all times to prevent any significant prolonged depletion of the controlled impurities.

The control of impurity levels in the recirculating helium loops shall be achieved by manual adjustment of micrometer metering valves from cylinders containing premixed contaminants in helium. The impurity levels in the circulating loops shall be monitored and controlled using equipment and procedures which are required to assure that impurity contents remain within specified limits.

Protective features shall include provision for isolation of all test units and shutdown of all test furnaces associated with the loop in the event of high oxygen level or reduced system pressure. The system shall have the capability of continuous readings of oxygen and water levels at both the header inlet to the test facilities and at the header leading from the test facilities.

The total loop pressure shall be between one and three atmospheres and it shall exceed one atmosphere by an amount sufficient to facilitate prompt detection of a system pressure drop.

3.5 TASK 5 - MECHANICAL PROPERTY EVALUATION

The contractor shall prepare test matrices for the planned mechanical property evaluations, conduct the evaluation program, and evaluate the test data in order to establish a data base of selected properties in simulated reactor environments. Mechanical properties shall be obtained in typical VHTR and DCHT reactor helium, and limited testing in air will be conducted when air data are required to establish needed correlations between properties in air versus impure helium. Candidate alloys will be subjected to screening-type creep, tensile and impact tests to provide data for selection of the preferred alloys which will be subjected to precision type stress-rupture, creep-rupture, creep and fatigue tests. The following data shall be obtained:

1. Screening creep data for exposures up to 10,000 hours between 1400° and 2000 F. All candidate materials selected for the VHTR applications shall be tested in the screening creep equipment according to a matrix including up to four (4) stress levels and up to four (4) temperature levels. The candidate materials selected for the DCHT applications shall be tested in the same equipment using a matrix including up to six (6) stress levels and up to four (4) temperature levels. All specimens will be removed from test at established intervals for creep strain measurements and visual examinations. Specimens will be retired when they creep beyond an established limit or reach 10,000 hours. A limited number of creep-rupture tests shall be performed in air on both VHTR and DCHT materials for comparative purposes.

The creep data shall be plotted in several forms in order to permit comparisons to be made between the candidate materials and the test environments at various percent creep levels.

2. Stress-rupture/creep-rupture data for exposures up to 10,000 hours between 1400° F and 2000° F. The materials selected for precision evaluation shall be tested in their respective VHTR/DCHT environments using a matrix involving up to four (4) temperature levels and up to five(5) stress levels. Stresses will be selected to permit determination of rupture strengths for 100-, 1000- and 10,000-hour exposures. Precision creep data will be obtained during all tests designed for durations greater than 5000 hours. A limited number of tests shall be performed in air on both VHTR and DCHT materials for comparative purposes. The rupture data shall be plotted in several forms to permit comparisons to be made between the materials and the test environments.
3. Precision creep data for exposures up to 15,000 hours between 1400° F and 2000° F. The materials selected for precision evaluations shall be tested in their respective VHTR/DCHT environments using a matrix similar to that used for the above stress-rupture testing. Stresses will be selected to permit determination of the allowable stresses for up to 1% creep in 15,000 hours. Precision strain data will be obtained using extensometers attached to the specimens. Strain measurements will be made with LVDT equipment during primary creep, with dial gauges and LVDT equipment during early secondary creep, and with dial gauges and/or other equipment with equivalent precision during the remainder of the test. A limited number of tests shall be performed in air on both VHTR and DCHT materials for

comparative purposes. The precision creep data shall be plotted in a variety of forms in order to permit comparisons to be made between the candidate materials and the test environment at various percent creep levels up to maximum strains appropriate for the applicable components, but not to exceed 1%.

4. Fatigue strength data for endurance limits between 10^3 and 10^7 cycles at 1400 and 1600°F. The materials selected for precision evaluations will be tested in the as-received condition and after exposures of up to 10,000 hours in appropriate VHTR/DCHT environments. All tests will be conducted in static high-purity helium or an equivalent environment which will not significantly change the surface condition of the specimens. High-cycle fatigue tests shall be load controlled and shall be carried out to 10^5 to 10^7 cycles at two "A" ratios: ∞ and one to be selected later. Low-cycle fatigue tests shall be strain controlled and shall be carried out to 10^3 to 10^5 cycles. The fatigue data for DCHT turbine blade and vane alloys shall be presented as modified Goodman Diagrams using creep-rupture test data for the "A" = 0 data point. The fatigue data for VHTR and ducting alloys shall be presented as plots of pseudo stress versus number of cycles to crack initiation and/or failure for the various "A" ratios at the two test temperatures.
5. Tensile property data at room and selected elevated temperatures. All candidate materials selected for screening evaluations will be tested at room temperatures in the as-received condition and after thermal aging exposures of up to 10,000 hours in appropriate VHTR/DCHT environments at temperatures between 1400 and 2000°F. The alloys selected for precision evaluations will be tested also at the temperatures used for the aging exposures and selected creep tests, and in the temperature range of 600 to 1000°F (to check for ductility minimums). These alloys will be tested in the as-received and aged conditions and after creep exposures of up to 15,000 hours. All elevated temperature tensile tests will be conducted in static high-purity helium. Tensile test results shall be tabulated and plotted to illustrate the comparative tensile properties as a function of test temperature and prior history.
6. Impact property data at room and selected elevated temperatures. All wrought candidate materials selected for screening evaluations shall be tested at room temperature in the as-received condition and after thermal aging exposures of up to 10,000 hours in appropriate VHTR/DCHT environments at temperatures between 1400 and 2000°F. The wrought materials selected for precision evaluations will be tested also at one selected elevated temperature in the as-received condition and after long-term exposure in VHTR/DCHT environments at two selected aging

temperatures. Similar data shall be obtained on cast alloys should it be determined that useful information can be generated from these ductile materials. Impact test results shall be tabulated to illustrate the comparative impact properties as a function of test temperature and prior history.

3.6 TASK 6 - THERMAL STABILITY EVALUATIONS

The contractor shall conduct screening type thermal stability studies on all candidate alloys and additional more-intensive thermal stability evaluations on the preferred alloys selected for continued testing. In both the screening and intensive studies, thermal stability of the alloys will be evaluated by determining the effects of extended exposures in simulated reactor helium environments on microstructure and selected mechanical properties. All materials will be exposed in VHTR/DCHT atmospheres for periods of up to 10,000 hours at up to four (4) temperatures between 1400 and 2000°F. Specimen evaluations after stressed and unstressed exposures shall include metallographic examination by optical and electron microscopy and electron microprobe techniques to identify and characterize the nature and extent of instabilities, and tensile, impact and bend tests to quantify the magnitude of any structural instabilities.

The VHTR screening tests shall include up to fifteen (15) candidate alloys plus appropriate weldments, coatings and cast/wrought alloy comparisons. Small thermal stability specimens (pins or rods) and tensile and impact specimens shall be exposed in the unstressed condition, and stressed specimens shall be obtained from the screening creep tests. Specimen evaluations shall consist of metallographic examination, hardness testing and select phase identification for both stressed and unstressed specimens, and room temperature impact and tensile testing of unstressed specimens.

The VHTR intensive evaluations shall include up to six (6) selected alloys, four (4) weldments and two (2) coatings. In addition to the above specimens, a limited number of weld bend specimens shall be included. Specimen evaluations shall consist of those described above plus testing of the weld bend specimens and selected tensile and impact testing at appropriate elevated temperatures.

The DCHT screening tests shall include up to twelve (12) candidate alloys plus appropriate weldments and coatings. The DCHT intensive-study tests shall include up to four (4) alloys, and one (1) weldment and two (2) coatings. The specimen types, exposure matrix and evaluation plans shall be essentially the same as those for the VHTR screening and intensive studies.

The thermal stability data generated under this task and appropriate data from the other tasks shall be analyzed and used to identify the temperature, time and stress conditions which produce instability. The effects of such instabilities on mechanical properties shall be described. These results shall be tabulated and plotted in appropriate form to identify the conditions required for onset of instability.

3.7 TASK 7 - CORROSION RESISTANCE EVALUATION

The contractor shall conduct both screening and intensive corrosion testing evaluations on specimens exposed in appropriate VHTR and DCHT environments. Exposures of materials shall cover up to four (4) levels of temperature in the range from 1400° to 2000°F and times up to 10,000 hours. The number and type of alloys, weldments and surface coating systems to be exposed to DCHT and VHTR environments for both the screening and intensive tests shall be the same as stated for the thermal stability studies (Task 6). Specimens shall include specific corrosion specimens (small rods and/or coupons) and sections of other specimens intended primarily for testing under other tasks (thermal stability and mechanical property specimens). Specimen evaluations shall include weight change analysis and metallographic examination by both optical and electron microscopy, by electron microprobe analyses and by x-ray diffraction analysis of surface scale. The morphology of surface scale and subsurface corrosion shall be characterized and the extent of corrosion (depth of attack, weight change, etc.) shall be plotted as a function of time for those variables such as temperature, alloy designation, and various elemental constituents which may be determined to have significant influence on corrosion.

3.8 TASK 8 - DEVELOPMENT OF MODIFIED AND/OR NEW ALLOYS

The contractor shall analyze all test data and metallographic and analytical results generated under this program and shall conduct literature searches and review commercial alloy development efforts, for the purpose of identifying composition modifications and/or processing changes (including use of surface treatments or coatings) which could improve an alloy's environmental compatibility and/or structural stability in VHTR/DCHT atmospheres. The contractor shall identify any modified and/or new alloy compositions which he considers merit attention and shall propose to ERDA that such alloys and coatings or processing modifications thereto, be

added to the program and/or that specific alloy development efforts be undertaken. The rationale behind such recommendations shall be fully justified technically. ERDA approval shall be obtained by the contractor prior to initiation of any experimental effort.

3.9 TASK 9 - DATA ANALYSIS AND REPORTING

The contractor shall compile and analyze the test data and results generated and collected under this program and shall issue the following technical and management reports:

1. monthly management control reports (eight copies),
2. quarterly progress summary reports (twelve copies), and
3. topical alloy recommendation reports (twelve copies).

The monthly management control reports shall review the program status regarding the achievement of scheduled milestones and the planned versus actual expenditures. The quarterly progress summary reports shall review the progress made in each work area, any problems delaying progress and any significant achievements. The monthly reports due at the same time as quarterly reports shall be incorporated in the quarterlies.

The topical alloy recommendation reports represent the primary product of the program and shall receive appropriate emphasis. These reports shall contain detailed reviews of the data base used for the alloys being recommended. The data base shall include all the test data and results obtained under this program and shall be compiled in the form of standard data sheets for a Preliminary Materials Property Handbook. These reports shall be issued to meet major program milestones which are keyed to VHTR/DCHT project commitments as the following:

1. selection of alloys for construction of special materials and component testing facilities,
2. selection of alloys for special materials and component prooftesting, and
3. selection of alloys for additional, more extensive evaluations in a subsequent materials qualification program.

The contractor shall prepare a work plan, a program management plan and a financial management plan at the start of the program and shall provide continuous program management and technical coordination of the various efforts. The contractor shall utilize the services of a selected Program Advisory Review Board consisting of approximately seven highly

qualified and nationally recognized individuals in areas of technical specialization appropriate to the program. It shall be the function of this board to review plans and progress on the program at selected critical times and to provide advice, recommendations and overall assessment of the program to the Program Manager and to ERDA.