1 of 1

DOE/ER-0313/100

FUSION MATERIALS

Prepared for
DOE Office of Fusion Energy
(AT 15 02 03 A)

Prepared for
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
Managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract DE-AC05-84OR21400

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

FOREWORD

At the time of the reviews, briefings, and discussions conducted for this Evaluation of Vanadium Alloy Technology, it was believed that the base alloy composition V-5% Cr-5% Ti was the most promising. Since that time, in the period August–December 1993, it was found that a heat having the nominal composition V-5% Cr-5% Ti exhibited mechanical properties, specifically ductile-to-brittle transformation temperature (DBTT), inferior to a heat with nominal composition V-4% Cr-4% Ti. These results have led to additional studies of base composition, and the role of impurities coupled with the thermal-mechanical history, and their effect on the physical and mechanical properties of the alloy. This upholds the need for conducting the comprehensive and aggressive program outlined in this report to properly define and qualify the alloy for the ITER.

**TECHNICAL EVALUATION
OF THE
TECHNOLOGY OF VANADIUM ALLOYS FOR
USE AS BLANKET STRUCTURAL MATERIALS
IN FUSION POWER SYSTEMS**

Committee Members:

**Howard K. Birnbaum
John W. Davis
James N. Doggett
William D. Manly**

August 4, 1993

CONTENTS

SUMMARY	ix
WHY VANADIUM	1
ITER DESIGN	1
SELECTION OF V-5Cr-5Ti	3
DATA BASE	3
ENGINEERING ISSUES FOR VANADIUM USE	5
PRODUCTION CAPABILITY	6
1993 VERSUS SPACE ERA	7
COST EXPERIENCE FOR MATERIAL QUALIFIED (CODE CASE)	8
SCALEUP OF ALLOY PRODUCTION	8
COMPONENT OR PROTOTYPE FABRICATION	9
MATERIAL BEHAVIOR TESTING	10
ENGINEERING TEST LOOPS	12
GENERIC ISSUES	13
Beryllium Bonding	13
MHD Insulating Coatings	13
COMMITMENT AND COST SUMMARY	14
CONCLUSIONS	15
RECOMMENDATIONS	16
APPENDICES	17
A. Vanadium Alloy Specifications	19
B. American Metal Market	21
C. Material List - Vanadium Alloy ITER Blanket	23
D. Teledyne Wah Chang Albany Cost Estimates	25
E. Letter, F. W. Wiffen to William D. Manly, May 4, 1993	27
F. Charter for the Evaluation of Vanadium Alloys	29
G. Agendas and Attendance at Committee Meetings	31
DISTRIBUTION	43

SUMMARY

The Committee's evaluation of vanadium alloys as a structural material for fusion reactors was constrained by limited data and time. The design of the International Thermonuclear Experimental Reactor (ITER) is still in the concept stage, so meaningful design requirements were not available. The data on the effect of environment and irradiation on vanadium alloys were sparse, and interpolation of these data were made to select the V-5Cr-5Ti alloy.

With an aggressive, fully funded program, it is possible to qualify a vanadium alloy as the principal structural material for the ITER blanket in the available 5 to 8-year window. However, the data base for V-5Cr-5Ti is limited and will require an extensive development and test program.

Because of the chemical reactivity of vanadium, the alloy will be less tolerant of system failures, accidents, and off-normal events than most other candidate blanket structural materials and will require more careful handling during fabrication of hardware.

Because of the cost of the material, more stringent requirements on processes, and minimal historical working experience, it will cost an order of magnitude more to qualify a vanadium alloy for ITER blanket structures than other candidate materials.

The use of vanadium is difficult and uncertain; therefore, other options should be explored more thoroughly before a final selection of vanadium is confirmed. The Committee views the risk as being too high to rely solely on vanadium alloys.

In viewing the state and nature of the design of the ITER blanket as presented to the Committee, it is obvious that there is a need to move toward integrating fabrication, welding, and materials engineers into the ITER design team.

If the vanadium alloy option is to be pursued, a large program needs to be started immediately. The commitment of funding and other resources needs to be firm and consistent with a realistic program plan. The total cost of developing vanadium for the ITER is estimated to be \$130 million over 5 to 8 years, exclusive of the cost of irradiation facilities.

WHY VANADIUM

Vanadium alloys have long been viewed as desirable materials for fusion reactor structures in the first wall and blanket regions. These alloys offer the potential of higher heat loads and higher operating temperatures than steels, evidence of resistance to degradation under irradiation, and excellent compatibility with liquid lithium. Activation product radioisotopes in vanadium decay with modest decay-heating rates and manageable half-lives. Care in the selection of alloying additions produces structures with attractive accident consequence and waste management potential at the end of reactor service.

In addition to vanadium alloys for possible use in the International Thermonuclear Experimental Reactor (ITER) in approximately 1999, vanadium is a strong candidate for the demonstration fusion power plant to be built in 2025.

ITER DESIGN

The ITER is a magnetic fusion device designed to produce from 1.5 to 3.0 GW of fusion power. The machine is toroidal in shape with a donut-shaped plasma of approximately 8-m major radius that is contained inside a vacuum vessel by the combined magnetic field generated by a set of superconducting magnets and a 25-MA current flowing in the plasma itself. Figure 1 is a vertical cross section of one-half of the ITER showing the location and shape of the internal components. The bulk of the energy produced by the plasma is in the form of energetic neutrons that are slowed and absorbed in the blanket and shield structure.

The ITER design is in the very formative stage, and drawings that show the details of the components are nonexistent. The two systems that have been proposed as potential applications for vanadium are the blanket/shield and the divertor. For the purposes of the Committee's evaluation of vanadium alloy development, only the blanket/shield has been considered. It should be noted that there is, so far, no definition of the entire primary cooling loop associated with the blanket. The nature of the external piping and the primary heat exchangers may have some impact on the development needs.

The blanket modules, which number several tens, are basically tall, boxlike structures that are mounted on the inboard and outboard sides of the plasma vacuum vessel and subsequently joined together by welding, in situ, to form two toroidally continuous structures. The modules do not extend to the bottom of the vacuum vessel; therefore, all piping and cabling runs enter and leave through the top. Each module has a cross section at the mid-plane of 0.65 m wide by 0.5 m thick and is approximately 12 m high. A horizontal cross section at the mid-plane

Fig. 1. ITER Vertical Cross Section.

ITER

JULY 19 1993

WORKING PROPOSAL

LEVEL : SKETCH

SAN DIEGO CO-CENTER

for an inboard blanket module is shown in Fig. 2. The module cross-section varies in width along the vertical direction and becomes more complex at the top and bottom. The boxlike structure is assumed to be all fabricated from formed and welded vanadium alloy sheet and plate. The sheet and plate vary in thickness from a few millimeters to a few centimeters. There are two blanket/shield options, both filled with liquid lithium. The first option is a self-cooled circulating liquid lithium system; the second is indirectly cooled by high-pressure helium circulating in tubes.

The front or plasma-facing surface intercepts a neutron flux of 1.5 to 3.0 MW/m² with a radiative heat load of 40 to 70 W/cm². In addition, the first wall is bombarded with fuel and impurity particles that escape from the core of the confined plasma. The first wall will be coated with beryllium in order to minimize the amount of high-Z material sputtered and returned to the plasma. The first wall is highly thermal stressed, which is the primary limitation on the operating temperature.

SELECTION OF V-5Cr-5Ti

V-5Cr-5Ti has been chosen as the reference alloy for development. The data so far developed by the vanadium alloy research and development (R&D) program have identified it as the alloy with the most potential to attain the combined goals of high-temperature capability, fabricability, low nuclear activation, acceptable after heat, and in the case of the ITER, compatibility with liquid lithium. Appendix A gives the tentative specification for the alloy of choice. The selection is based on limited test data from two small heats of the alloy plus extrapolations of data from other alloys. Some testing of the sample heats has been accomplished, and additional tests, including irradiated material tests, are under way.

DATA BASE

Although there is a large body of information developed for pure vanadium, there is only a limited data base available for any of the vanadium alloys. This is simply because there is not any significant commercial use for structural vanadium alloys.

In order to qualify V-5Cr-5Ti for use in the ITER, the whole range of material, fabrication, and joining data will need to be developed. These data will have to include values for both unirradiated and irradiated alloys:

Fig. 2. Horizontal Cross Section at
Mid-Plane for In-Board Blanket Module.

ITER

JULY 19 1993

WORKING PROPOSAL

LEVEL : SKETCH

SAN DIEGO CO-CENTER

- physical properties (0 to 650°C) - electrical and thermal conductivity, expansion coefficient, specific heat, etc.;
- mechanical properties (0 to 650°C) - Young's modulus, yield strength, ultimate strength, elongation, shear modulus, Poisson's ratio, hardness, fracture mechanics data, creep, fatigue strength, and environmental effects, e.g., stress corrosion, hydrogen embrittlement, and helium embrittlement; and
- engineering design data:
  - sensitivity of properties to product form - sheet, tube, and thick sections;
  - vacuum properties - outgassing rates, bakeout requirements, galling, and porosity;
  - available product forms and size limitations;
  - machinability;
  - cold-forming properties - bend radius, cold-working, upsetting, cross-grain properties, and springback;
  - weldability - filler materials, properties of the heat-affected zone, transitions to other materials, and effects of thickness;
  - brazing and bonding techniques;
  - chemical reactivity - corrosion sensitivity to air, water, hydrogen isotopes, and possible coolants; and
  - techniques for and properties of insulating, joining, and protective coatings.

ENGINEERING ISSUES FOR VANADIUM USE

The use of vanadium alloy as a principal structural material in the ITER requires an extensive data base on the engineering properties of the material. There is essentially no industrial experience in the design and fabrication of significant structures from any vanadium alloy. The largest identified vanadium alloy structure known in the United States consisted of a table-top size loop of tubing.

There is a large body of engineering data on other refractory metals that is generally useful in dealing with vanadium alloys. However, in order to qualify a vanadium alloy for this critical application in a nuclear facility, it will be necessary to have a complete knowledge of the peculiarities of this particular material. In addition to the materials data that will be developed under the vanadium research and development plan, there needs to be extensive work on the practical design, fabrication, and repair of components made from this alloy.

Vanadium is extremely sensitive to oxygen contamination at elevated temperatures such as encountered during welding, forging, stress relief, and annealing and, therefore, requires the use of inert shielding or vacuum during hot processing. Inert gas facilities large enough to house the fully assembled blanket module will be required. The welds used for final installation in the field will require special consideration.

If the blanket design chosen employs circulating liquid lithium for cooling, the entire liquid-metal contacting surface will need to be coated with an insulating material to reduce the pressure drop from electromagnetic effects of flowing a conductor across a magnetic field. This coating will need to be complete, and some method of detecting and repairing damage will be required. This is a generic issue for all self-cooled liquid-metal blanket systems, but requires a material-specific solution. Furthermore, this coating will need to be compatible with the use of liquid lithium to control the tritium and deuterium levels in the vanadium blanket material.

If portions of the flowing liquid-metal systems are made from materials other than vanadium, for cost or safety reasons, transition joints will be required. The joints themselves should be easily developable. However, the use of two materials in the cooling loop will require a complete understanding of mass transfer effects that may limit the lifetime of the components.

PRODUCTION CAPABILITY

At the present time, there is only one supplier of vanadium existing in the United States: Teledyne Wah Chang Albany, Albany, Oregon. However, other refractory metal producers, such as Cabot Performance Materials, Boyertown, Pennsylvania, and H. C. Starck GmbH, New York, New York, have the facilities to produce vanadium and vanadium alloys, but they have no apparent interest in diversifying into vanadium alloy production. The titanium industry in the United States is now depressed; therefore, their melting furnaces, forges, and mills could be used for vanadium alloy production. MetalWerke Plansee, Austria, and GFE Metallgesellschaft, Germany, have the capability to produce pure vanadium and vanadium alloys. It has been suggested that the Russians have limited capabilities.

Vanadium raw material is quite abundant. The present V_2O_5 supplier, Strategic Minerals Corporation (STRATCOR), Danbury, Connecticut, is quoting \$14.00/lb for high-purity material. Large quantities are available from Florida and Idaho phosphates and from Venezuela crude oil. Impure V_2O_5 (98%) has been priced on the market in 1975 at \$2.95/lb and in 1993 at \$1.80/lb with spot prices

at \$1.20 to \$1.40/lb. The American Metal Market (see Appendix B) shows raw material prices are headed downward. Other raw materials for producing the alloy, high-purity Al for the aluminothermic reduction of the V_2O_5 (one U.S. supplier, Reynolds) and alloy elements Cr and Ti, are readily available.

Teledyne Wah Chang Albany's ingot price has varied from \$300 to \$400/kg to \$200 to \$400/kg depending on order size, etc. Today, the price for small quantities of ingots is \$124.36/kg, and for large quantities, it is \$95.65/kg. For mill products, the price has varied from \$400 to \$600/kg to the present quote of \$159.40/kg. The price could change as a result of quantities, specifications, and tolerances for width, thickness, and flatness.

The Bill of Materials for the ITER (see Appendix C) is quite preliminary, and better information needs to be developed, including tolerances for the various product forms. Using the June 22, 1993, prices from Teledyne Wah Chang Albany (see Appendix D) suggests the mill products for the ITER for vanadium would cost \$100 to \$150 x 10⁶. Using data on prices for 316 SS and alloy-type steels from the June 18, 1993, American Metal Market would generate a 316 SS mill products cost of \$4.5 x 10⁶ and for alloy steel, \$0.8 to \$1.6 x 10⁶.

However, the vanadium cost estimates are subject to considerable change. The latest quote from Teledyne Wah Chang Albany, dated August 2, 1993, from Bob Kinney to Dennis Lee of McDonnell-Douglas Aerospace suggests a cost range from \$265 to \$464 x 10⁶ for the mill shapes to construct the ITER, depending on whether Li or He cooling is used. From the wording of the quote, it appears that Wah Chang does not consider vanadium and vanadium alloy mill products as a commercial product, due to the exceptions taken.

1993 VERSUS SPACE ERA

The situation with the development and production of vanadium alloys today should be compared to the situation with refractory metals in the Space Era. During the Space Era, the following eight metal producers existed: DuPont, Stauffer, Fansteel, National Research Corporation, Teledyne Wah Chang Albany, KBI, Westinghouse, and Haynes Stellite of Union Carbide Corporation. Today, there are only three U.S. producers: Teledyne Wah Chang Albany, Cabot Metals, and H. C. Starck, GmbH. Secondary metal fabrication capabilities existed then at Precision Sheet Metal, Nooter, Superior Tube, Ladish, and Wyman Gordon. Programs were under way at Boeing, Rockwell, Martin Marietta, General Dynamics, McDonnell Douglas, Lockheed, Pratt & Whitney, and General Electric. The extensive refractory metal program was actively supported for many years by

the National Advisory Committee for Aeronautics-National Aeronautics and Space Administration, Department of Defense, and Atomic Energy Commission. An estimate was made of the total researchers and engineers working on the program at 150 to 200 with a total expenditure of $\$500 \times 10^6$ to $\$750 \times 10^6$ during the 1958-72 time period.

In a recent talk presented by Jim Laidler from Argonne National Laboratory (ANL) on January 15, 1993, at Dallas, Texas, he described the development of stainless steel cladding and duct materials for the Liquid Metal Fast Breeder Reactor (LMFBR). His data showed that the reference alloy was studied from 1966 to 1987 at a cost of $\$101 \times 10^6$, and the advanced alloy was examined from 1972 to 1990 at a cost of $\$77 \times 10^6$.

COST EXPERIENCE OF MATERIAL QUALIFICATION (CODE CASE)

No matter how the sighting and operational approval for the ITER will be obtained, the project will need to develop a data base equivalent to an American Society for Testing and Materials/American Society of Mechanical Engineers Code case. During the Committee's meeting at ANL on June 3-4, 1993, W. Buckman presented some information on this and quoted a figure of $\$10 \times 10^6$ to obtain the necessary data for IN-718, which was a commercial alloy for 20 years when this was done in 1975. The experience of Oak Ridge National Laboratory (ORNL) for the modified 9 Cr-1 Mo steel Code case cost $\$16 \times 10^6$ over a 12-year period.

The above quoted costs were to cover only the tests to develop necessary data for the Code cases. Obtaining data for vanadium alloys will cost much more due to material costs and complexity of testing due to vanadium's propensity to pick up impurities.

SCALEUP OF ALLOY PRODUCTION

Unalloyed vanadium ingots have been melted up to 5000 lb and in vanadium alloy only 200 to 500-lb ingots. In order to develop the necessary reproducibility in melting and meeting specifications, it is suggested that ten 10,000-lb heats be melted and the ingots converted to various mill product forms shown in the ITER Bill of Materials. This Bill of Materials should be refined as the design proceeds. These mill product forms could then be used to develop the various mechanical and physical properties, construct engineering corrosion test loops, perform welding development studies, and start the secondary fabrication work to develop necessary parameters and techniques to produce the ITER hardware. This program should be started now and run for approximately 3 years with a cost of $\$20$ to $\$25 \times 10^6$.

This program will also determine if the necessary mill equipment, i.e., forges, rolling mills, bar mills, and wire drawing equipment, exists and can make the product. In addition, it will provide information on the ability to meet tolerances for width, thickness, surface quality, straightness, and flatness for plate and sheet. Tubing in refractory metals is traditionally started from an extruded tube shell and then either rocked or swagged down to a size that can be drawn to final diameter. The difficulty in producing tubing is to remove all of the drawing lubricants from the inside of long tube lengths to prevent contamination during annealing. Tubing diameters specified in the Bill of Materials are within the capability of many of the tubing manufacturers, but development will be required if they have not produced refractory metal tubing in the last few years. This development will be directed toward determining the amount of reduction per draw and the total amount of cold-work allowed before annealing. The minimum length of tubing specified in the Bill of Materials is unrealistic in any material because it would be damaged in normal handling. Refractory metal tubing can be supplied in nominally 3650-mm (12-ft) lengths without modification of equipment. Beyond that size will require the installation of special cleaning and annealing equipment. Concern has been expressed that the necessary large vacuum annealing furnace and pickling and cleaning facilities do not exist. Their cost of \$3 to \$6 x 10⁶ is included in the \$20 to \$25 x 10⁶.

Additional information was learned in recent discussions with Teledyne Wah Change Albany personnel on the vanadium alloy product flowchart, availability of equipment, product recoveries, and pricing of individual mill shapes. Using these data and producing each of these items only three times, as suggested by Teledyne Wah Chang Albany for reproducibility, would give a cost of \$6.5 x 10⁶ for just the inboard and outboard back plates, module tube canister, and ribs for the module. They concurred with our suggestions that an annealing furnace and pickling and cleaning facilities would be needed.

COMPONENT OR PROTOTYPE FABRICATION

In general, the elevated-temperature strength, susceptibility to interstitial contamination, and resistance to chemical attack make vanadium more difficult and expensive to fabricate than stainless steel. Typically, the cost to fabricate niobium or vanadium is 2 to 3 times the cost of stainless steel and 1.5 to 2 times the cost of titanium. While these costs do not appear to be large, when the cost of the raw material is added to the fabrication cost, the difference can approach factors of 7 to 10 depending upon complexity of the design. Very little information is available on the secondary fabrication of vanadium or vanadium alloys. What little information is available was summarized in a report entitled

Refractory Metals Fabrication Technology as Applied to Fusion Reactors, published by Battelle Northwest Laboratory (BNWL-2053, July 1976). That report indicated that based on the information available, it appeared that the standard machining techniques such as milling, turning, and drilling were essentially similar to niobium. If this is the case, then the manufacturing costs would be similar to niobium. Virtually no information was available relative to flow characteristics, which is required to develop forming information to fabricate ITER relevant components. Historically, component fabrication is the area where most of the difficulties with refractory metals are encountered. While refractory metal suppliers can produce flat sheet, plate, and tubing, converting those shapes into curves and bends, along with the associated heat treatments, usually results in several failures or redesigns. Since much of the forming requirements tend to be design specific, it is worthwhile to fabricate a series of subscale prototypes that use essentially the same size of starting materials. By doing this, one will develop the necessary manufacturing specifications while developing the fabricating processes. For example, in one of the concepts, a sharp bend is required with bend radius at roughly 2 to 3 times the section thickness. While this bend should be able to be made with minimal difficulty, in vanadium, putting a compound curve along this bend will cause it to buckle. Therefore, producing a quarter-scale component would not only assist in developing the fabrication data base, but also the information could be subsequently fed back into the design to reduce risk. Component fabrication is more than forming metal; it also involves developing complex welding, cleaning, and heat treatments. In developing this data base through the forming, joining, and heat-treating assemblies, valuable information is developed that will help in designing components because it establishes the limits on materials. While the Committee estimated that it would cost between \$40 to \$50 million over a 4-year period to develop this fabrication data base, it should be recognized that a portion of the cost would apply to the development of any material, including steel, since the fabrication requirements for an ITER-type structure are more complex than traditionally thought and approach aircraft-type structures in their complexity. In the case of aircraft, even with an extensive fabrication data base in titanium, mock-up, and prototypes are always fabricated prior to production to ensure that hidden fabrication issues are discovered before final design.

MATERIAL BEHAVIOR TESTING

The selection of V-5Cr-5Ti alloy was made after reviewing various vanadium alloy data from irradiated and nonirradiated tests. Since the vanadium 5Cr-5Ti alloy has been selected, testing should center on that composition and start obtaining meaningful statistical data on the physical and mechanical properties.

The data needed include: tensile and yield strength, elongation, shear modulus, elastic modulus, Poisson's ratio, thermal conductivity, thermal coefficient of expansion, work-hardening coefficient, creep/stress rupture, relaxation characteristics, impact properties, fatigue, and fracture toughness. These data should be derived from various heats tested under irradiated and nonirradiated conditions. Also needed is an understanding of the material's behavior under thermal cycling conditions after thermal aging.

Welding studies must be performed on various heats and product forms to develop proper techniques for various weld joints and to determine shrinkage, distortion, etc., as a function of method, product form, and thickness. Various welding types should be tried: gas tungsten arc, electron beam, resistance seam welding, and welds under restraint. Weld filler metal must also be developed, and may differ in composition from the base metal to produce welds with optimal properties. It is assumed that most welding will be performed in a dry box since no nondestructive tests (i.e., "go-no-go") exist to determine whether impurities are picked up during welding if a lead/trail gas shield is used. The technique of constant monitoring of the dry box atmosphere for impurities used by the refractory metal researchers on the Space Program was impressive.

Compatibility tests of vanadium alloys exposed to Li, He and H₂ should be conducted to determine temperature gradient mass transfer, dissimilar metal mass transfer, impurity pickup, and H₂ buildup. These tests should be conducted on engineering-type loop tests as well as on smaller bench tests.

An extensive irradiation testing program has to be conducted to determine the effect of irradiation on physical and mechanical properties and especially to measure fracture properties, including the ductile-to-brittle transition temperature shift. In looking at the requirements to develop this data base, the Committee is concerned about the limited capability to develop the required irradiation effects data base. At the present time only the Experimental Breeder Reactor (EBR-II) and the High Flux Isotope Reactor (HFIR) appear to be available within the United States to develop this type of data. In presentations, it was pointed out that in HFIR, the thermal spectrum transmutes vanadium into chromium. For long irradiation times [e.g., >5 displacements per atom (dpa)] this has the potential for altering the stoichiometry of the alloy and thus its properties. Changes in properties may occur due to compositional changes, and these would not necessarily occur in a fusion spectrum. As a result, irradiations in the HFIR may be limited, and the bulk of the irradiation would have to be conducted in the EBR-II. Fast reactor irradiations also pose limitations. First, in the EBR-II or the Fast-Flux Test Facility (FFTF), the lowest temperature that can easily be achieved

is about 370 to 400°C. Thus, the critical temperature regime for irradiation effects on fracture cannot be explored. Second, in the fast neutron spectrum, very little He is produced from (n, α) transmutations relative to the fusion spectrum. A significant campaign will have to be mounted to investigate He/dpa effects using dynamic helium charging experiments (DHCE). The first experiment of this type is now being evaluated at ANL. The availability of the EBR-II and the possibility it may be shut down is also a significant concern, although it may be possible to conduct the irradiation in a non-U.S. reactor (e.g., BOR-60 in Russia). While there is a large amount of irradiation information generated for the Fast Reactor Program, the bulk of the data is either not on the alloys of interest or addresses the wrong properties. For the ITER, the type of data needed is irradiation creep, changes in fracture toughness, changes in ductility, and tensile strength up to roughly 50 dpa and a function of temperature with irradiations from approximately room temperature to 100°C above the operating temperature. In presentations, the cost to develop this information was estimated to be in the range of \$35 million and would require 6 years to develop the complete data base.

The costs of the studies discussed in this section are summarized as follows:

Baseline Materials Properties	\$6 million
Welding/Preliminary Fabrication	\$5 million
Corrosion/Compatibility/H ₂	\$20 million
Irradiation Testing	\$33 million

ENGINEERING TEST LOOPS

Coolant compatibility is an area of concern for all structural materials, particularly when they must operate in a nuclear environment. To help screen materials and to develop engineering information on mass transfer, engineering test loops are used. For a vanadium alloy, the construction and operation of a coolant loop would provide information not only on coolant compatibility but also provide valuable fabrication information through the design and construction of the loop. The ITER program has not made a decision on coolants and is currently looking at liquid metals, water, and helium. While available data show that vanadium is compatible with lithium, these data need to be verified and expanded. A very serious concern with vanadium and water is the potential for embrittlement from the hydrogen produced by the decomposition of water. For helium, the issue is how clean one could produce and maintain the helium in an engineering system and how much interstitial contamination would occur. Interstitial contamination is a critical area for refractory metals, such as vanadium, since the alloys can be embrittled by interstitial elements (carbon, oxygen, nitrogen, and hydrogen). To

protect them from embrittlement, they are typically used in a vacuum environment. Inert gases have occasionally been used but traditionally are not successful in long-term applications. The vacuum in a fusion reactor will likely protect vanadium from interstitial contamination, but beyond the vacuum boundary, it will have to be protected by a coating or cladding. The high cost of vanadium and the difficulty in fabrication of large pipe makes it unlikely that vanadium would be used outside of the blanket and shield region. Therefore, the heat transfer system probably would transition to another metal such as steel or titanium. In transitioning to steel, there is concern about the mass transfer of interstitial elements into the vanadium with the potential of embrittling it. As a result, loops need to be fabricated in vanadium and tested, then portions of that loop replaced with candidate transition materials to examine mass transfer. In the presentations, it was estimated that this activity would cost approximately \$20 million over a 5-year period.

GENERIC ISSUES

Several pressing materials issues in the design and construction of the ITER were briefly reviewed, and include: joining beryllium to the wall material, developing an insulating coating on the surface of the wall, and the divertor. These problems are generic to the design regardless of the selected wall material.

Beryllium Bonding

The beryllium wall material must be well bonded to the structural material to provide adequate heat transfer and to withstand the repeated thermal cycles. Unfortunately, beryllium forms brittle intermetallic compounds with several of the more common metals, including vanadium. Also, to develop the bond, some type of brazing approach using an alloy system that would be compatible with the environment should be considered. In other engineering designs, such bonding problems have been solved by a combination of diffusion barriers and brazing alloys. Solutions must be developed for the beryllium-vanadium alloy system.

MHD Insulating Coatings

Preliminary work on the requirement for an insulating coating on liquid-metal-containing piping has shown promise that a coating can be developed by aluminum plating and then forming a nitride from nitrogen-contaminated lithium. Considerably more engineering-type tests must be conducted to determine if the insulating coating has the proper insulating properties, degree of coverage, spalling characteristics, and if the coating is self-healing in the nitrogen-containing lithium.

How to best coat the wall material with aluminum should be studied. Several methods exist, from simply dipping the material in molten aluminum through a flux to complex coating methods that include thermal spray, electrochemical, and vapor deposition. The coating method chosen should consider how to minimize the thermal distortion of the wall hardware. The coating material must be compatible with the transfer of tritium and deuterium from the vanadium alloy to the lithium.

COMMITMENT AND COST SUMMARY

If vanadium is to be considered as a viable structural material, then there will have to be in place an aggressive, well-funded program that focusses on developing the technology to the point that it can be confidently considered for use in the ITER. This program would require the development of an industry to supply the material and develop a fabrication data base as well as a design data base. The program would require the production of sheet, plate, rod, and tubing from several heats of material and then fabrication of these materials into the complex geometries representative of the type of components of interest to the ITER. Because of the constraints of the current ITER schedule, this program would have to be completed within 5 to 8 years and be structured to provide "go-no-go" information within 3 years after inception. It is the Committee's opinion that the cost of this activity should be in the range of \$130 million, which is modest when one considers that the development costs for the reference alloy in the LMFBF Cladding and Duct Program were \$101 million in 1970-80 dollars. In that program, the fabrication development consisted of developing high-quality, thin-walled tubing and an irradiation data base that only considered changes in tensile strength, creep, and swelling. Figure 3 shows the schedule for developing vanadium for the ITER; including the three primary activities that must be run in parallel to achieve the goal. It should be recognized that this is a success-oriented program that will require a significant commitment to implement. Since the United States is perceived as the leader and advocate of vanadium for the ITER, it is likely that the bulk of the burden of development of this material will fall on the United States. If this is the case, the United States must be prepared to make a long-term commitment, both in funding and in providing the necessary scientific staff to make this happen. Since vanadium offers potential for reactor-relevant machines beyond the ITER, the United States needs to be prepared to continue the development, once begun, even if it is not selected for ITER, assuming fundamental problems are not found with the material. This level of commitment, while it has been demonstrated in the breeder program, has not been seen in the fusion program. As a result, the Committee has concerns regarding the staying power of the United States fusion program in developing a new material.

Activity	Year											
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Alloy Scaleup	\$20-30M											
Component Fabrication			\$40-50M									
Database Generation												
Unirradiated	\$6M											
Irradiated			\$35M									
Compatibility				\$20M								
ITER	EDA					Construction						

Fig. 3. Vanadium Alloys Developed Activities and Schedule.

CONCLUSIONS

As a result of its evaluation of the input and data on the development of a vanadium alloy for use as the structural material for use in the ITER blanket, the Committee came to the following conclusions:

- With an aggressive, fully funded program, it is possible to qualify a vanadium alloy as the principal structural material for the ITER blanket in the available 5 to 8-year window. However, the data base for V-5Cr-5Ti is sparse and will require an extensive development and test program to support the characteristics that have been shown by limited testing of small heat samples or inferred from the performance of other alloys of the same family.
- From a safety standpoint, vanadium alloys have relatively high temperature limits and low inventories of activation products. However, because of the

chemical reactivity of vanadium, structures made from its alloys will be less tolerant of system failures, accidents, and off-normal events than most other candidate blanket structural materials.

- Because of the cost of the material, more stringent requirements on processes, and minimal historical working experience, it will cost roughly an order of magnitude more to qualify a vanadium alloy for ITER blanket structures than other candidate materials.
- The use of vanadium is difficult and uncertain; therefore, other options should be explored more thoroughly before a final selection of vanadium is confirmed. The Committee views the risk too high to rely solely on vanadium alloys.
- In viewing the state and nature of the design of the ITER blanket as presented to the Committee, it is obvious that there is a need to move toward integrating fabrication, welding, and materials engineers into the ITER design team.
- If the vanadium alloy option is to be pursued, a large program needs to be started immediately. The commitment of funding and other resources needs to be firm and consistent with a realistic program plan. The total cost of developing vanadium for the ITER is estimated to be \$130 million over 5 to 8 years, exclusive of the cost of irradiation facilities.

RECOMMENDATIONS

- The ITER program should immediately initiate a material development program to qualify a blanket structural material for ITER application. That program needs to include both a vanadium alloy and a steel alloy.
- The Department of Energy (DOE), the other Parties, and the ITER Joint Central Team (JCT) should formally establish a firm commitment to the entire schedule and full funding requirements of an ITER blanket structural materials development and qualification program.
- DOE, through its channels to the JCT, should strongly press for the incorporation of fabrication, welding, and engineering materials specialties into the ITER design team.

APPENDICES

Appendix A

TENTATIVE SPECIFICATION FOR V-5 CR-5 TI

5 ± 0.5% Cr
5 ± 0.5% Ti
Si - 500 to 1000 ppm
O - 400 ppm
N - 100 ppm
C - 200 ppm
Nb - 4 ppm* (historical data)
Mo - 2 ppm* (historical data)
Fe - 200 to 400 ppm
Al - 200 to 400 ppm
P - ALAP**
S - ALAP
Ag - ALAP
Balance Vanadium

---

*Below 1 ppm is desired.

**ALAP - As low as possible.

Appendix B

AMERICAN

MONDAY, JUNE 14, 1993

METAL MARKET

VOLUME 101, NUMBER 113

\$5.00

NEWS BRIEFS

S. Africa sees vanadium price danger

JOHANNESBURG, South Africa — The Department of Mineral and Energy Affairs said an oversupply developing in the world vanadium market could lead to a collapse of prices if pending projects to increase production went forward. It reported that world capacity currently stood at about 100,000 metric tons of vanadium pentoxide per year but less than 65 percent was used, Reuters reported. New vanadium projects totaling some 20,000 tons of pentoxide were in various stages of planning.

Appendix C

MATERIAL LIST - VANADIUM ALLOY ITER BLANKET

● Backplate

- Inboard
7 cm thick x 60 cm wide x 12 m long
48 pieces
3.0 Tonne each
144 Tonne total
- Outboard
7 cm thick x 100 cm wide x 12 m long
72 pieces
5.0 Tonne each
360 Tonne total

● Module Canister

- 0.5 cm thick x 93 cm wide x 12 m long
360 pieces
0.34 Tonne each
121 Tonne total

● Ribs for Module

- 0.5 cm thick x 19 cm wide x 12 m long
360 pieces
204 kg/piece
24.6 Tonne

● Tubes (He-cooled design only)

- 12 tubes per module
2.3 cm OD x 2 mm wall x 24 m long
2160 pieces
21.6 kg/piece
46.8 Tonne total

- 12 tubes per module
3.0 cm OD x 3 mm wall x 24 m long
2160 pieces
40.7 kg/piece
87.9 Tonne total

Note: Self-cooled design = 650 Tonne; He-cooled design = 785 Tonne.

Appendix D

JUN-22-1993 13:42 FROM TELEDYNE WAH CHANG ALBANY TO

917082523604 P.01

**TELEDYNE
WAH CHANG ALBANY**

1800 N.E. OLD SALEM ROAD

P.O. BOX 400

ALBANY, OREGON 97321-0400

(503) 420-4811

FAX (503) 987-8884 - MARKETING

June 22, 1993

Mr. Dale L. Smith, Director
Fusion Power Program
Argonne National Laboratory
9700 Cass Avenue - Bldg. 205
Argonne, IL 60439

Dear Dale:

**RE: COST ESTIMATES FOR VANADIUM ALLOY
WELDING POSSIBILITIES**

Following are my best rough estimates of costs for V5Cr5Ti:

<u>600-800 T Lots</u>	<u>\$ PER KG INGOT</u>	<u>\$ PER KG FABRICATED</u>
PRESENT PRODUCTION	124.36	207.26*
DISCOUNTED FOR LARGER VOLUME SAVINGS	95.65	159.40*

*This is for plate and sheet with actual costs for the large pieces, seamless tube and pipe would be approximately 40-50% higher.

The earlier costs we talked about at ANL were based on actual costs for the smaller ingot with some projections for savings. These estimates are based on production costs for pure vanadium and estimates of how this will work out for the larger quantities. There are no assumptions made for any changes in cost of the raw materials due to market fluctuations or changes in the requirements for impurities, i.e., silicon, molybdenum, niobium or silver or any of the other possible concerns. The more we make the greater our confidence that we can meet these prices.

Appendix E

Department of Energy
Washington, DC 20585

May 4, 1993

Mr. William D. Manly
Rural Route 1, Box 197A
Kingston, Tennessee 37763

Dear Bill,

Enclosed is the Charter for the Evaluation of Vanadium Alloys that you have agreed to conduct for this office. John Davis of McDonnell Douglas Aerospace, Howard Birnbaum of the University of Illinois, and Jim Doggett of Lawrence Livermore National Laboratory have agreed to serve with you in this evaluation. Dale L. Smith at Argonne National Laboratory (ANL) and Everett E. Bloom at ORNL will provide technical support, if your group needs it, and ORNL will provide administrative and secretarial support. I will be your point-of-contact at DOE, and will help in any way I can. Any of us will be happy to identify other contacts in the fusion community as needed.

You are asked in the Charter to provide the evaluation by about July 1, 1993. We would like to see a study plan and your working assumptions by about May 15, 1993. Design requirements for the use of vanadium alloys in the International Thermonuclear Experimental Reactor (ITER) will need to be developed early in this evaluation - we would like to also review these by about mid-May.

If the July 1 date proves to be a problem, it is important to the ITER project that at least an interim report be available by that time. Furthermore, evaluation relative to use in DEMO and other longer range, longer plant life application is of less urgency than the ITER questions.

Recent work on vanadium alloys, involving mainly alloy development and radiation effects, has been concentrated at ANL. Dale Smith is the key to this information. Work through 1977 was reviewed for DOE by Westinghouse. R. E. (Bob) Gold was the key author of that review, and he will make time to brief your group on that review.

Thank you for your willingness to help the fusion program with this evaluation of vanadium alloy technology. My own involvement with vanadium alloys started in early 1967, so I am very interested in the results.

Sincerely,

A handwritten signature in dark ink, appearing to read "F. W. Wiffen", is written over the typed name.

F. W. Wiffen
Advance Technology Program
Advanced Physics and Technology Division
Office of Fusion Energy
Office of Energy Research

Enclosure

Appendix F

CHARTER

TECHNICAL EVALUATION OF THE TECHNOLOGY OF VANADIUM ALLOYS FOR USE AS BLANKET STRUCTURAL MATERIALS IN FUSION REACTORS

Vanadium alloys have long been viewed as desirable materials for fusion reactor structures in the first wall and blanket regions. These alloys offer the potential of higher heat loads and higher operating temperatures than steels, evidence of resistance to degradation under irradiation, and excellent compatibility with liquid lithium. Activation product radioisotopes in vanadium decay with modest decay heating rates and manageable half lives. Care in selection of alloying additions produce structures with attractive accident consequence and waste management potential at the end of reactor service.

The Fusion Program needs an evaluation of the technology of vanadium alloys, relative to the use of these alloys in the blanket structure of a fusion reactor. This evaluation is needed by about July 1, 1993. It should include the current state of technology and identify the steps needed to be ready to use these alloys in construction of the International Thermonuclear Experimental Reactor (ITER) in 1999. The needs for use of vanadium in a demonstration fusion power plant in 2025 should also be addressed.

This assessment should be planned in detail by the Assessment Committee, in consultation with the DOE Program Manager and key ITER U.S. Home Team members (Wiffen, Smith, and Bloom). Activities should probably include a workshop to develop wide input from the materials research and development, design, production, fabrication and other segments of industry that would have to be involved in successfully building a vanadium alloy blanket for ITER.

The following questions should be included in this Technology Assessment:

Is the evidence adequate to concentrate on a single vanadium composition for use in the ITER First Wall/Blanket/Shield?

What is the state of the data base on candidate alloys, relative to that needed for ITER design and construction?

What must be done to be able to produce the required quantities and product form mix needed for ITER:

- for alloy qualification and technology development
- for component development and testing
- for engineering data base development
- for licensing or regulatory approval
- for ITER construction?

What is required to develop the fabrication, joining and inspection technology to produce vanadium alloy components?

Is the available information adequate to define approximate bounds on the use of vanadium alloys with respect to:

- temperature limits
- irradiation lifetime
- coolant and coolant purity limits?

The product of this activity should be a written technical evaluation that answers the questions posed here, and other questions that may be developed by your group. This Technology Assessment should not attempt to produce a program plan, but should identify the steps (tasks) and major facilities needed. Estimates of costs and schedules are also requested. We would like to have the report by about July 1, 1993.

Appendix G.1

Preliminary Agenda
Evaluation of Vanadium Alloys for Fusion
Building 205, Conference Room L-252
Argonne National Laboratory
June 3-4, 1993

Thursday, June 3

8:30 a.m.	Coffee	
9:00 a.m.	Introduction	W. Manly
9:15 a.m.	ITER Blanket Design	Y. Gohar
10:30 a.m.	Break	
10:45 a.m.	ITER Divertor Design	J. Haines
11:15 a.m.	Materials Performance/Lifetime	R. Mattas
11:45 a.m.	Background - V-Alloy Development	D. Smith
12:00 Noon	Lunch	
1:00 p.m.	Production/Fabrication of V-Alloys	R. Peterson
1:40 p.m.	Review of V-Alloy Data Base Assessment	Bill Buckman
2:40 p.m.	Current V-Alloy Data Base	
	Baseline Properties	D. Smith
	Irradiation Effects	B. Loomis
3:30 p.m.	Break	
4:40 p.m.	Compatibility of Vanadium	J. DeVan
5:00 p.m.	Adjourn	

Friday, June 4

8:30 a.m.	Coffee	
9:00 a.m.	Special Topics/Discussions	
10:30 a.m.	Summary and Planning	Committee
12:30 p.m.	Lunch/Adjourn	

Appendix G.2**Evaluation of Vanadium Alloys for Fusion
Building 205, Conference Room L-252
Argonne National Laboratory
June 3-4, 1993****Participants**

Dale Smith	Argonne National Laboratory
Bill Wiffen	Department of Energy
Bill Buckman	RMT
Jim Doggett	Lawrence Livermore National Laboratory
John Davis	McDonnell Douglas Aerospace
Bill Manly	Consultant, Oak Ridge National Laboratory
Roger Peterson	Teledyne Wah Chang Albany
Jack DeVan	Oak Ridge National Laboratory
Hanchung Tsai	Argonne National Laboratory
Ben Loomis	Argonne National Laboratory
Dai-kai Sze	Argonne National Laboratory
Everett Bloom	Oak Ridge National Laboratory
Ken Wilson	Sandia National Laboratories
Siegfried Malang	Argonne National Laboratory
Rich Mattas	Argonne National Laboratory
John Haines	McDonnell Douglas Aerospace
Yousny Gohar	Argonne National Laboratory

Appendix G.3

Agenda
Evaluation of Vanadium Alloys for Fusion
Bldg. 304, L3W, Rm. 353
McDonnell Douglas Aerospace, St. Louis, MO
June 24, 1993

8:00 a.m.	Coffee Welcome	J. Davis
8:05 a.m.	Introduction	W. Manly
8:10 a.m.	Space Systems Applications and Experience with Refractory Metals	E. Hoffman
9:30 a.m.	Safety and Licensing Concerns - Code Case INEL Input to Committee	TBD*
10:00 a.m.	Near-Term Engineering Tests of Vanadium Alloy	TBD*
10:30 a.m.	Break	
10:45 a.m.	Refractory Metal Fabrication Technology and Capability - United States	D. Smith
11:15 a.m.	Hydrogen - Tritium Effects on Vanadium Alloy	D. Smith
11:45 a.m.	Lunch	
12:45 p.m.	Coatings for Vanadium Alloys: Electrical Insulators for Liquid Metals	D. Smith
1:15 p.m.	Special Topics and Discussions Second Supplier of Vanadium Alloy Beryllium/Vanadium Alloys Others TBD*	All
2:30 p.m.	Summary and Planning	Committee
3:00 p.m.	Adjourn	

---

*To be determined.

Appendix G.4

**Evaluation of Vanadium Alloys for Fusion
Bldg. 304, L3W, Rm. 353
McDonnell Douglas Aerospace, St. Louis, MO
June 24, 1993**

Participants

Howard K. Birnbaum	University of Illinois	217-333-1370 Phone 217-244-2278 Fax
Everett E. Bloom	Oak Ridge National Laboratory	615-574-5053 Phone 615-574-7659 Fax
John W. Davis	McDonnell Douglas Aerospace	314-233-6200 Phone 314-234-4506 Fax
James N. Doggett	Lawrence Livermore National Laboratory	510-423-0782 Phone 510-423-0783 Fax
Eugene E. Hoffman	Department of Energy, Oak Ridge	615-576-0735 Phone 615-574-9275 Fax
V. Dennis Lee	McDonnell Douglas Aerospace	314-233-8212 Phone
William D. Manly	Oak Ridge National Laboratory, Consultant	615-574-4344 Phone 615-574-7659 Fax
G. Dave Morgan	McDonnell Douglas Aerospace	314-232-9098 Phone
Larry Pronke	McDonnell Douglas Aerospace	314-232-1320 Phone 314-234-8915 Fax
Dale L. Smith	Argonne National Laboratory	708-252-4816 Phone 708-252-5287 Fax
F. W. (Bill) Wiffen	Department of Energy, Washington	301-903-4963 Phone 301-903-2791 Fax

Appendix G.5

Evaluation of Vanadium Alloys for Fusion

**Manly Conference Center
Kingston, Tennessee
July 21-22, 1993**

**Manly Conference Center
Kingston, Tennessee**

July 21, 1993

**Attendance: E. E. Bloom, John W. Davis, James N. Doggett,
William D. Manly, Dale L. Smith, and F. W. Wiffen**

Agenda

- (1) Production Capability and Scaleup
Time and Dollars**
- (2) Secondary Fabrication
Time and Dollars**
- (3) Material Behavior Testing**
- (4) Engineering Testing**
- (5) Hydrogen and Tritium Concerns**

Appendix G.6

Evaluation of Vanadium Alloys for Fusion

**Manly Conference Center
Kingston, Tennessee
July 22, 1993**

Attendance: John W. Davis, James N. Doggett, William D. Manly, and
F. W. Wiffen (part-time)

Agenda:

Outlining Report

Writing Assignments

Develop Conclusions and Recommendations

DISTRIBUTION

- 1-7. Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
H. M. Chung
D. R. Diercks
R. F. Mattas
D. L. Smith (3)
H. C. Tsai
8. Auburn University, Department of Mechanical Engineering, 201 Ross Hall, Auburn, AL 36849
B. A. Chin
- 9-10. Bechtel National, Inc., P.O. Box 193965, San Francisco, CA 94119-3965
H. Forsen
J. Gilleland
11. Bechtel National, Inc., 151 Lafayette Drive, Oak Ridge, TN 37830
S. L. Thomson
12. Burns and Roe Company, 800 Kinderkurnak Road, Oradell, NJ 07649
J. R. Sudol, Jr.
- 13-14. EG&G Idaho, Inc., Fusion Safety Program, P.O. Box 1625, Idaho Falls, ID 83415-3523
G. Longhurst
D. A. Petti
- 15-16. Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94304
F. L. Culler
J. Stringer
17. Fusion Power Associates, 2 Professional Drive, Suite 249, Gaithersburg, MD 20879
S. O. Dean
18. Georgia Institute of Technology, Nuclear Engineering Department, ESM Building/0225, Atlanta, GA 30332
W. M. Stacey, Jr.
- 19-22. General Atomics, P.O. Box 85608, San Diego, CA 92138
R. Freeman
J. L. Luxon
D. Overskel
C. W. Wong
23. General Dynamics, Space Systems Division, P.O. Box 85990, MZ K3-8260, San Diego, CA 92186-3990
R. Hora
24. Grumman Aerospace and Electronics, Sunrise Highway, MS A43-43, Great River, NY 11739-0544
R. Weber

- 25-27. ITER Co-Center San Diego, 11025 North Torrey Pines Road, Suite 200, LaJolla, CA 92037
 F. Puhn
 P. H. Rebut
 P. Smith
- 28-29. ITER Garching Joint Work Site, Max-Planck-Institut für Plasmaphysik, Boltzmannstrasse 2, D-85748 Garching bei München, Germany
 Y. Gohar
 R. Parker
- 30-32. ITER NAKA Joint Work Site, 801-1 Miyukoyama, NAKA-machi, NAKA-gun, Ibaraki-ken, 311-01, Japan
 D. Holland
 M. Huguet
 W. Linquist
- 33-39. Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
 D. Baldwin
 R. H. Bulmer
 J. N. Doggett
 A. J. Glass
 D. Lang
 W. M. Nevins
 K. L. Thomassen
- 40-41. Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
 E. H. Farnum
 R. E. Siemon
- 42-43. Massachusetts Institute of Technology, Plasma Fusion Center, 167 Albany Street, Cambridge, MA 02139
 D. B. Montgomery
 D. J. Sigmar
44. R. Ballinger, 77 Massachusetts Avenue, Room 24-215A, Cambridge, MA 02139
- 45-49. McDonnell-Douglas Missile Systems Company, Mail Code 306 4204, P.O. Box 516, St. Louis, MO 63166
 J. W. Davis
 R. J. Krieger
 V. D. Lee
 G. D. Morgan
 L. Pronke
- 50-92. Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831
 C. C. Baker
 R. D. Benson
 E. E. Bloom (20)
 J. H. DeVan
 C. A. Flanagan
 W. Fulkerson
 M. K. Gouge
 M. L. Grossbeck
 J. N. Herndon
 D. Hoffman
 R. L. Klueh
 D. C. Lousteau
 W. D. Manly
 B. E. Nelson
 A. F. Rowcliffe
 J. Sheffield
 D. W. Swain
 N. A. Uckan

Central Research Library
 Document Reference Section
 Laboratory Records Department (2)
 Laboratory Records-RC
 Patent Section

- 93-98. Pacific Northwest Laboratory, P.O. box 999, Richland, WA 99352
       J. F. Clarke   M. L. Hamilton
       D. S. Gelles   R. H. Jones (3)
- 99-106. Princeton University, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08540
       J. L. Anderson   D. M. Meade
       S. Bernabei   P. H. Rutherford
       S. A. Cohen   N. R. Sauthoff
       R. Davidson   K. M. Young
107. D. Grove, 191 Riverside Drive, Princeton, NJ 08540
- 108-109. Raytheon Engineers and Constructors, Inc., Ebasco Division, 2 World Trade Center, New York, NY 10048-0752
       W. Ellis
       R. C. Iotti
110. Refractory Metals Technology, Box 10055, Pittsburgh, PA 15236
       B. Buckman
111. Rensselaer Polytechnic Institute, Nuclear Engineering Department, Tibbitts Avenue, Troy, NY 12180
       D. Steiner
112. Rockwell International Corporation, Advanced Programs, Rocketdyne Division, 6633 Canoga Avenue, Canoga Park, CA 91303
       H. C. Wieseneck
- 113-114. Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-5800
       R. T. McGrath
       M. A. Ulrickson
115. Sandia National Laboratories, Livermore Division 8316, Livermore, CA 94550
       K. L. Wilson
116. Stone and Webster Engineering Corporation, P.O. Box 2325, Boston, MA 02107
       J. Landis
117. TRW Space and Electronics Group, One Space Park, Mail Station Building R1, Room 2104, Redondo Beach, CA 90278
       T. Romesser
- 118-119. Teledyne Wah Chang Albany, P.O. Box 400, Albany, OR 97321-0450
       J. R. Peterson   C. Wojcik

120. University of California UCSD, School of Engineering, 9500 Gilman Drive, La Jolla, CA 92093-0403
R. Conn
- 121-122. University of California, Department of Chemical and Nuclear Engineering, Santa Barbara, CA 93106
G. E. Lucas
G. R. Odette
- 123-124. University of California, Department of Chemical, Nuclear, and Thermal Engineering, Los Angeles, CA 90024
M. A. Abdou
N. M. Ghoniem
125. University of Illinois, Materials Research Laboratory, 104 South Goodwin Avenue, Urbana, IL 61801
H. K. Birnbaum
126. University of Illinois, Nuclear Engineering Department, 104 South Goodwin Avenue, Urbana, IL 61801
J. Stubbins
127. University of Texas, Austin, Fusion Research Center, RLM 11,218, Austin, TX 78712
R. Hazeltine
128. University of Wisconsin, Nuclear Engineering Department, 1600 Johnson Drive, Madison, WI 53706
G. L. Kulcinski
129. Vanalloy Corporation, R.R. 4, Box 198A, Nashville, IN 47448
B. A. Loomis
130. Varian Associates, 3050 Hansen Way, M/S V130, Palo Alto, CA 94304-1000
C. Lob
131. Westinghouse Electric Corporation, Systems, Processes, and Technologies Division, Science and Technology Center, 1310 Beulah Road, Pittsburgh, PA 15235
S. Harkness
132. Department of Energy, DOE Oak Ridge Field Office, P.O. Box 2008, Oak Ridge, TN 37831-6269
Assistant Manager for Energy Research and Development
133. Department of Energy, Office of Basic Energy Sciences, Washington, DC 20585
R. J. Gottschall
- 134-145. Department of Energy, Office of Fusion Energy, Washington, DC 20585
S. E. Berk   W. F. Dove
M. M. Cohen   T. R. James
D. H. Crandall   R. E. Price
N. A. Davies   F. W. Wiffen (5)

146. Department of Energy, Oak Ridge Field Office, P.O. Box 2008, Oak Ridge, TN 37831-6269

E. E. Hoffman

147-148. Department of Energy, Office of Scientific and Technical Information, Office of Information Services, P.O. box 62, Oak Ridge, TN 37831

DATE

FILMED

7/26/94

END