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INTERNATIONAL ENERGY R&D:
A PICTURE COMPILED FROM OPEN SOURCES

E. A. Green

March 27, 1975

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FOREWORD

The International Security Affairs Division of the Atomic Energy Commission asked us to determine how complete an assessment of foreign energy research and development could be made from searches of data bases and literature. This report, prepared by the Energy & Resource Planning Group of the Lawrence Livermore Laboratory, presents our findings.

Our general conclusion is that publication lag, incomplete reporting, and proprietary data restrictions limit the effectiveness of an assessment compiled from literature. Such an assessment would be improved considerably by personal scientist-to-scientist contact. Therefore, we feel that it is especially important to attend foreign technical society meetings and to visit foreign scientists in their laboratories and field installations.

Comments on this report are welcome.

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I. OBJECTIVES, CONCLUSIONS, AND INFORMATION SOURCES

E. A. Green

OBJECTIVES OF THE STUDY

- Assemble a set of data bases covering foreign energy R&D.
- Interrogate the data bases for foreign energy R&D information.
- Compile a picture of foreign energy R&D using data base information and:
 - Foreign government and industrial reports
 - Scientific/trade journals
 - Conference proceedings
 - Resource people.
- Determine the foreign centers of excellence in specific energy technologies.

CONCLUSIONS ABOUT FOREIGN ENERGY R&D

- Significant energy R&D is underway abroad.
- Foreign government spending on energy R&D is less than U.S. government spending.
- Most foreign energy R&D is conducted by industrial firms.
 - It is aimed at short- to medium-term payoff.
 - Proprietary considerations limit disclosure of research results.

SEARCH METHODS AND INFORMATION SOURCES

Data Bases

- Data bases offer fast access to the post-1969 journal and report literature.
- Data bases are limited by the 1- to 2-year journal publication lag.
- The search system interrogating the data base is important.
 - The searcher must understand the system's key-word conventions thoroughly.
 - The systems vary in search capability.
- Data bases do not cover planning information.

Reports and Journals

- Trade periodicals are important because they publish planning information.

Conference Proceedings

- Valuable, especially as journal preprints.

Resource Person

- A resource person is the best source of information on R&D.
- A resource person must be an able professional concentrating in a mainstream research area.
- The resource person must attend meetings and utilize the contacts made there.

(See Appendix I-1 for the data bases available for search.)

SEARCH METHODS AND INFORMATION SOURCES

Technology	Search methods		Principal information sources used			
	Manual	Data base/ results	Reports	Scientific/ trade journals	Conference proceedings	Resource person
Petroleum	Limited	Yes Good		X	X	
Coal	Yes	Yes Fair	X	X		X
Nuclear reactors	Yes	Yes Fair		X		
Nuclear fuels	Yes	No		X		
Fusion	Yes	No			X	X
Transportation	Yes	Yes Fair	X	X	X	X
Electricity	Yes	Yes Fair	X	X	X	
Advanced systems						
Solar	No	No				X
Geothermal	No	No				X
Hydrogen	Yes	No	X		X	X
Bio-enviromental research	Yes	No		X	X	X

CHARACTERISTICS OF FOREIGN ENERGY R&D

- There is significant foreign work in every major energy research category.
- The level of technical detail available in the open literature is limited by proprietary considerations.
- Foreign government spending on energy research is low compared to the U.S. The 1974 spending in nine categories was in billion U.S. \$:

<u>U.S.</u>	<u>Other</u>
1.14	0.28

"Other" includes Belgium, Canada, Denmark, Federal Republic of Germany (FRG), Ireland, Italy, Japan, Netherlands, Norway, and U.K.

CHARACTERISTICS OF FOREIGN ENERGY R&D

Technology	Significant foreign work	Technical detail available	Proprietary interests
Petroleum	Not in West; USSR not examined	Very limited, royalty agreements possible	Very important
Coal	Yes	Fair	Important
Nuclear reactors	Yes	Limited technical detail in the open literature	Very important
Nuclear fuels	Yes	Good in some areas; enrichment is limited	Important in enrichment; less important in mining
Fusion	Yes	Excellent	Negligible
Transportation	Yes	Fair detail available	Very important
Electricity	Yes	Varies by topic; some are highly proprietary	Generally important; especially fuel cells
Advanced Systems			
Solar	Yes	Good	Limited
Geothermal	Yes	Good	Limited
Hydrogen	Yes	Good	Important
Bio-environmental research	Yes	Good	Negligible

APPENDIX I-1: ENERGY-RELATED DATA BASES AVAILABLE FOR SEARCH

Data base	Coverage	Scope	Availability			
			RECON	Lockheed	SDC	LLL/MC
COMPENDEX	General engineering. 1970+	International		X	X	X
GEOREF	Geology. 1967+	International			X	
Nuclear Science Abstracts	Nuclear science, AEC research, recently non-nuclear energy. 1968+	International	X			X
INSPEC	Three data bases: physics abstracts, electrical and electronics abstracts, computer and control abstracts. 1969+	International		X		
Chemical condensates	Chemistry. 1970+	International		X	X	
PANDEX/ TRANSDEX	Science and technology, current titles. TRANSDEX covers translations. 1970+	International		X		
Government research abstracts	U.S. Government-sponsored research. 1964+	U.S. only		X	X	
INFORM	Business: energy economics. 1971+	International		X	X	

II. PETROLEUM

R. G. Liptai

B. Rubin

WORLD PETROLEUM SITUATION – IMPLICATIONS FOR R&D

- By regions, the Middle East dominates the petroleum reserves picture, holding 66% of all non-Communist petroleum reserves (Fig. 1).
- The Middle East, Africa, and Latin America are the chief exporting regions; Western Europe, Japan, and the United States are the chief importers.
- Most of the world's petroleum has, until recently, been controlled by privately held companies. The majority of these companies are either U.S. firms, or affiliates of U.S. firms.
- The bulk of oil and gas research is done by these companies. General information about their R&D activities is available, but details are considered proprietary.
- The United States does more production research because there are more old oil fields in the U.S.
- Development of the North Sea demands better off-shore technology. North Sea conditions (deep water and inclement weather) have not been such severe problems in other off-shore regions. U.S. firms are active in these developments.
- Some oil industry processes are already available under license (see Appendix II-1).
- Most petroleum R&D falls into the following categories:
 - Exploration methods
 - Drilling methods
 - Completion and pipelining
 - Advanced recovery methods
 - Oil shale and tar sands
 - Liquified natural gas
 - Oil storage methods
 - Refining.

Fig. 1. Petroleum: world reserves, production, and consumption. Source: *Project Independence Summary*, November, 1974, Federal Energy Administration, Washington, D.C.

EXPLORATION METHODS

Four general types of geophysical exploration are used in locating oil and gas. All methods are in widespread use by the international companies (Fig. 2).

- Seismic methods
 - Seismic reflection and refraction techniques are the predominant methods used to search for oil and gas (97% of 1972 worldwide exploration expenditures).¹
 - In 1972, 75% of the worldwide seismic effort was onshore; 25% offshore.
 - Data collection techniques are well developed. Current improvements are directed towards computerized data analysis and better data interpretation.
 - Recent innovations have been directed towards equipment for remote area and arctic exploration: mini-helicopters and air-transportable highly equipped small boats.²
- Gravity methods
- Magnetic methods
- Electrical and electromagnetic methods
 - Only 3% of worldwide 1972 expenditures on oil and gas exploration were spent on the above three non-seismic methods.
 - These can provide broad area coverage, but in general do not give sufficient detail for precise location of oil and gas traps.
 - Recent developments in the magneto-telluric method show promise for area coverage with increased resolution.³

The 5-year trend for petroleum industry geophysical exploration shows approximately equal spending in the East and West— but the 1972 trend in the West is up --

-- and the East is slightly down.

Fig. 2. Petroleum geophysical expenditures — all methods. Source: *Geophysics*, V. 39; No. 1, February, 1974.

DRILLING METHODS

- Conventional Rotary Drilling
 - Rotary drilling is the method used for essentially all oil and gas wells. Over 75% of world drilling was done in the U.S.
 - Improved instrumentation and computer controlled automation of drilling functions are the latest developments.¹
- Advanced Drilling Methods
 - High-pressure jet drilling has been under evaluation by a group of eight U.S. companies.
 - Although more expensive, drilling rates may be 2-3 times higher (Fig. 3).
 - The method appears economically advantageous for expensive (deep, remote, or offshore) sites.
 - Dutch Shell has reported on extensive jet drilling laboratory research.
- Offshore Drilling Methods
 - Offshore production accounts for 18% of world oil output and 10% of world gas production.
 - Intensive worldwide offshore drilling operations are underway. (The North Sea is a particularly active area). Many new drill ships and drilling platforms are under construction.
 - Very large, very expensive, semi-submersible drill ships were used in the past. Currently, there is some shift towards smaller, less costly rigs.¹
 - New designs for bottom-supported jack-up rigs in deeper water (400 ft or more) are becoming available.¹
 - Britain, Norway, and Holland are engaged in intensive North Sea efforts through petroleum contractors.

High-pressure jet drilling rates are 2 - 3 times greater than conventional drilling rates - -

Drilling rates in E. Texas

- - and the overall costs are lower in deep or offshore areas.

High-pressure drilling costs

Fig. 3. Comparison of high-pressure jet and conventional drilling rates. Source: *Oil and Gas Journal*, July 23, 1973.

COMPLETION AND PIPELINING

- Offshore Structures
 - Very large platforms – up to 475 ft tall – for drilling and production already have been installed in the North Sea.^{1,2}
 - Towers up to 1500 ft high have been designed for deeper water – up to 40 wells per tower could be drilled and completed.³
- Undersea Completion Systems
 - Pressure chambers on the ocean floor can provide working environments for well completions.
 - Systems have been designed and successfully tested by three companies, Lockheed, SEAL, and Exxon. Transworld Drilling is also developing such a system.⁴⁻⁷
- Undersea Pipelining
 - Methods for laying pipelines in deep, hostile ocean environments are almost completely developed.⁸
 - Pipelines to deliver oil from North Sea platforms and gas from Algeria to Italy are under contract.^{9,10}
 - Several new pipelaying barges have been launched in recent years, some for operation in very deep water.¹¹
- Arctic Pipelining
 - Methods for laying pipelines in extreme Arctic environments and on the ocean floor beneath ice are under development in Canada.¹²

**SEABED—WELL COMPLETION SYSTEMS
ARE THE KEY TO EXPANDING OFFSHORE PRODUCTION**

- The most promising area for increased petroleum production is offshore.
- Platform drilling and completion techniques are expensive and have practically reached their depth limitations.
- A reliable, atmospheric pressure, seabed system will be cheaper than the present platform system.

ENHANCED RECOVERY METHODS

- Waterflood is the most widely used method for recovering oil ("secondary" recovery) from reservoirs whose primary gas drive has been depleted (Fig. 4).
- Several more advanced ("tertiary") methods for further treating such reservoirs have been developed in the U.S.¹
 - *In situ* combustion ("fire flood")
 - Miscible oil drive
 - Caustic solution drive
 - Carbon dioxide drive
 - Steam drive
 - Polymer flooding
 - Micro-emulsion flooding
- The recovery of oil-in-place by use of these methods is projected to increase from an average of about 35% at present, to about 60% ultimately.
- There is a large U.S. effort.²
 - More than 170 projects were underway or just completed in March 1974.
 - An additional 35 projects are scheduled for future startup.
- Most of the technologies are available for licensing from U.S. companies.³
- Relatively little foreign work in oil recovery methods is being done.
 - Most foreign (non-communist) oil fields are not yet depleted.
 - Some projects are underway in Venezuela and Canada; France has done laboratory research on polymer flooding.¹
- Methods to increase gas production from tight gas sands are being developed or proposed in the U.S.⁴
 - Massive hydraulic fracturing
 - Nuclear stimulation
 - High explosive fracturing⁵
- Essentially no foreign R&D on gas stimulation is being done, except in the USSR.

Fig. 4. Graph showing recoverable and unrecoverable oil vs. time. The actual and predicted recovery efficiencies are presented (from the Office of Oil and Gas, U.S. Dept. of Interior). Source: C.R. Smith, *Mechanics of Secondary Oil Recovery*, p. 4, Reinhold, New York, 1966.

OIL SHALE AND TAR SANDS

- Although many countries have had an oil shale industry in the past, only three nations have a current ongoing effort.¹
 - Brazil has a pilot demonstration plant (2000 tons/day) for the production of oil and gas from shale.
 - The USSR has long had an extensive well-developed industry; shale is fired directly for electric power generation and also is used for production of petrochemicals, liquid fuels, and town gas. Annual consumption (in 1971) was about 24 million tons.
 - The People's Republic of China has the largest shale industry. Annual consumption in 1971 (unconfirmed) was 45-55 million tons.
- At current oil prices of \$11/bbl, there is considerable U.S. evaluation of surface-retorting technology for production of oil, but no commercial process has been initiated.
- Important limitations on the application of already known technology are the availability of federally owned oil shale lands and strict environmental controls. A restrictive leasing program with stringent environmental requirements was initiated in 1973 by the Department of Interior.²
- The development of oil shale *in situ* processing methods is proposed for the U.S. Successful development could be important for reasons of deeper resource recovery and minimal environmental impact.³ Figure 5 is an artist's conception of an *in-situ* oil-shale recovery process.
- Canada has the only commercial tar sands processing plant, a 45,000 bbl/day facility that utilizes surface mining. A second larger facility is planned. Development of very large, deeply buried resources must await the development of efficient *in situ* methods.⁴ Such work is in process.⁵
- The U.S. tar sands, mostly in Utah, are comparatively small and also must await the development of effective recovery methods.⁶

Fig. 5. *In situ* oil-shale rubblization/recovery process.

OTHER OIL AND GAS TECHNOLOGIES

- **Liquified Natural Gas (LNG)**

The technology for transporting natural gas in liquid form has become highly developed; the major feature was development of cryogenic tankers to transport the very cold liquified gas.^{1,2} France and the U.S. have been the leading innovators in this field, but most of the consuming countries (Europe and Japan) are now heavily committed to receiving cryogenic shipments and regassifying the LNG.³⁻⁵ One area for further study is the potential fire/explosion hazard which might result from a large LNG spill.

- **Oil Storage**

- Methods for undersea oil storage are of increasing importance for offshore production operations, for receiving terminals or super ports, and for strategic storage.

- Very large concrete or steel storage tanks are being planned; several already have been constructed and installed in the North Sea and the Middle East at depths to 500 ft. Deeper ones are under design.⁶
- French companies have proposed mining caverns below the ocean floor.⁷
- Caverns constructed in salt domes by solution mining methods are proposed for strategic storage.⁸
- The use of nuclear explosives to create undersea caverns has been proposed and studied by the U.S. and the French.^{9,10}

- **Refining**

- The petroleum refining industry is truly world-wide; practically every nation that consumes appreciable amounts of petroleum products refines crude oil.¹¹
- Of 65 million bbl/day world-wide capacity, the U.S. has 21.5%, Western Europe 28%, and Japan 7.5%
- European refineries tend to be less complicated than U.S. ones; they have fewer catalytic crackers and other advanced refining units because they produce a smaller ratio of gasoline to middle distillates (typically, 35% of crude is processed to gasoline in Europe; 65% in U.S.).
- Refining technology, although complex and involving many subjects, is extremely widespread. New innovations rapidly diffuse through the industry; most of the current technologies are available through licensing arrangements.

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APPENDIX II-1: AVAILABLE PETROLEUM TECHNOLOGY FOR HIRE^{a,b}

	Union Oil of California	Amoco Production Company	Chevron Research Company	Shell Development Company
Production techniques	Wax inhibitor	In-place casing repair Oil-water separation Sand control	Tru-Pic down-hole impression Graded sand pack	Gas field performance program Sand control Production-surveillance technology
Drilling methods	Clay substitute	Drilling fluid technology Lost circulation materials	Nitrate ion method Mud acid	Self-neutralizing acidization
Drilling		Directional drilling Drilling optimization Drilling assistance	Foam cleanout Directional jet drilling Torsional oscillation measurements	Computer casing design
Secondary- tertiary recovery	Uniflood soluble oil flooding Caustic flooding	Down-hole ignition Miscible floods Thermal floods Improved sweep efficiency		Residual oil determination Nuclear magnetic logging
Hydraulic fracturing	Deformable diverting agent	Hydro-fracturing	Hydraulic perforation cleaning	Hydraulic fracturing
Offshore			Blue computer program for semi- submersible vessel motion Space frame computer program Wave force	Tubular joint fatigue data Mud slide technology Curved conductors

APPENDIX II-1: AVAILABLE PETROLEUM TECHNOLOGY FOR HIRE^{a,b} (Continued)

	Union Oil of California	Amoco Production Company	Chevron Research Company	Shell Development Company
Arctic			Ice force data	
Pollution			Floating contain- ment barrier	
Pipelines				Pressure calculations Pipe surge Pressure loss program Pipelaying weather effects Marine pipe-laying core-flow technology

APPENDIX II-1: AVAILABLE PETROLEUM TECHNOLOGY FOR HIRE^{a,b} (Continued)

	Atlantic Richfield Company	Marathon Oil Company	Exxon Production Research Company	Texaco Development Company
Production techniques	Scale precipitation calculations		Gravel packs	
Drilling method			Mud cleaner	Shale control mud
Drilling	Bit optimization Hydraulic flow programs Pressure surge codes Water analysis		Casing leak detector Torque turn joint program	Torquemeter Surface drilling log
Secondary- tertiary recovery		Maraflood oil recovery Petroleum sulfonate manufacture	Residual oil tracer	
Hydraulic fracturing			Polymer emulsion fractures	
Offshore			Mooring calculations Drilling riser calculations	
Arctic	Freeze-back pressure in permafrost Thermal simulations of permafrost			Permafrost-density logger

^aSource: *Oil & Gas Journal*, September 30, 1974

^bPartial listing of technologies available from various companies of the oil industry. Most companies offer much of their developed technology (in addition to those listed) for sale through royalty and license arrangements.

APPENDIX II-2: PUBLISHED REFERENCE PUBLICATIONS ON OIL AND GAS

- International Petroleum Encyclopedia (1974)
- Twentieth Century Petroleum Statistics (1973)
(DeGolyer and MacNaughton)
- Oil – The Present Situation and Future Prospects (OECD)
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- Summary Petroleum Statistics (USGS Paper 817)
- 1972 Oil Statistics (OECD)
- Proceedings, World Energy Conference, 1974

III. COAL

C.J. Anderson

W.J. Ramsey

WORLD COAL SITUATION

- Coal is a widely distributed, widely used resource (Fig. 6).
- At present, coal provides about one-third of the world's energy.
- Coal use has more environmental impact in production and consumption than alternative fossil fuels. Coal was a declining industry when oil imports were cheap; it is turning around now that oil prices are up.
- Increased coal production is planned in all countries with significant coal resources, e.g., United States, China, Soviet Union, Poland, Federal Republic of Germany,¹ and the United Kingdom.²
- New technology will play a part in increased coal use.

Fig. 6. World coal production and consumption. Source: *World Energy Supplies, 1968-1971*, U.N. Statistical Papers, Series J, No. 16, 1973.

NEW COAL TECHNOLOGIES

- New technologies for the use of coal for electric generation and process heat will make possible the substitution of coal for oil and natural gas. New technology will also improve thermal efficiencies and ameliorate environmental impacts in coal's traditional markets.
- Conversion of coal to synthetic fuels makes coal use possible in the pipeline gas and, most important, the transportation markets.
- Advanced mining, preparation, and transportation methods development will enhance the safe, efficient movement of coal from mine to market.

COAL CONVERSION AND EXTRACTION TECHNOLOGIES

- Advanced conversion to electricity and process heat
 - Low Btu gasification – surface and *in situ*
 - Gas turbine – steam turbine
 - Solvent refined coal
 - Stack gas cleanup
 - Advanced combustion
- Conversion to synthetic fuels
 - High Btu gasification – surface and *in situ*
 - Methanol – surface and *in situ*
 - Syncrude
- Advanced mining, preparation, and transport
 - Automated mining
 - Hydraulic mining
 - Slurry transport to surface

LOW BTU GASIFICATION

- Low Btu gas (150-300 Btu per cubic ft) called "town gas" was made from coal in surface plants in most industrialized countries before World War II. Most town gas has now been eliminated from the market by natural gas. High gas prices have re-kindled interest in this process.
 - The United States has several programs in various stages of development.¹
 - The United Kingdom has pilot plants and proposes further work. Development of coal-to-synthesis-gas ($\text{CO} + \text{H}_2$) processes is also proposed.²
 - The Lurgi and Koppers company in West Germany sell commercial-scale, low Btu gasification systems.
 - Japan plans to have a 2000-ton/day, high-pressure, fluidized bed gasifier in operation by 1980 for use with an advanced boiler demonstration. Also, there are plans to demonstrate plasma gasification (5000 kW capacity) by the end of the 1980's.³
- *In situ*, low Btu gasification is "commercial" at three sites in the Soviet Union,⁴ is the subject of field and laboratory studies in the U.S.,^{5,6} and has been tried and abandoned in the United Kingdom and Japan.⁷

STATUS: LOW BTU GASIFICATION

Surface

- United States: laboratory studies and pilot plants (several).
- United Kingdom: pilot plants, phasing out commercial plants.
- Federal Republic of Germany: commercial.
- Japan: commercial.

In Situ

- United States: field and laboratory studies.
- United Kingdom, Japan: abandoned experiments.
- Soviet Union: abandoned and commercial applications.

ADVANCED CONVERSION

- One of the major uses for low Btu gas from coal would be as fuel for combined cycle (gas turbine, steam turbine) electrical generating plants. Both the Bureau of Mines¹ and the utilities (through Electric Power Research Institute) are supporting pilot plant studies in the U.S. In the United Kingdom, the COGAS pilot plant is operating,² while in the Federal Republic of Germany the STEAG plant is operating.³ The Japanese plan to be operating a 200-MW system by about 1980.⁴
- Solvent refining coal removes almost all of the ash and most of the sulfur, yielding a product suitable as a boiler fuel or as a feed stock for conversion to synthetic liquids. Two pilot plants exist in the U.S.: one is funded by the Office of Coal Research;⁵ the other is funded by private industry. Both the United Kingdom⁶ and Japan⁷ propose to have pilot plants by about 1980. The United Kingdom process is an unique one, using a super critical gas as the solvent. Laboratory studies are also going on in Poland and the USSR.
- Removal of sulfur oxides from flue gases from coal burning plants has been developed in the U.S. and Japan.⁸ Advanced processes are under development with private and government⁹ support.
- Fluidized bed combustion of coal offers potential advantages in thermal efficiency and pollution abatement. This technology is under development in U.S.¹⁰ and the United Kingdom.¹¹

STATUS: ADVANCED CONVERSION

- Combined Cycle
 - United States: pilot plant
 - United Kingdom: pilot plant
 - Federal Republic of Germany: small-scale demonstration plant.
 - Japan: plans
- Solvent Refined Coal
 - United States: pilot plants
 - United Kingdom: laboratory studies
 - Japan: laboratory studies
 - Soviet Union and Poland: laboratory studies
- Stack Gas SO_x Removal
 - United States: virtually commercial; new systems development
 - Japan: commercial
- Advanced Combustion
 - United States: pilot plants
 - United Kingdom: pilot plant proposals

COAL-BASED SYNTHETIC FUELS

- Pipeline quality (900-1000 Btu per cubic ft) gas can be made from coal. In the U.S., four pilot plants are in or near operation, and several commercial plants are planned. A demonstration plant at Westfield, Scotland, sponsored by a group of U.S. oil companies has operated successfully.¹ A research and development program in Japan is planned to lead a 35-MMcf-per-day demonstration plant by the mid 1980's.²
- An *in situ* process leading to pipeline gas from coal is under development in the U.S.³
- Methanol may be an acceptable substitute for gasoline. Commercial processes for making methanol from coal were used in the past. In the U.S., this process was abandoned when conversion of natural gas proved to be cheaper. An *in situ* process for methanol production has been proposed for development in the U.S.⁴
- Processes for making synthetic crude oil from coal are under development in many countries. In the U.S., pilot plants are in operation and under construction.⁵ There is also significant non-government activity in coal-liquefaction development in the U.S. (Gulf, Exxon, etc.), but details are proprietary. The United Kingdom proposes to have a pilot plant built by 1978,⁶ and Japan plans pilot plants by the early 1980's.² Japan is also negotiating with Australia for syncrude production from Australian coal. The USSR and Poland have laboratory studies under way. In the Union of South Africa, the SASOL plant makes gasoline and other products on a commercial basis.

STATUS: COAL-BASED SYNTHETIC FUELS

- High Btu Gasification – Surface conversion
 - United States: pilot plants, commercial plans
 - United Kingdom: demonstration plant
 - Japan: laboratory studies
- High Btu Gasification – *In situ* conversion
 - United States: laboratory studies
- Methanol – Surface conversion
 - United States: abandoned commercial
- Methanol – *In situ* producer gas production
 - United States: laboratory studies
- Synthetic crude oil
 - United States: pilot plants
 - United Kingdom: laboratory studies
 - Union of South Africa: commercial
 - USSR and Poland: laboratory studies
 - Joint venture, Japan and Australia: plans

MINING, PREPARATION, AND TRANSPORTATION

- Coal mining research and development is carried out actively in most of the coal-producing countries of the world.
- The goals of these programs are greater safety, higher productivity, more efficient resource recovery, and enhanced environmental acceptability.
- Technology developments in the United States, the United Kingdom, the Federal Republic of Germany, the Soviet Union, Poland, Canada, Australia, and South Africa are well reviewed in Refs. 1 and 2. Some Japanese developments are discussed in Refs. 3, 4, and 5.

INTERNATIONAL COAL PRODUCTION RESEARCH

- United States: advanced mining technology, effects of mining on ground water, and mine siting and reclamation.
- United Kingdom: remote mining, automatic control, and advanced mining technology.
- Federal Republic of Germany: advanced mining and reclamation technology.
- Japan: hydraulic mining and slurry transport to surface.
- Poland and USSR: extensive mining research and development.

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IV. NUCLEAR REACTORS

P.H. Moulthrop

FISSION REACTORS WILL DOMINATE ELECTRICAL GENERATION GROWTH

- Worldwide electrical generation capacity will grow at about 6% annually.¹ (See Fig. 7.) Fission reactor systems will grow at a faster rate, and increase their share of total generating capacity from 4% at present, to about 40% by 2000.²⁻⁴
- Reactors will capture this market share because nuclear systems will generate electricity more cheaply than fossil systems, and opportunities for hydroelectric growth are limited.
- This projected market growth implies a large potential payoff for successful research and development on advanced reactors and fuel cycles.

Fig. 7. A rapid growth of nuclear electricity is forecast.

CHARACTERISTICS OF ADVANCED FISSION REACTOR SYSTEMS

- Advanced reactors offer improved thermal efficiency and better fuel economy than present light-water reactors (LWR). (See Fig. 8.) Thermal efficiency will improve with the advent of higher temperature reactors; fuel economy will improve with fully developed fuel reprocessing and with the implementation of advanced converters and breeders.
- Current light-water systems have thermal efficiencies of about 33%. By comparison, the best base-loaded central-station fossil plants have thermal efficiencies of about 40%. Higher thermal efficiency cuts waste-heat production significantly.
- Advanced systems, especially gas-cooled systems, will operate at higher temperatures and have higher thermal efficiencies. A 16-MW_e gas-cooled reactor at Jülich, West Germany, is operating with a helium outlet temperature of 950°C.¹
- Development of the fuel cycle is incomplete. Reprocessing spent light-water-reactor fuel and use of the recovered uranium will reduce mining and milling requirements per reactor by 10%. Plutonium recycle will cut mining and milling requirements an additional 10%; in addition, plutonium recycle will cut enrichment demand by 10%.²
- All reactors convert some of the fertile ²³⁸U in their fuel to plutonium. "Converters" produce less fissile material than they consume; "breeders" produce more than they consume. Present light-water systems have a conversion ratio of 0.55.
- An advanced reactor, with a conversion ratio of 0.75, while not a true breeder, will require only half as much uranium mining as a light-water reactor.³
- In a mature industry, with sufficient breeder capacity, uranium mining can cease entirely. Breeders, rather than enrichment plants, will supply the required fissile material. The required plutonium will be bred from the ample supplies of ²³⁸U in the enrichment plant "tails".⁴ Some thorium mining will still be required to supply the fertile material for producing ²³³U.

Fig. 8. Advanced reactors use less uranium and provide higher temperatures.

ADVANCED CONVERTERS AND THERMAL BREEDERS

- In a thermal reactor, there are more excess neutrons per fission from ^{233}U than from Pu. Thus, all thermal breeder concepts use the thorium- ^{233}U cycle.
- Molten salt breeder reactor (MSBR) fuel is a mixture of lithium-7, beryllium, thorium, and uranium fluorides. About 10% of this liquid is chemically purified each day. Removal of the protactinium and rare-earth fission products enhances breeding performance.¹
 - A 7.4-MW_{th} reactor has been operated successfully at Oak Ridge. (Fig. 9).
 - A group is attempting to obtain support from U.S. utilities, the AEC, and Japanese industry for a 250-MW_e test reactor.
 - France has a small program, and there is interest in other countries.
- Light-water breeder reactors (LWBR) use two strategies to improve neutron economy; coarse control of reactivity is accomplished by neutron captures in thorium, and core water volume is minimized to increase fast fissions in the thorium.^{2,3}
 - A 50-MW_e demonstration reactor in Pennsylvania is scheduled to come online in 1975.
 - There is interest in the LWBR in other countries, but we know of no other program.
- An organic-cooled thorium cycle CANDU breeder has been described by Canadian authors.⁴ Breeding is achieved by fuel movements which reduce reactor availability and increase fuel fabrication costs. A fuel management program resulting in $C = 0.9$ conversion ratio is actually more economical than fuel management aimed at $C = 1.0$.
- In Japan, a 165-MW_e advanced thermal reactor (ATR) is under construction. It is a heavy-water moderated, light-water cooled design.⁵⁻⁷ On a plutonium cycle it is expected to convert at about $C = 0.75$.
- High-temperature gas reactors (HTGR) have operated in both the U.S. and West Germany. Minimum cost occurs when they are operated at about $C = 0.62$, although a higher conversion rate is possible.

Fig. 9. The U.S. leads in thermal breeder and converter research.

FAST-BREEDER REACTORS

- Liquid-metal fast-breeder reactor (LMFBR) programs are being pursued in several countries. In Fig. 10, the width of the bar is proportional to the electrical output of the plant.
 - The French reactor, Phenix, has been at full power since March 1974.¹ Experience with Phenix will contribute to the decision on whether or not to go ahead with Super Phenix.
 - Britain's Prototype Fast Reactor (PFR) is due online soon.²
 - Some significant technical information on these reactors is not available to U.S. workers. Certain ERDA policies, encouragement of joint ventures for example, could alleviate the problem.
 - Present LMFBRs use uranium/plutonium oxide fuels. Successful development of advanced carbide/nitride fuels could increase the amount of plutonium produced annually by a factor of two.³ Large components and safety are also important research and development areas.
- Gas-cooled fast-breeder reactors (GCFBR) have a more energetic neutron spectrum than LMFBRs. This improves breeding ratio and shortens doubling time.⁴
 - There is an active proposal to build a 300 MW_e GCFBR in Texas.⁵ The construction time is estimated to be 10 years.
 - The Gas Breeder Reactor Association in Brussels comprise industrial firms from eight European countries. They anticipate ordering a 600 MW_e demonstration plant in 1978.
 - There are also gas breeder efforts in West Germany and in the Soviet Union.

Fig. 10. France leads in fast breeder development.

HIGH-TEMPERATURE REACTOR CONCEPTS

- The first large high-temperature gas reactor (HTGR) is a 340-MW_e plant in Colorado; it is scheduled to come online in 1975. The second is a 300-MW_e plant in West Germany, scheduled for 1977.¹
 - Both plants use helium for primary cooling and exchange heat with a steam loop for power generation.
 - More advanced plant designs, which expand helium through a turbine without heat exchange, are proposed.² These designs can use small dry cooling towers and thus avoid cooling water problems.
 - Helium turbines for these reactors are under development in the U.S., Switzerland, and West Germany.²
- Molten-salt breeder reactors also offer high temperature capabilities.
 - The table below and Fig. 11 compare the temperatures and efficiencies of the high temperature systems. Although the HTGR has a higher coolant outlet temperature, it also has a large internal power requirement for the helium circulators, hence lower efficiency.³

	<u>Coolant outlet temperature (°C)</u>	<u>Efficiency (%)</u>
LWR	300	Steam cycle: 33
HTGR	750	Gas turbine: 36 Steam cycle: 40 Combined cycle: 48
MSBR	700	Steam cycle: 44

Fig. 11. High reactor temperature can increase efficiency and flexibility.

PROCESS HEAT APPLICATIONS

- West Germany plans a 750-MW_{th} high-temperature reactor for coal gasification (Fig. 12). The reactor design outlet temperature is 950°C. Design objective is the gasification of 50 tons of coal per hour. Adding process heat from a nuclear source enables the system to produce 50% more gas per ton of coal.¹
- Other high temperature process heat concept studies are going on:
 - German studies on the ADAM and EVA process are being carried forward.²
 - Japan plans a 50-MW_e reactor with a 1000°C outlet temperature for process heat applications. A feasibility study of a large reactor for nuclear steelmaking is in progress.³
 - The European nuclear steelmaking club, which has seven full members including British Steel Corporation, is conducting a similar study.⁴
 - A group of U.S. steel companies has sponsored a similar study.³

FEDERAL REPUBLIC OF GERMANY:

Coal Gasification - 50% more gas per ton of coal in comparison with conventional gasification methods

ADAM & EVA energy transmission process

JAPANESE, EUROPEAN AND U.S. GROUPS:

Nuclear Steelmaking

Fig. 12. High-temperature process heat techniques are under development in both W. Germany and Japan.

LOW-QUALITY STEAM APPLICATIONS

- District-heating that operates with power plant waste-heat improves air quality. Studies in Sweden, Finland, Switzerland, and elsewhere show that customers, up to 30 km from the reactor, can be economically served.¹
- Heat from the Soviet fast-breeder BN-350 is used for desalination. This use has been studied in France, Finland, and elsewhere.¹
- Matching a reactor's steam output to industrial requirements is difficult. A large reactor supplies more steam than the average plant needs, and reactor availability is not as high as industrial plant requirements demand.
 - An exception to this general situation is the Dow Chemical (Michigan) plan to use 4 million pounds per hour of process steam supplied by a 1300-MW_e electric plant located close by. The reactors are scheduled to come online in 1981.²

HOT WATER AND STEAM CAN BE USED FOR
DISTRICT HEATING AND INDUSTRIAL PROCESSES

District Heating	Desalination	Process Steam
Sweden (O & P)	USSR (O)	USA (C)
Finland (P)	France (P)	
Switzerland (P)	Finland (P)	

Notes:

- (P) Planned or Proposed
- (C) Under construction
- (O) In operation

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V. NUCLEAR FUELS

I.Y. Borg

URANIUM SUPPLY AND DEMAND

- Three heavily industrialized nations (FRG, UK, and Japan) are virtually without uranium resources.
- Many nations, including some in Western Europe, are potentially self-sufficient to the year 2000 (Canada, Australia, Argentina, Sweden, Portugal, South Africa, Niger, Gabon).
- World supply of \$77/kg U_3O_8 is not too disparate with world demand to year 2000 (Fig. 13).

Fig. 13. World supply of U₃O₈. Source: Wash-1139 (74) Case Y (medium foreign demand); World Energy Resources, 1974; Alder, H., USAEC, Grand Junction, Colo., October 1974.

THORIUM RESOURCES

- Reasonably assured thorium reserves (\$25/kg or less) are more than adequate to meet the total nuclear demands of many countries (Fig. 14).
- Additional, hypothetical, reserves are, in many cases, enormous; e.g., in the U.S. they represent 95% of total resource.
- Brazil and India have never lifted 1951 and 1946 embargos on the export of ThO_2 .
- Large-scale, low-cost production of ThO_2 as a by-product in monazite (Ce and other RE), uranium, ilmenite (Ti), zircon (Zr) and rutile (Ti) operations has throttled development of independent domestic industries.
- Both domestic and foreign thorium is being stockpiled by industry since current supply exceeds demand.
- HTGRs, which use highly enriched uranium, require ten times more natural U_3O_8 than ThO_2 on initial loading.

Fig. 14. Reasonably assured thorium reserves. Source: World Energy Conference Survey of Energy Resources, 1974; WASH-1535 (1974); WASH-1139 (74) (1974).

GEOLOGICAL RESEARCH – URANIUM/THORIUM RESOURCES

- Worldwide exploration for uranium and thorium is primarily by airborne high-sensitivity γ -surveys. (See Fig. 15.)
- Exploration is largely financed by governments through subcontracts to private industries.
- Where government policies do not inhibit foreign exploration, supra-national consortiums flourish.

(See Appendix V-1.)

Fig. 15. Summary of airborne and ground radioactivity surveys. Source: *Geophysics* 39 (1), 95-109 (1974).

EXTENSION OF URANIUM RESOURCES

(See also Fig. 16.)

- Shales

In Sweden, experimental uranium operation in 0.03% alum shales on full production scale, at \$26-39/kg.^{1,2} Commercial production of 1300 tons/year is expected in the early 1980s.^{2a}

- Seawater

Estimated costs in 1974 is \$60/kg U for plant in the Menai straits between Anglesey and the rest of Wales, U.K.^{3,4} Japanese have plans to use reactor heat to extract 3400 tons/year by the 1990s; cost estimates are \$50-\$60/lb.^{4a}

- Phosphate rock

After much R&D, uranium is being recovered as a by-product of the phosphate (fertilizer) industry. Estimate is 1 lb U_3O_8 for 1 ton P_2O_5 and profitable with U_3O_8 in the \$14.30 to \$17.60 kg price range. Potentially the by-product can supply 7 to 10% of U.S. demand in 1985.⁵⁻⁷

- Copper Ore

Ion exchange and solvent extraction techniques have been developed but have not been employed by major U.S. copper producers. Some recovery is affected at the copper-ore processing plant at the Palabora carbonatite complex, South Africa.^{8,9}

- Uranium Mine Waters

Field and pilot plant tests using improved ion exchange columns have processed more than 5×10^6 gallons of water at the Ambrosia Lake district, New Mexico, with >98% recovery rates.¹⁰

- *In-Situ* and Heap Leaching

Underground leaching has been used sporadically in the U.S., Canada and USSR since the early 60s. Bacterial leaching at the Stanrock mine in Canada yields about 7% of total production. In 1968 the cost was estimated to be about \$9/kg.¹¹⁻¹⁶

- Hydraulic Extraction

Borehole mining best suited to localized high grade resources in friable rock.¹⁷

(See Appendix V-2.)

Exploration for high grade sources	Airborne surveys > 1000 ppm	Ground surveys	Drilling	
Novel low grade sources	Shales 60-300 ppm	Seawater 0.0033 ppm	Phosphate rock (by-product) 100-200 ppm	Copper ore (by-product) 1-12 ppm
Special recovery techniques	Uranium mine waters 9-12 ppm	In-situ and heap leaching ~ 400 ppm	Hydraulic extraction	

Fig. 16. Activity designed to increase uranium resources.

INTERNATIONAL EFFORTS IN ENRICHMENT TECHNOLOGY

- Three techniques are used at pilot or production scale to separate ^{235}U from ^{238}U :
 - Gaseous diffusion is the first method developed to enrich uranium; most of the world's capacity, and almost all U.S. capacity, is of this type.
 - Centrifuge techniques have been perfected, and some centrifuge capacity has been installed in Europe.
 - Less developed and less understood is the Becker nozzle technique. Some nozzle capacity is under construction in West Germany and probably in South Africa.
- Investments in uranium enrichment facilities are risky because:
 - Optimally sized plants are large, and therefore costly.
 - About ten years are required to build and begin operation of a new diffusion plant.
 - Fuel users have been unwilling to enter into firm contracts for enrichment services because of chronic reactor delays.
- To spread the substantial risks, consortia have formed to engage in feasibility studies, R&D, or actual construction of enrichment facilities; at least 13 Western nations are engaged in some aspect of nuclear fuels. Some commercial consortia have dissolved after feasibility studies.
- Enrichment pools create a larger market for nuclear fuels, and provide a vehicle for spreading the risk. The largest one is World Nuclear Fuels, which has about 70 members in the U.S.
- Laser separation of uranium isotopes is under investigation at the present time. This technique offers the possibility of lowering the price of separative work through reduced power requirements and reducing the tails concentration of ^{235}U to less than 0.1%. Current techniques, by comparison, are operated to achieve a tails concentration of 0.3%. If perfected, it can come close to tripling ^{235}U resources. A 1%-scale pilot plant is proposed by U.S.-LLL for construction in FY 1979.

(See Appendix V-3).

INTERNATIONAL LEADERS IN ENRICHMENT TECHNOLOGY

Diffusion	Nozzle	Ultra-centrifuge	Laser
1. US-ERDA-ORNL Oak Ridge, Tenn.	1. Gesellschaft für Kernforschung, Karlsruhe, FRG	1. URENCO, -CENTEC Netherlands - 33%	1. US-ERDA-LLL - LASL
2. EURODIF, SA France - CEA 45.5% Italy - CNEN 12.2% Italy - AGIP Nucleare - 12.2% Spain - ENUSA - 10% Belgium - SIBESI - 10% (uncommitted) - 10%	2. STEAG, Power & Coal, FRG	ultra centrifuge Germany - 33% URANIT GnV U.K. - 33% British Nuclear Fuels Ltd.	2. Garrett AiResearch Corp. 3. Exxon Nuclear Corp. US 4. Tel Aviv Univ., Israel
3. Garrett AiResearch Torrance, Calif.		2. Garrett AiResearch Corp., Torrance, Calif. 3. ACE (12 nations)	5. Battelle Institute, Frankfurt, Federal German Republic

DIFFUSION AND NOZZLE ENRICHMENT CAPACITIES

- Large amounts of capital (\$3B/10,000 SWU/a) are needed to build gaseous diffusion plants.
- Supra-national and industrial consortiums are an answer to the technological and capital problems (e.g., EURODIF), but many do not survive beyond feasibility studies (e.g., UEA-Uranium Enrichment Associates.) (See Fig. 17.)
- Enormous capital requirements require utility contracts be negotiated as long as 10 years in advance for enriched uranium over the plant lifetime. EURODIF has already sold its future production.
- EURODIF to be in operation in 1981; UCOR-Uranium Enrichment Corp. — South Africa, using what is generally assumed to be a modified nozzle technique, is in advanced stages of construction.
- Cascade improvement program (CIP) and Cascade upgrading program (CUP) when completed at U.S. diffusion plants in 1981 will increase existing capacity 38%.

Fig. 17. Diffusion and Becker nozzle enrichment capacity.

ULTRA – CENTRIFUGE

- Ultra-centrifuge techniques (Fig. 18) are universally considered to be superior to gaseous diffusion for several reasons:
 - Power use is only 10-15% of gaseous diffusion requirements.
 - Capacity can be brought on stream in steps, which reduces risks and start-up capital requirements.
 - Technological improvements can be incorporated at low cost relative to gaseous diffusion technology.
 - Because the UF_6 inventory is smaller, centrifuge plants pose less of an environmental hazard than a diffusion plant of equal capacity.

Fig. 18. Capacity of operating and planned ultra-centrifuge enrichment (10^6 SWU/year). Source: D. Smith, *Nuclear Eng. Int'l*, July 1974; *Weekly Energy Report*, September 23, 1974.

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APPENDIX V-1: GEOLOGICAL RESEARCH – URANIUM RESOURCES

Research Organizations

U.K. M. Davis, UKAEA, London
S.H.U. Bowie, Institute of Geological Sciences, Geochemical Div., London

U.S. W. Finch, U.S. Geological Survey, Denver, Colorado

Airborne Survey Information

Canada A.G. Darnley, Dept. of Energy Mines and Resources, Geological Survey of Canada,
Ottawa, Canada

U.S. ERDA, B. Bowyer, Director (Resources Division), Grand Junction Office,
Colorado

Geophysical Contractors in Uranium Exploration

U.S. Geometrics Intern'l Corp., 914 Industrial Ave., Palo Alto, CA
Aero Service Corp., 4219 Van Kirk St., Phila, PA (Div. of Litton)
Texas Instruments, Inc., Box 1444, Houston, TX 77001 (Geodata, Inc.)

Canada Barringer Research Ltd., 304 Carlingview Dr., Metro. Toronto, Rexdale, Ontario,
Canada
Geoterrex Ltd., 2060 Walkley Rd., Ottawa, Canada
Scintrex Ltd., 222 Snidercroft Rd., Concord, Ontario, Canada
Northway Survey Corp., 1450 O'Conner Dr., Toronto, Ontario, Canada

U.K. Hunting Geology and Geophys. Ltd., Elstree Way, Boreham Wood, Hertsfort, U.K.

F.R.G. Saarerg-Ingenleure (Div. of Saberwerke AG), Trierer-Strasse 1, Saarbrucken,
Saarland.

APPENDIX V-2: EXTENSION OF URANIUM RESOURCES

- SHALES

AB Atomenergi, Ranstad, Sweden

- SEAWATER

AERE, Harwell, Didcot, Berkshire, U.K. (N. Keen)

Japanese Trade Ministry, Tokyo, Japan

- PHOSPHATE ROCK

Uranium Recovery Corporation — W.R. Grace Company, Barstow, Fla.

Westinghouse Electric Corp. — Gardinier Corp., Tampa, Fla.

Gulf R&D Corporation — AGRICO Chemical Company, Pierce, Fla.

- COPPER ORE

U.S. Bureau of Mines, Salt Lake City, Utah

- MINE WATERS

United Nuclear Inc. (J.M. Johnson) — Kerr-McGee Corp. (E. Maur) Ambrosia Lake,
New Mexico

U.S. Bureau of Mines, Salt Lake City, Utah (J.R. Ross)

- *IN SITU* AND HEAP LEACHING

Denison Mines, Ltd. (Stanrock Mine), Elliot Lake, Ontario (R.A. MacGregor)

Compagnie Francaise des Minerais d'Uranium, Langogne (Lozere) Deposit, France

Wyoming Minerals Corp., Denver, Colorado (R. Jacobson)

ARCO/U.S. Steel, Clay West Leaching Operation, Live Oak Co., Texas

- HYDRAULIC EXTRACTORS

Hydro-Jet Services, Inc., Amarillo, Texas (A.B. Ely)

APPENDIX V-3: INTERNATIONAL EFFORTS IN ENRICHMENT TECHNOLOGY

Diffusion

US-ERDA, Oak Ridge National Laboratory, Oak Ridge, Tennessee
EURODIF, S.A., 116 Ave. A. Briand, 92220 Bagneaux, France

Nozzle

Institut für Kernverfahrenstechnik der Universität und des Kernforschungszentrums, Karlsruhe,
F.R.G. (E.W. Becker, W. Bier)
Steinkohlen Electro AG (STEAG), Essen, F.R.G. (H. Geppert, H. Volcker)

Centrifuge

URENCO-CENTEC Tlanthofsweg 81, Almelo, Netherlands
Ultra-centrifuge (UCN), The Hague, Netherlands (M. Bogaardt)
Uran-Isotopentrennung GmbH (URANIT), Jülich, F.R.G. (P. Jelinek-Fink) Gesellschaft
für Nukleare Verfahrenstechnik GmbH (G.n.V.), Bernsberg, F.R.G. (K. Einfeld)
British Nuclear Fuels Ltd (BNFL) Risley, U.K. (J. Tatlock)
Garrett AiResearch Corporation, 9851 S. Sepulveda Bldg., Torrance, Calif. 90045
Association for Centrifuge Enrichment (ACE), 120 High Street, Eton, Bucks, U.K. (R.B. Kehoe)

Laser

US-ERDA, Lawrence Livermore Laboratory, P.O. Box 808, Livermore, CA 94550
(B. Snavely)
US-ERDA, Los Alamos Laboratory, Los Alamos, NM (C.P. Robinson, R. Jensen)
Garrett AiResearch Corporation, 9851 S. Sepulveda Bldg., Torrance, Calif. 90045
(J.W. Eerkens)
Exxon Nuclear Co., Bellevue, Washington (R.H. Levy, G.S. Janes)
Battelle Institute, Frankfurt, F.R.G. (K. Gurs)
Tel Aviv University, Haifa, Israel (M. Levin, I. Neberzahl)

VI. FUSION

R.F. Post
P.H. Moulthrop

CONTROLLED THERMONUCLEAR RESEARCH

- Research in controlled nuclear fusion reactors has been a major international undertaking since declassification in 1958. (See Fig. 19.) It is characterized by an unusual and thorough interchange of information and a high degree of international cooperation. Regular international conferences communicate new research results quickly.
- Fusion power development is, at present, wholly a research activity. Current estimates in the fusion community are for a demonstration of scientific feasibility within the next ten years, and commercial fusion reactors about the year 2000.
- Fusion power is very attractive because the primary fuels, lithium and heavy hydrogen are so abundant as to be virtually inexhaustible. In addition to assured fuel availability, fusion power concepts promise to avoid diversion problems (no fissile materials are employed) and disposal problems (no radioactive wastes are generated).
- Practical fusion power is a difficult objective. For fusion reactors to be self-sustaining, the fuel must be heated to kinetic temperatures of millions of degrees. To avoid quenching the reactions, the heated fuel charge must be isolated from the reactor vessel long enough to produce net energy.
- The pie chart on the opposite page gives a breakdown on the percentage of the total effort spent by each major country for magnetic confinement in 1973; total effort in magnetic confinement was about 3100 scientific man years.

Fig. 19. Distribution of effort in controlled fusion research (magnetic confinement only).

MAGNETIC CONFINEMENT CONCEPTS

- Magnetic confinement research has concentrated on three general approaches:
 - “Tokamak” systems, pioneered in the Soviet Union, confine the plasma in a doughnut-shaped toroidal chamber.
 - “Theta-pinch” systems are high density plasma systems which use shock heating and compression to produce the plasma.
 - “Mirror machines” use intensified magnetic field regions at the end of the tubular reaction vessel to confine the plasma.

- Tokamaks are receiving the most research attention at the present time because they produce the longest confinement times. In the long run, the other concepts have substantial advantages that may weigh more heavily than the sole issue of confinement. A broadly based effort should be pursued until the issue is much clearer than it is at present.

PARTIAL INVENTORY OF MAGNETIC CONFINEMENT EXPERIMENTS (1973)

Type (worldwide total)	Installation	Status	Major diam.	Minor diam.	Ion temp.	$n\tau$
Tokamak (27)	Ormac (USA)	Oper.	80 cm ⁽¹⁾	27 cm ⁽²⁾	0.1 keV	2×10^{11}
	T-4 (USSR)	Oper.	100	17	0.7	
	TFR (France)	Oper.	98	20	0.85	3×10^{11}
	PLT (USA)	1975	130	45		
	T-10 (USSR)	1975	150	40		
Theta Pinch (15)	Scyllac (USA)	Oper.	400 cm ⁽¹⁾	4.4 ⁽²⁾	0.75 keV	1.5×10^{11}
	ISAR(III) (FRG)	Oper.	135 cm ⁽¹⁾	5.4	0.15	9×10^{10}
	HELIX (FRG)	Oper.	700 cm ⁽³⁾	18.5 ⁽⁴⁾		
Mirror Machine (27)	2XIIB (USA)	Oper.	150 cm ⁽³⁾	10 cm ⁽⁵⁾	1-10 keV	2×10^{10}
	PR-7 (USSR)	Oper.	100 cm ⁽³⁾	(5)	0.2-0.5	3×10^9
	Pleiade V (Fr.)	Oper.	60		1.4 ⁽⁷⁾	
Stellarators & Related Devices (18)	Wendlestein VII (FRG)	Const.	250 cm ⁽¹⁾	36 cm ⁽²⁾		
	Cleo (UK)	Oper.	90 cm ⁽¹⁾	135 cm ⁽²⁾		
	URALAN (USSR)	Oper.	1035 cm ⁽⁶⁾	10 cm ⁽²⁾		

Notes:

- (1) Major radius
- (2) Minor radius
- (3) Plasma length (linear system)
- (4) Coil inner diameter
- (5) Plasma diameter
- (6) Racetrack length
- (7) Electron temperature

Source: "World Summary of Major Facilities in Controlled Fusion Research," Nuclear Fusion Special Supplement 1973, published by the IAEA, Vienna.

INTERNATIONAL LASER FUSION RESEARCH

- Pellet compression concepts depend upon creating a sufficiently intense, well-focused laser or electron beam that can heat and compress pellets of fuel. The objective is to produce a series of micro-explosions that yield net energy from the system.
- The major industrial countries have laser fusion efforts. Research sites within foreign countries are given on the facing chart. Major installations in the United States are included in the next chart.

FOREIGN LASER PROGRAMS

- USSR

Lebedev Institute, Moscow

Physical Institute, Minsk

Kurchatov Institute, Moscow

Efforts expanding 25% per year

10^4 Joule system being developed for Kurchatov.

- France

CEA facility Limeil

Compagnie Generale D'electricite

(Developed first high power laser technology)

Laser development is now at a plateau.

- Japan

Osaka University

Nagoya University

Jeol Ltd.

Hoya Glass Works Ltd.

Ushio Elect. Ltd.

A small, highly motivated combine of government, university, and industry, growing rapidly.

- FRG

Institute for Plasma Physics – Garching

Small growing effort collecting data.

- United Kingdom

Culham Laboratory

University of Hull

Small exploratory effort underway.

- China

Laser fusion program established.

LASER FACILITIES

- The maximum power available from a solid-state laser is approximately $5 \times 10^9 \text{ W/cm}^2$, thus a 100 cm^2 aperture can provide approximately $0.5 \times 10^{12} \text{ W}$. A power in this range is required in order to carry out significant compression of a pellet. The largest lasers are at the Lebedev Institute in Moscow, at the University of Rochester in New York, and at the Lawrence Livermore Laboratory in California. (See Fig. 20.)
- These lasers are not prototypes for the lasers in an actual power-producing facility, because the efficiency with which they convert electrical energy to light is very low. However, they are well-suited to pellet compression experiments, pending development of more efficient lasers.

Fig. 20. Worldwide solid-state laser facilities.

VII. TRANSPORTATION

J.W. Bell

L.G. O'Connell

TRANSPORTATION OVERVIEW

- Transportation is a significant part of the energy problem in Europe, Japan, and the United States. Despite good public transportation, the Highway Vehicle System (HVS) still consumed about 80% of European/Japanese transportation energy in 1972.
- Since they have limited domestic petroleum reserves, reductions in petroleum consumption are even more important for Europe and Japan than for the U.S.
- There are several research areas that can increase present-day HVS efficiency or reduce petroleum requirements by substituting other fuels:
 - Improved current vehicle systems
 - Advanced heat engines
 - Alternate vehicle propulsion systems
 - Alternate fuels
- Many different technical approaches are contained in the four topics above. Figure 21 gives one version of the succession of specific power plants which may be developed to serve the highway vehicle system in the future.
- Public transportation is also a means of saving transportation energy. Higher population densities make public transportation more practical in Europe and Japan than in the U.S. Because of this, there are significant public transportation development efforts abroad.

PETROLEUM DEMAND – 1972

Region	Total Energy		Petroleum		
	Demand (10 ⁷ mtoe)	% Petroleum	Total demand (10 ⁷ mtoe)	Trans. demand (10 ⁷ mtoe)	% Imported
Western Europe	73.2	77.6	56.8	10.9	88.5
Japan	33.4	75.4	25.2	3.3	99.7
U.S.	155.3	52.3	81.2	42.1	30.6

Fig. 21. The dominant highway vehicle system power plant will change.

IMPROVED CURRENT VEHICLE SYSTEMS

Improving current vehicles requires work in two areas:

- Power train improvements
- Overall vehicle design

Power train improvements, engine and transmission design, are prime research topics.

- Fuel conditioning
 - Improved carburetion
 - Improved fuel injection
 - Onboard catalytic reforming
- Fuel ignition
- Fuel combustion
 - Computer models of combustion
 - Lean burning systems for high efficiency, low emissions
- Emissions
 - Exhaust gas treatment systems

Light vehicles are more efficient, but more vulnerable in crashes

- Safety
 - Controlled crush body design
 - Improved brakes
- Aerodynamics
 - Reduced air drag
- Suspensions

(See Appendix VII-1 for a listing of organizations working in these areas.)

IMPROVED CURRENT VEHICLE SYSTEMS

- ENGINES

England
West Germany
Italy
France

- TRANSMISSIONS

England
West Germany
Netherlands
Italy

- VEHICLE

- Safety

Sweden
England
West Germany
France
Italy

- Aerodynamics

England
West Germany
France
Italy

- Suspensions

England
West Germany
Italy
France

ADVANCED HEAT ENGINES

- Successfully introducing a new engine concept depends upon many factors.
 - Market considerations
 - Efficiency
 - Environmental acceptability
 - Compatibility with existing manufacturing facilities
- The next generation of heat engines will resemble current technology.
 - Stratified charge
 - Diesel
- The Stirling engine requires additional development, but might emerge after the stratified charge and diesel if another generation of heat engines is required.
- European research places less emphasis on environmental concerns, apart from noise, when compared to U.S. work. Europeans are doing significant work on diesel noise and diesel emissions.

ADVANCED HEAT ENGINES

- Stratified Charge — Porsche AG, Weissach FRG
Volkswagenwerk AG, Wolfsburg, FRG
Technische Hochschule Aachen, FRG
Lehrstuhl für Angewandte Thermodynamik
Klöckner-Humboldt-Deutz AG, Köln, FRG
Honda Motor Company, Ltd., Tokyo, Japan
Fuji Heavy Industries Ltd., Japan
Toyota Motor Co., Japan
Mitsubishi Motor Co., Japan
- Diesel — Ricardo & Company Engineers, Ltd., England
Dept. of Environment, Vehicle Engine Division, London England
Perkins Engines Company, Petersborough, England
Rolls-Royce, England
British Leyland, England
- Gas Turbine — Nissan Motor Company, Ltd., Yokosuka, Japan
Volkswagenwerk AG, Wolfsburg, FRG
- Stirling Engine — Philips Research Laboratories, Eindhoven, Netherlands
Maschinenfabrik Augsburg-Nürnberg, FRG
KB United Stirling, Malmö, Sweden
University of Birmingham, England
- Rankine — Saab-Scania, Sweden
- Rotary — Audi NSU Auto Union AG, Neckarsulm, FRG
Toyo Kogyo, Japan
Svenska Rotor-Maskiner, Sweden
Rolls-Royce, England
Norton Villiers Triumph, England
Fichtel & Sachs, FRG
- Warren — Volkswagenwerk AG, Wolfsburg, FRG

ALTERNATE VEHICLE PROPULSION SYSTEMS

- Mechanical or electrical energy storage systems can be developed for use in highway vehicles. Such systems can be the sole power source in the vehicle, or they can be combined with an internal combustion engine to make a hybrid vehicle. (See Fig. 22.)
- Both specific energy and specific power characteristics of present battery systems are inadequate for electric vehicles. Likewise, flywheel energy storage systems are not yet good enough for vehicle use except as power boosters in hybrid systems.
- Japan, France, the United Kingdom and the United States have both government and private programs underway, Germany has privately-sponsored work in progress. Electric vehicles are the major focus of interest, little mechanical flywheel work is being undertaken.
- The Japanese government sponsors a consortium of industrial firms developing an urban electric vehicle in a five-year program which began in 1971.
 - The program goal is to develop a vehicle with performance adequate for urban use.
 - In 1973 the program had produced a 3600 lb vehicle with 110 mile range and a top speed of 58 mph.
- The French government, through Electricité de France, has been sponsoring electric vehicle development since 1965. The program includes work in batteries, motors and controls, and is being done by a consortium including Renault, Saviens and Serie. Additional work at the Laboratory de Marcoursses aimed at a 100 watt-hour/kg soluble zinc-air battery is also underway. It is recharged by replacing the soluble zinc electrolyte slurry.
- Electric vehicle use is common in the United Kingdom, with 140,000 vehicles in operation. Support for further development is coming from the Electricity Council, which has ordered 8000 small passenger vehicles from Enfield Automotive.
- Several private electric vehicle programs are underway in the United States. Government efforts are limited to EPA sponsorship of system studies and battery development, Post Office use of electric Jeep vehicles, and NSF system studies.

(For a more extensive listing of public and private efforts see Appendix VII-2.)

Fig. 22. Alternate highway vehicle propulsion systems.

ALTERNATE HIGHWAY VEHICLE FUELS

- Cutting petroleum dependence by converting the transportation system to another fossil fuel is an attractive proposition, if the alternative is cheaper or embargo-proof. The commonly proposed alternates are:
 - Synthetic gasoline and coal distillates
 - Methanol produced from coal or wastes
 - Blends combining methanol, gasoline and/or water
 - Thermochemically produced hydrogen
- Given the difficulties of producing and distributing hydrogen in volume, it must remain a long-run possibility. The various proposed blends, on the other hand, are feasible medium-term prospects.
- Synthetic gasolines have the advantage of complete compatibility with existing systems. Methanol has been tried with some success in automobiles, but testing aimed at establishing the long-term effects of methanol use is still required. Methanol/gasoline blends have been tried, and may offer slightly better fuel economy than straight gasoline. Blends including water are in a more fundamental category, and much work is required to evaluate their properties.
- Only the U.K., Germany and the United States have sufficient coal reserves to justify coal-based alternate fuel development.
 - The National Coal Board in England is believed to have proposed a demonstration coal-to-oil plant, but the government position is that the country will be able to depend upon North Sea oil.
 - Germany, with substantial coal resources, is devoting some effort to methanol/gasoline and methanol/water blends.
 - Apart from these countries, Japan and the U.S., there appears to be little work on alternate fuels.
- Engine research on methanol/water blends appears in the Japanese literature. The work seems to be at an early stage. The justification for the work appears to be the fact that it is cheaper to import methanol than liquified natural gas. Experiments with blends containing up to 30% water have been reported. Deterioration of lubricating oils with methanol use has been reported; a similar result was obtained by Continental Oil Company.

ALTERNATE HIGHWAY VEHICLE FUELS

Germany

Daimler-Benz AG, Stuttgart

Hydrogen vehicle research — stored as
hydride, H_2 /gasoline blends

Volkswagenwerk AG, Wolfsburg

Methanol engine research — methanol/
gasoline blends

Porsche AG, Weissach

Stratified charge engines/methanol
Stratified charge engine/methanol
research

Maschinenfabrik Augsburg-Nürnberg (MAN)

Stratified charge engine/methanol
research

Technischer Überwachungs

Alternate fuel study

Verein Rheinland EV, Köln

Japan

Japan Automobile Research Institute

Methanol engine research

Methanol/ H_2O blends — to 30% H_2O

PUBLIC TRANSPORTATION

- Advanced rail systems are in use and under development in Europe and Japan.
 - Better inter-urban rail systems are under development in England, Germany, France, and Japan.
 - West Germany is planning a high-speed rail system to connect major German cities; England and France are operating test lines.
 - Japan has had high-speed (200 km/hr) trains in operation in the Tokyo-Osaka corridor for some years.
 - Urban rail systems require better automatic controls.
 - System cost is dominated by right-of-way acquisition and construction.
 - Improved control systems will allow greater transportation throughput on a given track segment.
 - The Paris, London, Montreal, and Tokyo underground systems have been developing automatic rapid transit systems similar to the new modern U.S. systems.
- Aircraft use of hydrogen fuels is being considered in Europe. The Europeans are not strongly attracted to hydrogen as an aircraft fuel because they do not have the equivalent of NASA's hydrogen handling experience.

APPENDIX VII-1: IMPROVED CURRENT VEHICLE SYSTEMS

GERMANY

Robert Bosch GmbH	Fuel conditioning, control
Bayerischen Motoren Werke AG	Emission
Daimler-Benz AG	All aspects
Deutsche Vergaser GmbH Co KG	Fuel conditioning & exhaust treatment
Universität Stuttgart Institut für Physikalische Elektronik	Mixture ignition
Universität Trier – Kaiserslautern	Mixture ignition
Technische Hochschule Aachen	
Lehrstuhl für Angewandte Thermodynamik	Combustion
Institut für Motorenbau	Pollution
Maschinenfabrik Augsburg-Nürnberg AG	Combustion
Porsche AG	All aspects
Volkswagenwerk AG	All aspects
Siemens AG	Fuel conditioning, ignition, & control
Klöckner-Humboldt-Deutz AG	All aspects
ZF	Transmissions

JAPAN

Osaka University	Multifuel systems
University of Osaka Prefecture	Fuel ignition
Government Mechanical Laboratory	Combustion
Nagoya University	Instrumentation
Gunma University	Combustion
Sophia University	Engine Modeling
Kyoto University	Gas flow studies
Nagasaki Technical Inst.	Intake air surge
Hokkaido University	Diesel air preheat
Honda Motor Company	Stratified charge
Mitsubishi Automobile Industry Company	Stratified charge

ENGLAND

Transportation & Road Research Lab.

Dept. of Trade & Industry

Shell Research Ltd.

University of Sussex

University of Manchester

Rolls-Royce Ltd.

CAV Ltd.

University of Leeds

Perkins Engines Co.

University of Sheffield

Rover

Austin

British Leyland

Associated Engineering Developments Ltd.

Lucas Electric Co.

Automotive Products

Garrett-AiResearch

Westlake & Co.

Variable Kinetic Drive (VKD)

Borg-Warner

Bruckhouse

Zenith

GKN

Petrol Injection Ltd.

Aerospace Corp.

BP Research Center

(British Petroleum Group)

Vehicle design

General

Fuel general

Engine modeling, combustion

Noise

Rotary-Diesels, Diesels

Combustion

Fuel composition

Engine design Diesel

Combustion

General design

General design Diesel

Safety – Diesel – transmissions

Ignition – controls

Ignition – fuel injection

Suspension

Turbocharger

“

Infinitely variable transmission

Lockup automatic transmission

“

“

“

Advanced carburetors

Fuel injectors

Aerodynamics

Fuel

FRANCE

Citröen

Renault

Peugeot

General

“

“

AUSTRIA

Technische Hochschule

Österreichische Mineralölverwaltung

Fuel

Fuel

ITALY

Fiat

SNAM, Progetti

Esso Italiana Research Center

University of Perugia

CNPM Centro Nazionale per la

Propulsione de Milano

Petroleum Products Lab., Progetti

Poletic de Torino

General

Emissions, combustion

Emissions

Emissions

Lubrication

Combustion

Vehicle systems

SWEDEN

Chalmers Tekniska Hogskola

APPENDIX VII-2: ALTERNATE VEHICLE PROPULSION SYSTEMS

JAPAN

Electric Vehicles

Agency of Industrial Science & Technology of
Ministry of International Trade & Industry

Daihatsu Kogyo Company

Toyo Kogyo Company

Yuasa Battery Company

Nissan Motor Company

Toyota Motor Company

Mitsubishi Motor Company

Sony Corporation

Fuji Heavy Industries

Shimbu Electric Company

Sponsors E. V. Development

Development

Development

Development

Development—Rapid Battery Exchange

Development

Development

Development

Batteries

Yuasa Battery Company

Japan Storage Battery Company

Sanyo Electric Company

Shin Kobe Electric Company

Matsushita Electric Company

Sony Corporation

Fuji Heavy Industries

Shimbu Electric Company

Kyoto University

Development—Adv. Pb-Acid, Na-S

Development—Adv. Pb-Acid

Development—Zinc-Air

Development—Adv. Pb-Acid

Development—Fe-Air

Development—Soluble Zinc-Air

Research

Components

Hitachi Electric Company

Toshiba Electric Company

Mitsubishi Electric Company

Toyo Kogyo Company

Motor/Controller Development

Motor/Controller Development

Motor/Controller Development

Motor/Controller Development

ITALY

Electric Vehicles

Urbannia S.p.A.

Fiat S.p.A.

Piazzio & C. S.p.A.

Commercial

Development—Hybrid, Flywheel
Power Boost

Development

Components

Polytechnic of Milan

A.C. Motor/Drive Res.

ALTERNATE VEHICLE PROPULSION SYSTEMS

FRANCE

Electric Vehicles

Interministerial Task Force

TREGIE*

Electricité de France (EDF)

CEM-Oerlikon

Transport Research Institute

Departement Applications de l'Electricité

Sponsors E. V. Development

Development

Development

Development—Wayside Power

Market Research

Testing

Batteries

TREGIE

Laboratoires de Marcoussis

Compagnie Générale d'Electricité

Saft, Paitiens

Development

Development—Zinc-Air (Soluble
zinc) Na-S

Research

Components

TREGIE

Etablissements E. Ragonot

Cybermeca, La Verriere

Development

Development

Development

*TREGIE — Consortium — Renault, Saviem, Serie

UNITED KINGDOM

Electric Vehicles

The Electricity Council

Advanced Vehicle Systems, Ltd.

Enfield Automotive

Shell's Thornton Research Center

Sponsoring E. V. Development

Development

Development

Development

Batteries

Capenhurst Research Center

Shell's Thornton Research Center

Development—Na-S

Development—Hydrazine & Methanol
Fuel Cells

Chloride Silent Power (Chloride Technical)

Development—Na-S

Joseph Lucas, Ltd.

Development—Zinc-Air

Central Electricity Research Labs

Electrode Research

Components

Electricity Council Research Center

Testing

GERMANY

Electric Vehicles

Rheinisch-Westfälisches
Elektrizitätswerk AG

GES (Gesellschaft für Elektrischen
Strassenverkehr mbH)

Technical University of Berlin & Karlsruhe
Messerschmitt-Bölkow-Blohn GmbH

Volkswagenwerk AG

Deutsche Automobilgesellschaft mbH

Siemens AT

Maschinenfabrik Augsburg-Nürnberg (MAN)
Technische Hochschule Aachen

Research—Hybrids, rapid battery
exchange

Research—Hybrids, rapid battery
exchange

Research

Development—Delivery van, plastic
chassis

Development—rapid battery exchange

Research

Commercial

Development—Bus

Research

Battery Fuel Cells

Siemens AG

Varta Batterie

Battelle Institut — Frankfurt

Fuel cell research

Battery development

Battery research

Components

Robert Bosch, GmbH

Power train development

SWEDEN

Electric Vehicles

Monark Company

Scandinavian Electric Vehicle, Secretariat

Research

Information Center

NORWAY

Electric Vehicles

Elbil, A.S.

Development

NETHERLANDS

Stored Heat

Phillips Research Laboratory

Development

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VIII. ELECTRICITY

E. Behrin

ELECTRICITY

- Electrical energy R&D falls into four categories: storage, transmission, topping cycles and fuel cells.
- Electrical energy storage is important for efficient utilization of existing generating capacity, and is the key to large scale use of intermittent energy sources such as solar, wind, and tides.
- Electric power transmission research is receiving increasing attention due to rapidly increasing electrification and accompanying right-of-way problems. Research activities are directed at high voltage A.C. and D.C. technology, and the development of underground cryoresistive and superconducting cables.
- Topping cycles increase the thermal efficiency of present thermodynamic cycles. Successful approaches will either increase the peak cycle temperature or make the existing cycle a better approximation of the Carnot cycle. Active research areas include high temperature turbines, magnetohydrodynamic (MHD) conversion and metal vapor (Rankine) cycles.
- Fuel cells are isothermal conversion devices not subject to the Carnot efficiency limit; they are primary electrochemical cells that convert part of the free energy of the reactants into electrical energy. Practical energy efficiencies range from 40% to 70%.

STORAGE

- Electrical energy storage is being used by electricity suppliers throughout the world to reduce the effects of demand fluctuation. Low cost off-peak energy is stored and then later recovered during peak demand periods.
- Pumped water storage is, at present, the only widely used energy storage technique. Pumped storage facilities exist throughout the world. By utilizing off-peak base load power, pumped hydro plants are capable of supplying peaking power at lower cost than gas turbines or quick-cycling steam generation.¹
- Pumped air storage is another energy storage concept.² This procedure utilizes base load energy to compress air in a underground cavity. During peak demand periods the air is released, mixed with fuel, burned, and expanded through a turbine to generate power. The first plants are to be built at Neuenhundertorf, FRG and near Husquvarna, Sweden.³ This technique may become important as pumped hydro sites become scarce.
- In addition to pumped air and water storage, electrical energy can be stored in many other ways. It can be stored directly in super conducting inductors.⁴ It can be stored as kinetic energy in flywheels.⁵ The steam generated by power plants can be stored, and converted at a later time.³ It can be converted to chemical energy in electric batteries,⁶ (see Transportation Section) or stored as hydrogen (see Advanced Energy Systems Section).

ELECTRIC POWER TRANSMISSION

- Foreign power transmission research in both high voltage and cryogenic transmission is widespread. There are research projects in industrial laboratories, government laboratories and universities.
- In Germany, AEG-Telefunken, Siemens and Brown-Boveri have formed the "Arbeitsgemeinschaft HGU" to conduct high voltage research jointly.¹
- In the U.K., the major high voltage research effort is at CERL, Leatherhead.
- A joint U.S.-Swedish research effort is underway in the area of ultra high voltage (above 800 KV) transmission. The principals are American Electric Power and Allmanna Svenska Electriska Aktiebolaget.²
- Superconducting power cables have been constructed in the U.K., Japan, France, Germany, Austria and the USSR.^{3,4}

ELECTRIC POWER TRANSMISSION

	England	FRG	Japan	Canada	France
	CERL	Siemens AG	CRI	IREQ	
High-voltage technology	Univ. of Manchester	FGH Brown-Boveri & Cie AG AEG-Telefunken		Univ. of Waterloo	
Cryogenic and superconducting technology	CERL BICC CEGB	Siemens AG AEG-Telefunken	CRI Furakawa, Elect. Co., Ltd.		CGE Electricité de France LCIE

Notes:

England

- BICC - British Insulated Callender's Cables (with CEGB)
- CEGB - Central Electricity Generating Board, Capenhurst
- CERL - Central Electricity Research Laboratory, Leatherhead.

Federal Republic of Germany

- FGH - Forschungsgemeinschaft Hochspannungs und Hochstromtechnik, Mannheim

Japan

- CRI - Central Research Institute, Electric Power Industry, Tokyo

Canada

- IREQ - Hydro-Quebec Institute of Research, Varennes

France

- CGE - Compagnie Générale d'Electricité, Marcoussis
- LCIE - Laboratoire Central des Industries Electrique

TOPPING CYCLES – MHD

- An MHD generator expands a high enthalpic, conductive working fluid through a magnetic field to obtain electrical energy directly from charged particle motion. Open cycle systems utilize seeded combustion gases as the working fluid. Closed cycle systems using seeded noble gas plasmas can be used with future high temperature reactors.
- Current MHD research is directed toward the development of reliable long life channels, increased combustion temperatures, more powerful (> 6 tesla) converter magnets, and better peripheral equipment (e.g., seed injectors and extractors).
- Major MHD research and development efforts were started in the U.S., USSR, Japan, FRG, France and the UK about 1960. Today the major efforts are underway in the USSR, Japan and the U.S.
- In Russia, the U-25 installation near Moscow was completed in 1971 and its cost was between 100 and 150 million dollars. This facility has produced between 2 and 3 MW_e over a 24 hour period.
- In Japan a 4 year, \$25 million dollar program is underway at the Electro-Technical Laboratory in Tokyo.
- U.S. MHD efforts are funded at a level of approximately \$5 million dollars per year by government agencies and the electric utilities. Major research activities are underway at Avco-Everett, G.E. Space Sciences Lab., Westinghouse Research Lab., STD Research, and a number of universities. A joint U.S.-USSR agreement calls for a U.S. designed generator channel to be tested in the U-25 facility some time in 1975.⁵

MHD

U.S.	USSR	Japan	FGR	Netherlands	Italy
Avco, Everett, Mass.	Inst. for High Temperatures of the USSR	Electro- technical Laboratory, Tokyo	Institut für Technische Physik der Kernforschungs- anlage, Jülich	Eindhoven Univ. of Tech.	CNEN Laboratorio Conversione Diretta, Frascati (Rome)
G.E. Space Sciences Lab. King of Prussia, Pa.	Acad. of Sci., Moscow Krzhizhanovsky Power Inst., Moscow		Max-Planck- Institut für Plasmaphysik, Garching		
STD Research Arcadia, Calif.	Research Inst. of the Ukrainian Acad. of Sci., Kiev.				
JPL, Pasadena, Calif.					
Argonne Nat. Lab.					

TOPPING CYCLES – HIGH-TEMPERATURE TURBINES

- Gas turbine (Brayton cycle) efficiency improvements have come from materials improvements and better blade cooling. Inlet temperatures have increased at a rate of about 20°F per year since 1959 to a present temperature of about 2000°F.¹ Most advances have come through developments by the aviation industry.
- Both in the U.S. and abroad, turbine research is carried on at government labs and universities. The major research efforts, however, are undertaken by the aviation industry.
- High temperature materials research is concentrated on refractory ceramics (silicon carbide and silicon nitride) and high temperature composites (boron and graphite). Current ceramics research is directed at solving the two major limitations of these materials; brittleness and high processing cost.²

HIGH-TEMPERATURE TURBINES

U.S.	England	FRG	Switzerland	France
Pratt & Whitney (United)	Rolls-Royce Ltd. UKAEA ⁽¹⁾	Technical University, Hanover	Brown-Boveri, Zurich	Centre d'Etudes Nucleaires de Saclay
Allison (G.M.)	National Gas Turbine Establishment	Brown-Boveri, Mannheim		AGARD ⁽³⁾ SNECMA ⁽⁴⁾
General Electric				
Norton Co. ⁽²⁾ Worcester, Mass.	British Nuclear Fuels, Warrington			
Lawrence Livermore Laboratory ⁽⁵⁾	Joseph Lucas Ltd. Solehall Advanced Materials Ltd., Newcastle Upon Tyne			

Notes:

- (1) United Kingdom Atomic Energy Agency
- (2) Exchange agreement with Joseph Lucas Ltd.
- (3) Advisory Group for Aerospace Research and Development
- (4) Société Nationale d'Etude et de Construction de Moteurs d'Aviation
- (5) Helical Rotor Expander

FUEL CELLS

- There is a growing European fuel cell research effort, although the major work is centered in the United States. The largest European program is a joint effort between Jersey Enterprises (EXXON) and Alsthom of France, based on Alsthom's hydrazine-hydrogen peroxide cells. There is a \$10 million, five year effort started in 1970.
- Industry funded programs exist at Battelle in Frankfurt and Geneva.
- The major U.S. effort is at Pratt and Whitney Aircraft where the "Target" program has developed 12 KW_e fuel cells in a program funded by the gas industry. A more recent P&W program funded by electric utilities is developing a 20 MW_e fuel cell power plant.

FUEL CELLS

France	FRG	Switzerland	England
Alsthom Res. & Dev. Lab., Massy	Battelle-Institut, Frankfurt	Institut Batelle, Geneva	Shell Research Ltd., Chester
Inst. Francais Petrole, Rueil-Malmaison	Siemens A.G., Erlanger		Energy Conversion Ltd., Basingstoke
Centre Recherches, Cie. Générale d'Electricité	AEG Telefunken, Berlin/Frankfurt		
Laboratoire d'Electrolyse, Bellevue	Univ. of Braunschweig		

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4. W.V. Hassenzahl et al., "Magnetic Energy Storage and Its Application in Electric Power Systems," IEEE intercon technical papers, *Energy Utilization and Control*, Vol. 3, 1973.
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Fuel Cells

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IX. ADVANCED SYSTEMS

Hydrogen

W. J. Ramsey

Geothermal

J. H. Howard

Solar

F. E. Edlin*

*Consultant

HYDROGEN SYSTEMS

- Recently, proposals for a "hydrogen economy" based upon nuclear or solar-powered production of hydrogen have been put forward.^{1,2} Primary energy would be converted to an intermediate, hydrogen, which could be stored and transported. Final use of the hydrogen would be in fuel cells to generate electricity or in direct use to make heat. System studies are going on in many countries, and two international conferences on the subject were held in the U.S. this year.^{3,4}
- For large-scale use of hydrogen to be feasible, a cheap, efficient method of production must be developed. Promising thermo-chemical cycles for hydrogen production have been proposed and are under investigation in the United States, the Federal Republic of Germany⁵ and Italy.⁶
- A novel photovoltaic scheme has been reported by Japanese workers⁷ and bio-conversion systems are under study in the U.S. and Japan.
- Hydrogen storage is another key element in a hydrogen system. Work on hydride storage is continuing in the U.S., the Netherlands,⁸ and Switzerland. Liquid hydrogen storage has been developed by NASA.

THE HYDROGEN ECONOMY

- System Studies
 - United States
 - Federal Republic of Germany
 - Italy
 - Japan
- Hydrogen Production
 - Electrolytic: Commercial Improvements
 - Thermochemical Cycles
 - United States: Laboratory Studies
 - Federal Republic of Germany: Laboratory Studies
 - Italy: Pilot Plant Studies
 - Japan: Plans
 - Photovoltaic and Bio-Conversion
 - United States and Japan: Laboratory Studies
- Hydrogen Storage
 - Metallic Hydrides
 - United States: Pilot Plant, Laboratory Studies
 - Netherlands, Switzerland: Laboratory Studies
 - Liquid Hydrogen: US-NASA Technology

GEOTHERMAL ELECTRICITY GENERATION

Country	History/Status	Plans	
		R&D	Exploitation
Italy	Electricity has been generated from clean steam since 1904.	Reservoir modeling	Greater use of the clean steam resource.
Japan	State of the art flashed steam systems will be used.	Refinement of flashed steam systems – “hands-on” approach	A large investment in geophysical prospecting and power plants is planned.
Mexico	State of the art flashed steam systems are in use.	Refinement of flashed steam systems	
New Zealand	Original flashed steam system development.	Refinement of flashed steam systems	
USSR	The only known binary heat exchange system is in use here; it utilizes waters at less than 100°C.		

GEOTHERMAL RESOURCE STUDIES AND HEAT APPLICATIONS

Country	History/Status	Plans	
		R&D	Exploitation
Iceland	Geothermal energy is an important part of the energy budget; space heating is the main application.	A "sea-chemicals" plant is under consideration.	Continued use of geothermal energy for heating needs
	Strong, on-going university work in global tectonics.	Direct contact heat exchangers are under development.	
Italy		Ways of using saline brines are being developed.	
		Reservoir modeling, especially aimed at further use of the clean steam resource.	
FRG	Earth physics program	Improved mathematical modeling	
Japan		Expanded use of reflection seismology to define geothermal prospects; initial results are promising.	
France	Space heating of 3000 apartments using "normal gradient" water.	Improve space heating technology.	
Hungary	Greenhouse heating.		
USSR	Greenhouse heating, 10^7 m ² of greenhouses are in use.		

SOLAR ENERGY RESEARCH

- Electric Power Generation
 - Thermal Conversion
 - France — Mirror system to raise steam
 - Israel — Salt-gradient solar ponds
 - Italy — Mirror system to raise steam
 - Direct Conversion
 - France — Thermoelectric, thermionic, and photovoltaic research
 - Japan — Solar cells with reflectors
- Agricultural Applications
 - Australia — Lumber, ore and crop drying
 - Canada — Greenhouse design for low sun angles
 - Japan — Solar-heated greenhouses
- Solar Distillation
 - Limited application on Greek islands
 - Small efforts in several countries
- Solar Furnaces
 - France — Refractory phase studies at Odeillo
 - Japan — Refractory phase studies at Nagoya
- Sun Studies
 - Sun measurement studies (heliopyranometry) are widespread
- Building Systems
 - Heating
 - Australia — Water heating
 - France — Air heating
 - Small efforts in other countries
 - Cooling
 - Australia — Evaporative cooling, gravel bed storage
 - France, Israel — Night sky radiation cooling
 - Iran — Evaporative cooling

- Solar Water Heating
 - Australia — Limited commercial production
 - France — Various designs under test
 - India — Several types in use
 - Japan — Many designs in use
 - Efforts in other countries, some under A.I.D. sponsorship
- Developing Country Applications
 - Niger — U.N. sponsorship of a project to use local materials for solar heating
 - Pakistan — A.I.D. project covering building heating/water heating
 - Iran — Building heating/cooling, solar distillation

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7. A. Fujishima and K. Honda, *Nature* 238 (5358), 37-8 (July 7, 1972). Work done at Kanagawa University, Yokohama, Japan.
8. Proceedings from Reference 3, p. 54-1, Work at Philips Research Lab., Eindhoven.
9. Work at Battelle Memorial Institute Laboratories, Geneva.

APPENDIX IX-1: INTERNATIONAL EXPERTS IN GEOTHERMAL RESEARCH

Iceland

K. Ragnars (non-electrical applications)

National Energy Authority

Reykjavik, Iceland

G. Bodvarsson (geological prospecting)

School of Oceanography

Oregon State University

Corvallis, Oregon 97331

Italy

E. Tongiorgi

University of Pisa

International Institute for Geothermal Research

55 Lungarno Pacinotti

Pisa 56100, Italy

France

P. Sangier

Office of Scientific and Technical Research

Paris, France

FRG

O. Kappelmeyer

Geological Survey of Germany

3 Hanover

Buchholz, Germany

APPENDIX IX-1: INTERNATIONAL EXPERTS IN GEOTHERMAL RESEARCH (Continued)

Japan

J. Suyama (electrical generation)

Geological Survey of Japan

135 Hisamoto

Kawasaki-shi

Takatsu-ku, Japan

K. Baba (geophysical prospecting)

Geological Survey of Japan

135 Hisamoto

Kawasaki-shi

Takatsu-ku, Japan

Mexico

J. Guiza

Geothermal Resources Department

Federal Electricity Commission

Rodano 14 - Piso 9

Mexico 5, D.F., Mexico

New Zealand

R. James

Department of Scientific and Industrial Research

Taupo, New Zealand

Hungary

T. Boldizar

Geothermal Board

Naphegy Utca 27

Budapest, Hungary

X. BIO-ENVIRONMENTAL RESEARCH

B. J. Berger

RADIOACTIVE WASTE MANAGEMENT

- Management of high level radioactive waste from reactor fuel reprocessing will be of increasing concern as nuclear power generation increases.
- Solidification of high level liquid wastes for permanent or permanent-temporary storage is the trend in most countries.
- Technology for converting high-level radioactive waste from liquid to solid form is still under development.
- A program of technological cooperation between the U.S. and West Germany will emphasize safe disposal of high-level radioactive waste. The program includes exchange of experts and joint use of facilities.
- Disposal of medium and low activity waste is a continuing problem due to high volume. France presently employs incineration, compaction, and concentrating methods superior to those employed in the U.S.⁽⁶⁾
- A panel of the National Academy of Science Committee on Radioactive Waste Management (CRWM) has been reviewing the status of waste management in various foreign countries for potential use in this country. The CRWM report is expected early in 1975.

RADIOACTIVE WASTE MANAGEMENT

Country	Present ⁽¹⁾ Nuclear Capacity (GWe)	Year 2000 ⁽²⁾ Nuclear Capacity (GWe)	Present Fuel Reprocessing Plants (owner, type, ⁽³⁾ capacity [t/a]) ⁽⁴⁾	Present Waste Management and Policy	Proposed Future Waste Management and Policy
Belgium	--	16.4	Eurchemic; Reprocessing ceased ⁽⁵⁾ June 1974.	Interim storage.	Solidification and engineered storage.
Canada	2.5	118.0	No reprocessing presently; pending change in status of uranium economy.	Spent fuel stored intact at engi- neered facility.	Reprocessing depends upon changes in uranium prices.
France	2.9	90.0	Commissariat à l'Energie Atomique: M 800 M 900-1200 D 900	Liquid storage in surface tanks.	Solidification and engineered storage.
W. Germany	2.3	130.0	Gesellschaft zur Wiederauf- arbeitung von Kernbrennstoffen m.b.H. (G.W.K.): D 35-50	Liquid storage in surface tanks.	Solidification into boro- silicate glass blocks and burial in salt deposit. ⁽⁶⁾
Italy	.6	70.0	Sent to UK for reprocessing at British Nuclear Fuels Limited (BNFL).		
Japan	2.2	220.0	Sent to UK for reprocessing at BNFL.	Interim storage	Verification
Sweden	.4	25.0	Unavailable	Liquid storage	Unavailable

UK	4.5	130.0	BNFL: M 2500 D 300	Liquid storage in surface tanks.	Solidification and storage in engineered structures.
USSR	3.0	400.0	Unavailable	Liquid storage in surface tanks.	Solidification and storage in engineered structures.
USA	35.0 ⁽⁹⁾	1090.0	See note (8)	Liquid storage in surface tanks.	Engineered storage at retrievable surface storage facility (RSSF).

Notes:

- (1) Bulletin International Atomic Energy Agency, Vol. 16, No. 1/2, 1974.
- (2) E.J. Hanrahan, Atomic Energy Commission Headquarters, private communication to R. Liptai, LLL, July 1974.
- (3) M = Metallic uranium; D = Enriched uranium dioxide.
- (4) The Nuclear Power Industry in Europe, American Nuclear Society, May 1972.
- (5) ECG/ERD June 1974 Report.
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- (8) Note *re* present U.S. capacity. At present there is no commercial power reactor fuel reprocessing capability. Fuel for AEC and military reactors is reprocessed at Hanford, Savannah River and Idaho, capacity figures are unavailable. Two commercial plants will offer services:

<u>Date</u>	<u>Company</u>	<u>Capacity</u>
1977	Allied Gulf Fuel Reprocessing Barnwell, South Carolina	1500 t/a
1979	Nuclear Fuel Services Valley Spring, New York	1000 t/a

- (9) E. Hill, "U.S. Nuclear Plants on Order," Lawrence Livermore Laboratory internal document, October 1, 1974.

MAN-MADE RADIONUCLIDES POSE NEW ENVIRONMENTAL HAZARDS

- The operation of a world-wide nuclear power industry will introduce transuranic elements and fission products to many countries for the first time.
- Normal operation of the nuclear power system will not permit release of hazardous materials, but a reactor, reprocessing plant or transportation accident might allow a release.
- Evaluating the hazard of transuranic releases requires research in three areas:
 - Physical/Chemical Studies
 - Physical form of the release
 - Chemical form of the release
 - Resuspension phenomena
 - Role of sediments as sources/sinks
 - Radioecology
 - Transport of radionuclides in terrestrial/aquatic environments
 - Dose-to-man
 - Health Physics
 - Effects on animals, including man
 - Inhalation, ingestion effects
 - Method of tumor induction
- Present knowledge of the biological consequences of non-transuranic elements is uneven. Transfer coefficients and concentration factors of tellurium, ruthenium and the rare earths are unknown. The environmental and biological behavior of technetium and other long-lived isotopes is not well understood.
- Technological developments must be monitored for potential new pathways to the biosphere. Disposal of radioactive waste is particularly important.

(See Appendix X-1 for a summary of research institutes.)

BIO-ENVIRONMENTAL RESEARCH ON RADIONUCLIDES

Country	Transuranics	Fission Products	
	Health Physics and Radioecology	Health Physics	Radioecology
Denmark			X
Belgium			X
Canada			X
Finland			X
France	X		X
Germany	X		X
India		X	
Italy	X	X	X
Japan			X
Monaco		X	
Sweden		X	
UK	X	X	X
USSR	X	X	X
US	X		X

HEALTH EFFECTS OF AIR POLLUTANTS

- Foreign research is rarely taken into consideration when U.S. air quality standards are set.
 - Access to foreign language papers is limited because the Air Pollution Technical Information Center only translates a paper upon request.
- Three main research approaches are prominent in air pollution work.
 - Epidemiological studies examine the statistical indices of health effects in exposed populations.
 - Clinical studies examine effects on individual humans.
 - Toxicological studies are laboratory investigations aimed at identifying specific biological mechanisms.

Research which integrates these findings, to help the standard-setting process, is required. Further research is required for specific population subsets, e.g. children, elderly persons, and chronically ill individuals.
- At present, standards are based on inadequate data and simplistic assumptions. The effects of combined factors, such as combinations of pollutants, temperature, sunlight, and humidity need to be considered.
- Air pollution has international implications. An example is the acid rain problem resulting from sulfur oxide and nitrogen oxide emissions.
- A major compendium on air pollution is under preparation by the Environmental Protection Agency. The two volumes will collect, tabulate, codify and analyze the world's air quality management standards.

COMPARISON OF AMBIENT AIR QUALITY STANDARDS*

Country	Sulfur oxides ^b (ppm)	Nitrogen oxides ^b (ppm)	Oxidants ^b (ppm)	CO ^c (ppm)	Total suspended particulates ^a ($\mu\text{g}/\text{m}^3$)	Comments
Canada	0.06	n.s.	0.025	5	60	Standards review under way.
Czechoslovakia	0.06	0.05	—	0.9 ^b	150 ^b	Small effort.
France	0.38	n.s.	n.s.	n.s.	n.s.	Emphasis on CO.
W. Germany	0.15	0.5 ^e	—	—	100 ^e	Strong laboratory effort; no epidemiology; emphasis on CO and inorganics.
Italy	—	0.1	—	20	300 ^b	Epidemiological effort.
Netherlands	0.03 [†]	0.05	—	—	—	Epidemiological effort.
Japan	0.04	0.02	0.06 ^d	20	—	Strong epidemiological emphasis; dominates APTIC** international literature on air quality control.
Sweden	0.10	—	—	—	100 ^d	Emphasis on metal pollutants (cadmium, mercury) and acid rain.
UK	No ambient air quality standards					Historically strong epidemiological effort continuing at reduced level; extensive air monitoring delayed.
USSR	0.02	0.045	—	0.9 ^b	150 ^b	Based on neurophysiological effects and modifications in biochemical, subsensoral, and electroencephalographic reactions; emphasis on behavioral approach.
US	0.14 0.03 ^a	0.05 ^a	0.08 ^d	8.6	75	Based on changes in morbidity and mortality.
WHO	0.02 ^a	Insufficient data	0.06	9	40	World Health Organization Expert Committee, 1972; Guidelines for air quality standards.

Superscripts:

a = annual; b = 24 hr; c = 8 hr; d = 1 hr; e = 30 min;
n.s. = no standard

*Countries may vary in their measurement techniques, making
comparisons of standards difficult.

** Air Pollution Technical Information Center.

† Limits vary with particulate level.

POTENTIAL AQUATIC ECOSYSTEM DAMAGE

- More intensive use of coastal and estuarine waters for oil drilling and fuel shipping will expose these critical areas to further pollution opportunities.
 - Sub-lethal and long-term effects of oil spills require further study.
 - Clean-up technologies for oil, methanol and other bulk-shipped fuels need to be perfected if presently unavailable.
- The effects of thermal emissions require further investigation.
 - Thermal tolerance at critical trophic levels, the potential for immigration, and the interaction of thermal and chemical stresses are important.
- Access to international aquatic pollution information is aided by the extensive literature which has been compiled on the subject. In addition to the normal academic literature, there are files on various spill histories, and summaries of the international agreements covering aquatic environments. Appendix X-2 gives sources of information on aquatic pollution.

APPENDIX X-1: RADIONUCLIDE ENVIRONMENTAL RESEARCH

Denmark	Radioecology	A. Amkrog	Danish Atomic Energy Commission, Research Establishment Riso, DK 4000 Roskilde, Denmark
Canada	Transuranics	J.G. Hollins	Division of Biology, National Research Council of Canada, Ottawa, Canada K1A 0R6
Canada	Radioecology	I.L. Ophel P.J. Barry	Biology & Health Physics Division, Chalk River Nuclear Lab., Atomic Energy of Canada Ltd., Chalk River, Ontario
Finland	Radioecology Non-Nuclear Pollution	J.K. Miettinen	Department of Radiochemistry, University of Helsinki, Finland
France	Transuranics Radioecology	J. Lafuma	Commissariat à l'Energie Atomique, Dept. de Protection, B.P. No. 6, 92 Fontenay-aux-Roses, France
France	Radioecology	A. Grauby	Departement de Protection, CEA, Centre d'Etudes Nucleaires de Cadarache, St-Paul-lez-Durance, France
India	Radioecology	P.R. Kamath	Health Physics Division, Bhabha Atomic Research Centre, Bombay, India
Italy	Transuranics Health Physics	F. Breuer	CNEN, Division of Health & Controls, Rome, Italy
Italy	Radioecology	A. Berg	Biology Division, EURATOM Joint Research Centre, Ispra, Italy
Japan	Radioecology		Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki-ken, Japan
Monaco	Radioecology		International Laboratory of Marine Radioactivity, IAEA, Principality of Monaco
Sweden	Health Physics	B. Lindell	Swedish National Institute of Radiation Protection, Stockholm, Sweden
England	Health Physics	F.W. Spiers	Department of Medical Physics, The University of Leeds, England
England	Health Physics		Central Electricity Generating Board, Berkeley Nuclear Laboratories, Berkeley, Glos., U.K.
England	Transuranics	G.W. Dolphin	Biology Department, National Radiological Protection Board, Harwell, Didcot, Berkshire, U.K.

APPENDIX X-1: RADIONUCLIDE ENVIRONMENTAL RESEARCH (Continued)

England	Radioecology	N.T. Mitchell	Ministry of Agriculture, Fisheries and Food Fisheries Radiobiological Laboratory, Hamilton Dock, Lowestoft, Suffolk
England	Health Physics	D.M. Taylor	Department of Biophysics, Institute of Cancer Research, Royal Cancer Hospital, Sutton, Surrey, England
England	Radioecology	R. Scott Russell	Agricultural Research Council Letcombe Laboratory, Wantage, Berks, United Kingdom
USSR	Health Physics	*	Radiation Hygiene Institute, The RSFSR Ministry of Public Health, Leningrad, USSR
USSR	Health Physics Transuranics	Yuri I. Moskalev	Ministry of Public Health of the USSR, Institute of Biophysics, Zhivopisnaya 22, Moscow, D-182, USSR
USSR	Health Physics	P.P. Lyarsky	Institute of Industrial Hygiene on Sanitations and Occupational Diseases, Academy of Medical Science, USSR

*Radioecology papers appear in Russian literature.

APPENDIX X-2: SOURCES OF INFORMATION ON
AQUATIC ENVIRONMENTAL ISSUES

Directory of Experts on Marine Pollution

FAO, Dept. of Fisheries, Fishery Resources Division
Via delle Terme de Caracalla
00100
Rome, Italy

The International Politics of Marine Pollution Control, R.A. Shinn,

Praeger Special Studies in International Politics and Government
Praeger Publishers, New York, 1974, 216 pages

Marine Pollution Research Titles

Marine Pollution Information Centre
Marine Biological Association of the United Kingdom
Citadel Hill, Plymouth, Devon, United Kingdom
Published monthly since August 1974.

International Index of Current Marine Pollution Research

Marine Biological Association of the United Kingdom
Citadel Hill, Plymouth, Devon, United Kingdom

A Bibliography on Marine and Estuarine Oil Pollution, September 1971

D.S. Moulder and A. Varley (Eds.)
Marine Biological Association of the United Kingdom
Citadel Hill, Plymouth, Devon, United Kingdom

Oil Pollution: An Index-Catalogue to the Collection of the Oil Spill Information Center, 1972,
published by the University Library,

University of California at Santa Barbara
Santa Barbara, California 93106

Oil Spill and Oil Pollution Reports

Marine Science Institute
University of California at Santa Barbara
Santa Barbara, California 93106

Ocean Research Index

Frances Hodgson Ltd.
P.O. Box 74
Guernsey, Channel Islands, United Kingdom

GS/rt

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