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ABSTRACT

Attention is focussed upon the unique qualities of high energy fission particles, and upon the fundamental limits to the direct removal of their kinetic energy by electrostatic means and by cyclotron resonance deceleration. Efficiencies of secondary and tertiary product ionization and excitation produced by fission particles are examined. The potential for delivery of power through various non-thermal modes is discussed, and the significant unknowns relating thereto are identified.

INTRODUCTION

Direct Energy Conversion Research in the 1950's

The early era of fission reactor development saw a wide range of concepts examined through the research and development stage. Homogeneous and heterogeneous designs employed fuels which were solid, liquid, gaseous, slurry, metallic oxide or carbide. Water, heavy water, graphite, organics, Be, BeO, ZrH_2, or plastics were used as moderators, and virtually every conceivable fluid of low cross-section was considered for use as reactor coolant.

A plethora of novel energy conversion schemes were also explored.[1,2,3] Reactors were built employing semiconducting thermoelectric convertors, and detailed designs were developed for reactors containing cascades of thermionic cells centered on uranium fuel elements to permit direct conversion topping cycles. Studies of fission-electric cell reactor designs were carried out wherein energetic fission particles would be made to do work directly on repulsive electric fields. Miley's comprehensive review[4] includes examination of the practical difficulties met with in this approach.

The Winner! - Prior Proven Technology

Early workers in the nuclear energy field were, for the most part, trained as scientists, not as engineers. In the 1950's, as the various reactor development programs began to move into the design and prototype construction stages, individuals trained as engineers were called upon to assume an increasing fraction of program responsibilities. It soon became evident to these people that the scientists' preference for a "sealing wax and string" laboratory feasibility approach was far removed from the engineering necessitated when long-term dependability became the controlling criterion. The submarine reactor program, in particular, found it necessary to move away from more novel designs toward a design with no uncertainties with respect to containment vessel integrity and materials compatibility. With a minimum number of novel ingredients, such a design was employed in the first nuclear power station, the Shippingport PWR (pressurized water reactor). A reactor utilizing basically similar technology, the Dresden BWR (boiling water reactor), became the second to provide steady feed to a commercial electric power grid.

After a few years operation of these reactors, it became clear to utility management that such light water cooled and moderated (LWR) reactors could be economically competitive with conventional fossil-fired steam power plants. The subsequent rapid acceptance and building of a large number of LWR's by utility companies soon made it apparent that the available U-235 resources would be committed before the end of the 20th century. The breeder then became vitally important as a research and development objective. Remaining thermal neutron research and development work was redirected toward fuel element life extension, matters relevant to reactor safety, fuel safeguards practice, spent fuel transportation and reprocessing, and toward the accomodation of long-term changes to be anticipated in LWR components. Little interest has been shown in further exploration of direct energy conversion for application to fission reactors.

Is There Undiscovered Gold to be Mined Here?

An important reason for the choice of the LMFBR (liquid metal cooled fast breeder reactor) over the GCBR (gas cooled breeder reactor) or the MSBR (molten salt breeder reactor) for the breeder development program was the availability of substantial data concerning the use of molten sodium as a low pressure, high temperature reactor coolant. This had been developed in the EBR (experimental breeder reactor) and in the now-defunct sodium-cooled graphite-moderated reactor (SGR) programs. The LMFBR offers the opportunity of gaining not only the low fuel cost of a breeder cycle, but also thermal efficiency comparable with that attainable in modern fossil-fired steam plants.

While the attainment of 40% thermal efficiency would provide an important gain over the 30%+ now obtained in LWR plants, the fact that nearly twice as much heat is thrown away at the power plant as is provided to the customers served by the electrical distribution network seems most regrettable. This becomes especially distressing in view of the Nation's growing energy shortfall. It should be pointed out that this limitation arises from the thermodynamic characteristics of the practical heat conversion cycle. It does not arise from a limitation in the attainable source temperature. The inherent energy of fragments emitted from the fission reaction corresponds to the equivalent energy per particle of a hypothetical working gas at a temperature of over a trillion degrees (10^{12} C); even fossil fuel flame temperatures are of the order of 1800° C.

GOING BACK TO THE SOURCE OF IT ALL

The Cascade of Energy Degeneration

Better than 94% of the fission energy is recoverable as heat transferred from the reactor core by the coolant. The remaining 6% escapes by way of the intransigent neutrinos and through the residual stored nuclear energy of radionuclides removed with the spent fuel. It should be noted that if direct conversion of fission particle energy only were employed, only about 83% of the energy will be tapped. Thus, even if 100% conversion efficiency were attained, less than 87% of the energy released in the reactor could be utilized in the cell, the balance would have to be removed as thermal energy from the reactor volume.

Fission fragments are projected isotropically into the fuel medium at sub-relativistic velocities with initial degrees of ionization ranging from 16 to 22.[4] The stopping power of the medium, dE/dr (Figure 1) decreases as the particle picks up electrons and loses its high degree of coulombic effectiveness for long-range interactions. Near the end of its range, the decrease in the stopping power reverses and it passes through a lower maximum value. This is a characteristic of fixed-charge particle behavior when the particle attains velocities approximately matching that of bound electrons within the medium. The transit lifetime of a fission particle within a condensed medium is about 10^{-12} second.

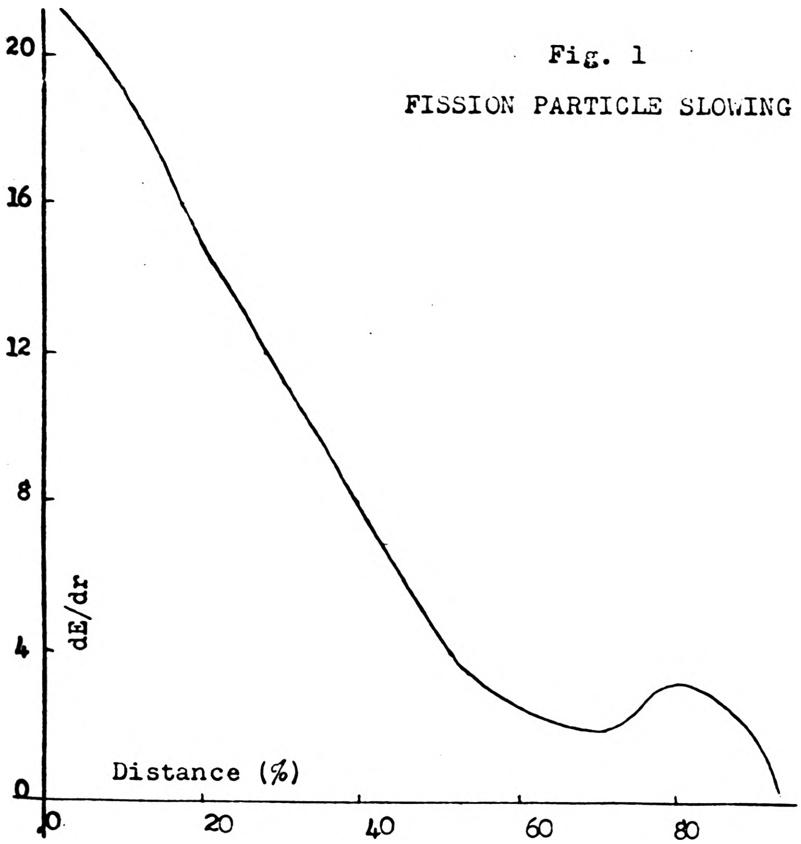

Fig. 1

FISSION PARTICLE SLOWING

The immediate depositories of fission particle energy in the medium traversed, in order of decreasing importance are

kinetic energy of heavy recoil atoms
excitation of recoil and non-recoil atoms
ionization of recoil and non-recoil atoms

If the fuel medium is UO_2, uranium atoms pick up about 60% of the recoil particle kinetic energy, and oxygen atoms about 40%. The recoil atoms have smaller charges than the incident fission particle, hence exhibit transit lifetimes of about the same duration as the primary fission particle (10^{-12} seconds). The internal excitation lifetimes for atom electronic states range from 10^{-14} seconds or longer for metastable states. Ionization states may show much longer lifetimes, persisting for up to 10^{-3} seconds in some cases.

The secondary recoil ion, in turn, traverses a branch path of its own, leading to deposition of its kinetic energy as

kinetic energy of tertiary recoil particles
excitation of electronic states
ionization

This and subsequent degradation of fission particle kinetic energy toward the ultimate conversion to electrical power through conventional thermodynamic working fluid driven turbogenerator means is shown graphically in Figure 2. Note that conventional energy conversion begins with coolant temperature elevation near the bottom of the cascade. The fission cell undertakes conversion of energy from the top of the cascade. It is the thesis of the present paper that the possible advantages to be gained by extraction of energy at intermediate levels of the cascade should be examined more thoroughly. In particular, two excitation levels having relatively long lifetimes; energetic free electrons and metastable excited electronic levels, should be given careful attention.

Dusty Corners

High temperature conversion devices without moving parts are the most conservative of the "wild schemes". The thermionic diode and the semiconductor thermocouple are two such. The inherent efficiency of both of these convertors is limited to less than 20% by the presence of by-pass modes of heat transport through conduction and thermal radiation. Design of such delicate electrical devices for long-term in-reactor operation appears formidable.

The same type of problem haunts the in-reactor fission electric cell. While the fission fragment slows in a medium while exhibiting an average electron charge of seven from an initial energy of about 90 million electron volts, it may entrain a cloud of possibly forty attendant electrons. As a consequence, special electrostatic or magnetic deflectors must be used to divert the electrons if the electrostatic energy of the fission fragment is to be collected. In his monograph[4], Miley recounts the many problems met with in this undertaking. Standing back of all again is the haunting spectre of the impossibility of maintaining high electrostatic potential gradients and stable electrical insulation in an intense radiation environment.

JUST SUPPOSE

Electron Cyclotron Resonance Maser

The author of this paper has proposed the induction of coherent cyclotron resonance emission from within a plasma whose high electron temperature is maintained by fission fragment ionization. To permit any appreciable energy yield, ω_{ce}/ν would have to be appreciably greater than unity (ω_{ce} being the electron cyclotron resonance frequency and ν the electron scattering frequency). A large superconducting coil surrounding the reactor would allow the achievement of a fairly uniform magnetic field of 4 teslas within the core, yielding ω_{ce} for electrons of

$$\omega_{ce} = \frac{eB}{m} = 7 \times 10^{11}\ sec^{-1}$$

The peak kinetic energies of recoil electrons trapped within this field would be 400 eV, corresponding to velocities of 1.3×10^7 m/sec. For electron collison frequencies to be less than $7 \times 10^{11} sec^{-1}$, the electron mean free path will have to be greater than

$$\lambda_{coll} = v/\omega_{ce} = \frac{1.3 \times 10^7}{7 \times 10^{11}} = 1.9 \times 10^{-5}\ \text{meters}$$

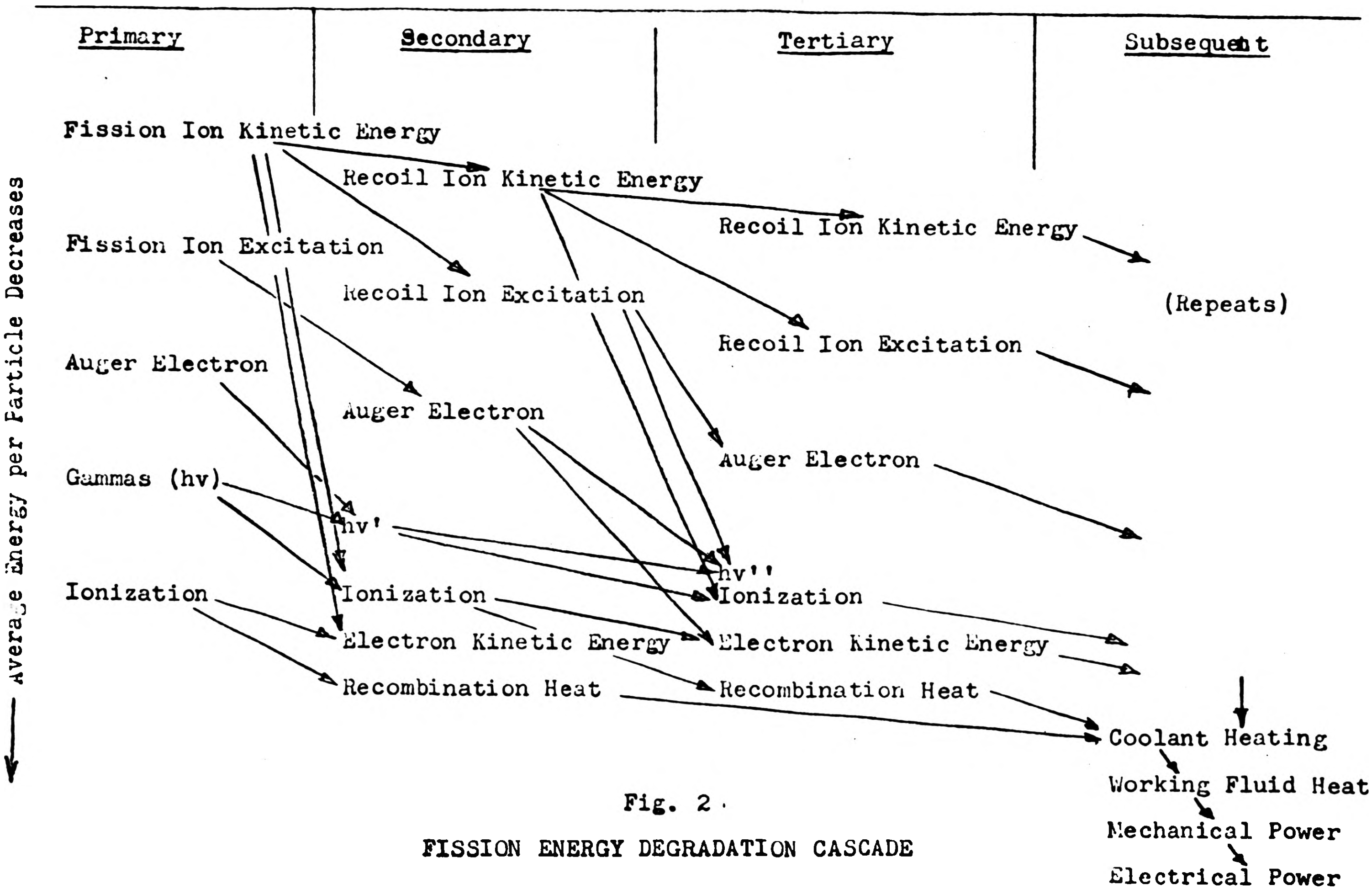

Fig. 2

FISSION ENERGY DEGRADATION CASCADE

This condition would be met in a 700°C (1300°F) alkali metal vapor at 1/10 atmosphere pressure,[6] and presumably would be approximately met by a fissile gas (say U^{235} Cl_4) under these conditions. To meet criteria for criticality such a reactor would have to be at least 10 meters in diameter and be surrounded by an efficient neutron reflector.

The wavelength of the cylotron resonance radiation existant as standing waves in the active gaseous medium will be of the order of 0.3 mm. To permit such a wave to build up to a self-sustaining level in the fissioning medium, it will be necessary to provide a high-Q multimode sub-millimeter microwave cavity within a reasonably uniform magnetic field. The homogenous reactor core will permit the advantages of continuous core fuel reprocessing (Figure 3). It remains to be seen just how multi-megawatts of submillimeter microwave power could be distributed and utilized.

X-Ray "Light Bulb Reactor"

The symbol "hν" in the cascade diagram (Figure 2) represents radiationless transfer of quanta from one ion to another in solids and liquids. It represents the exchange of visible, ultra violet, X-irradiation and γ-irradiation in gases. If the gas within which fission particles are being decelerated is highly ionized, say +6 on the average, the electromagnetic spectrum of excitation relaxation radiation will be shifted toward shorter wavelengths. This opens the possibility of removal of a significant fraction of energy from the active core as X-radiation.

Such a highly ionized gas could be contained through the use of magnetic fields, in a manner similar to that used to contain a fusion plasma of deuterons and tritons in the CNF (controlled thermonuclear fusion) program. Much of the work done in this program could be used in studying the feasibility of such an XLR concept.

Metastable Species

The clearing of political obstacles preventing the construction of a pipeline to the north slopes of Alaska was an important step in helping alleviate the immediate petroleum shortage in the contiguous forty-eight states. It also opened an important option for manufacture in northern Alaska of other commodities amenable to pipeline shipment. The possibility of achieving a nuclear power reactor design wherein an appreciable portion of the fission energy is converted to energy of metastable chemical species will be greatly

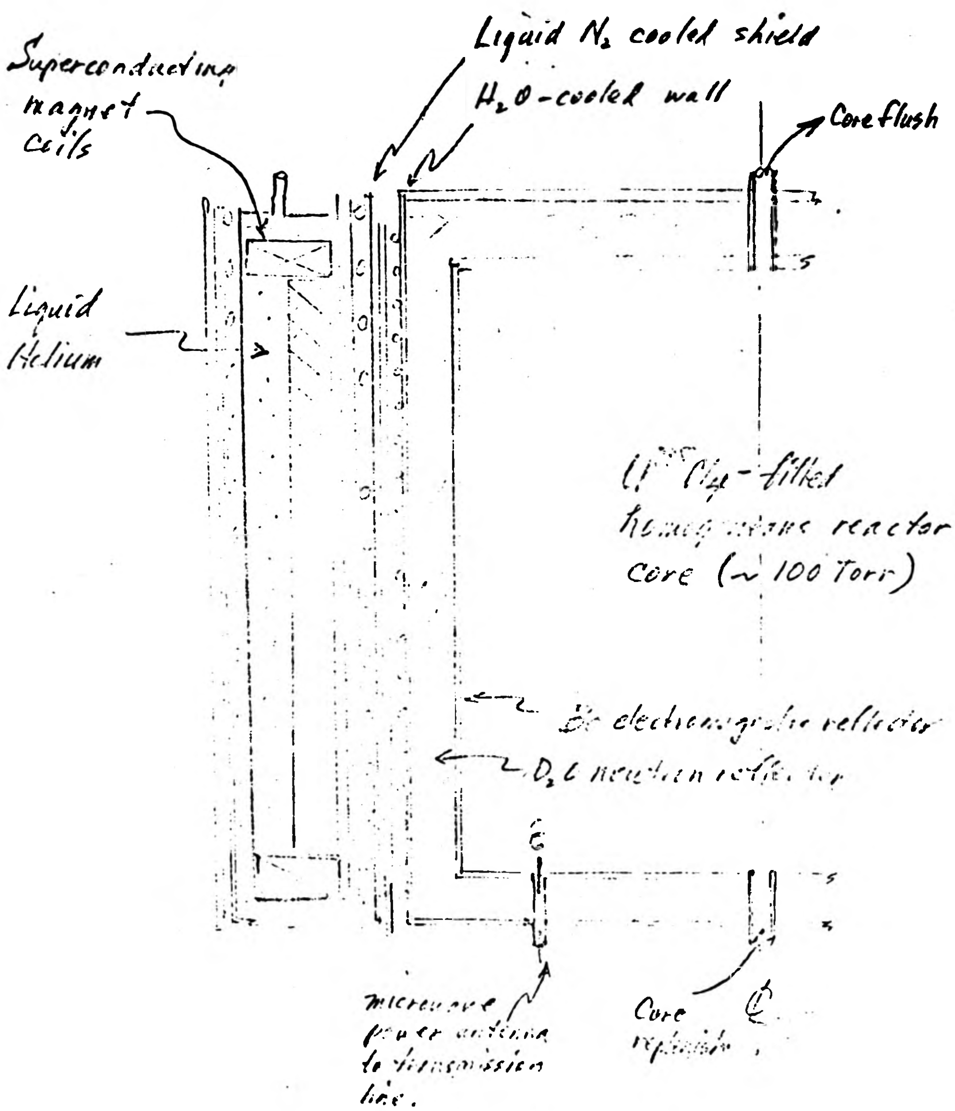

Fig. 3

ELECTRON CYCLOTRON RESONANCE
NUCLEAR GENERATOR

enhanced by operating the reactor at very low temperatures. The availability of the neighboring Arctic Ocean would make this feasible. Logistics of nuclear fuel supply to such a remote region would not be a problem, because of its small volume. If yet lower heat rejection temperatures are desirable, shepherding icebergs to the heat rejection interface with tugboats seems a viable possibility.

There is already at hand considerable experience with the forming of metastable species whose excess energy is derived from the fission process. While it is regarded as a nuisance, we must contend with the low temperature synthesis of undesired hydrogen in boiling water reactors. We also commercially produce polymers within intense gamma or beta fields. As in those cases, the exceedingly high excitation density achievable in the fission particle or recoil particle tracks will permit unique free radicals to be formed. Such "excitocules", when identified for various gases thus "intimately" irradiated, will open up a variety of possibilities for plasma chemistry sythesis and for pumping of chemical lasers.

Where May Break-Throughs be Sought?

If any of us had the answer to the question, we would be at home working instead of talking with one another here. Four basic research areas seem to hold promise for opening the doors to the intermediate energy conversion area of Figure 2. Despite limited immediate applications interest, intensive investigation of processes in fissile gaseous media should be undertaken. In addition to studies of neutron multiplication, scattering and absorption processes, the kinetics of the massive ion "tree" need be subjected to theoretical and experimental investigation. This should include ancillary description of ionization and excitation states produced and their decay processes through emmission of Auger electrons and photons. The behavior of the free electron gas should be determined experimentally using established plasma diagnostic techniques.

Thirdly, the behavior of an optically active medium which exhibits regenerative cyclotron resonance in a magnetic field should be explored. Such work may be performed initially using media excited by non-radioactive ions or by electromagnetic radiation. Systematics of active microwave cavities operating in high order modes need to be examined theoretically and experimentally. The qualities of low-loss surfaces made of corrosion resistant low cross section materials must be examined.

Lastly, the radiation chemistry of the production of free radicals by highly ionized particles has been given only limited attention by chemical engineers. The high efficiency of fission particles for the production of persistent radiation damage in solids is well known to reactor materials engineers. A systematic examination of the mechanisms of production of metastable species at moderate temperature in both inorganic and organic compounds promises to yield results of interest both to researchers and to applications engineers. Of most immediate concern is the vital need for the production of synthetic high energy content gases or liquids by irradiation of low energy content parent products.

In Summary, Are These Programs Feasible in a Lengthened Time Scale?

The exigiencies of the politics of government-sponsored research are well known to most of us. However basic a piece of research may be, it must nevertheless demonstrate a relationship to a useful product within about five years -- or else! The controlled thermonuclear fusion research program is one of the few surviving exceptions to this general rule. Its survival is no doubt attributable to widely publicized competitive undertakings in the Soviet Union. As a result of this general truism, the research work described above would best be pursued at a scale not requiring expensive, extensive Federal government sponsorship. Fortunately, the University of Missouri is well equipped to undertake this. On its Rolla campus it has an excellent medium power research reactor (Figure 4) within which much of the exploratory work on plasma chemistry could be undertaken. At Columbia an aggressive and innovative engineering program will permit the use of the high flux MURR (Figures 5,6,&7) for studies of electron behavior in a fission-excited gaseous medium in a magnetic field. This program will require a special amendment to the reactor license, since fissile material will need to be irradiated in the experimental volume.

While "break-throughs" can be hoped for, the program outlined should proceed on a time scale of at least two decades, and should entail strong interaction among nuclear engineers, plasma physicists, radiation chemists and materials technologists on all MU campuses. It will, I hope, reveal a truism which lies back of all successful applied science: great inspirations occur to those who accumulate adequate theoretical and experimental background. In a new field of knowledge, this can be built up only by blood, sweat, tears and time!

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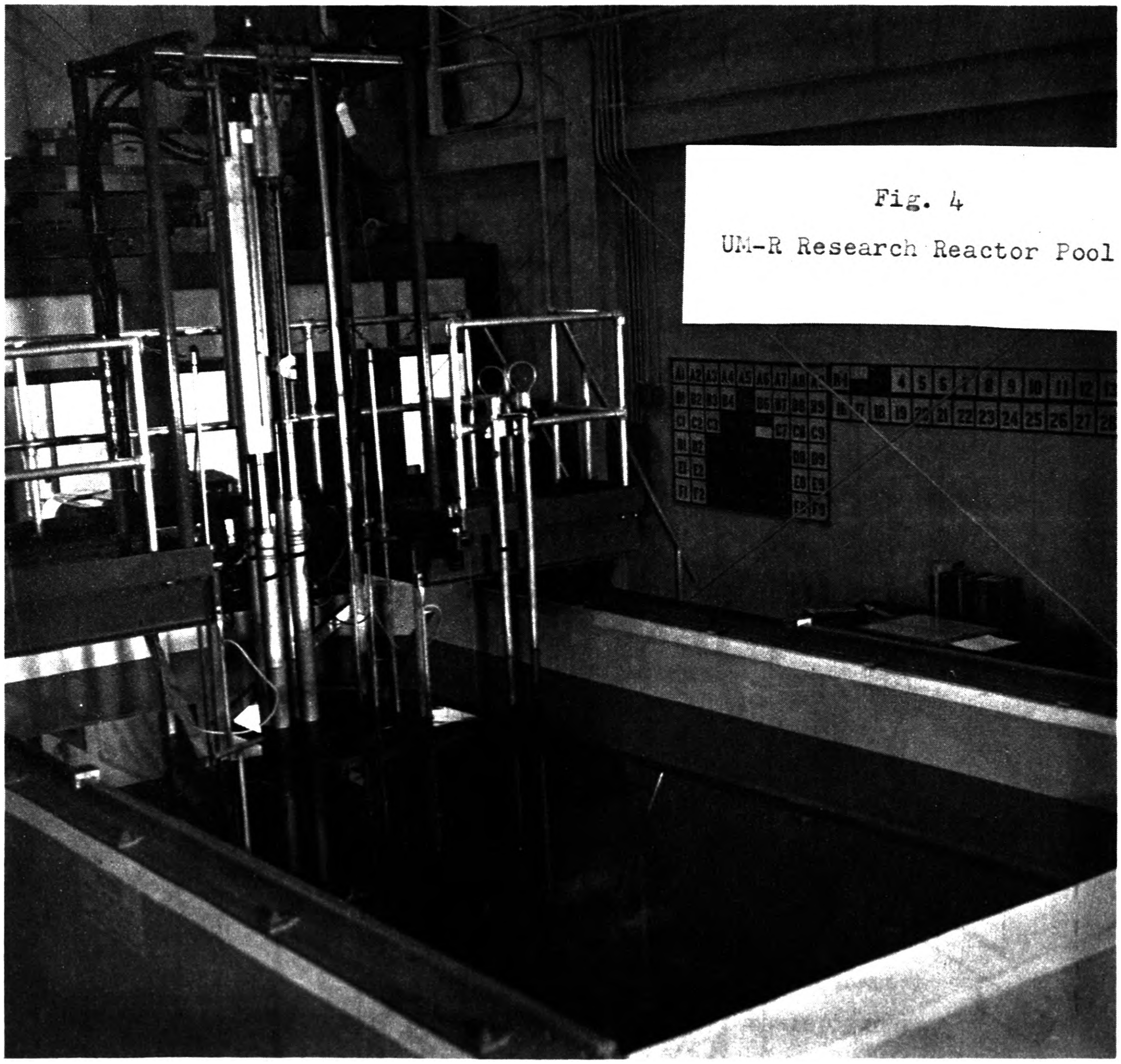

Fig. 4

UM-R Research Reactor Pool

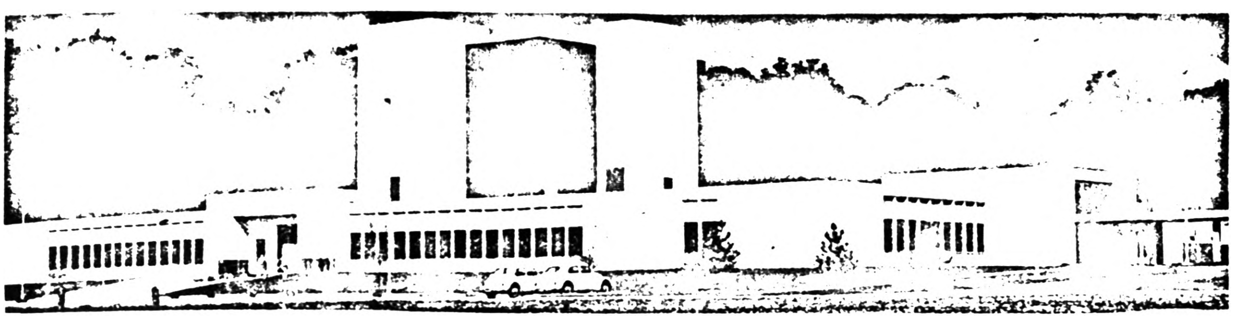

Fig. 5

Outside View, MURR Columbia

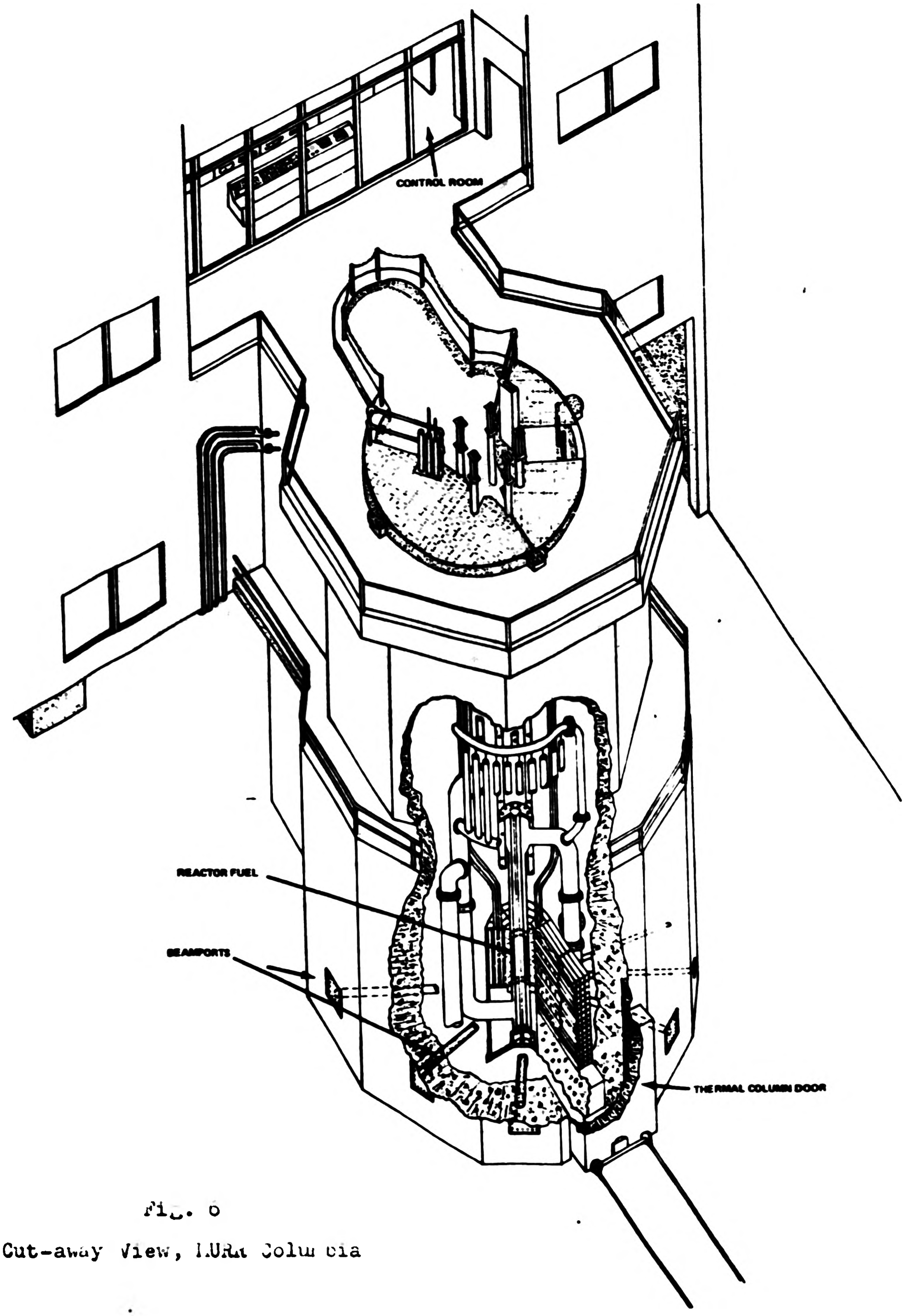

Fig. 6

Cut-away View, MURR Columbia

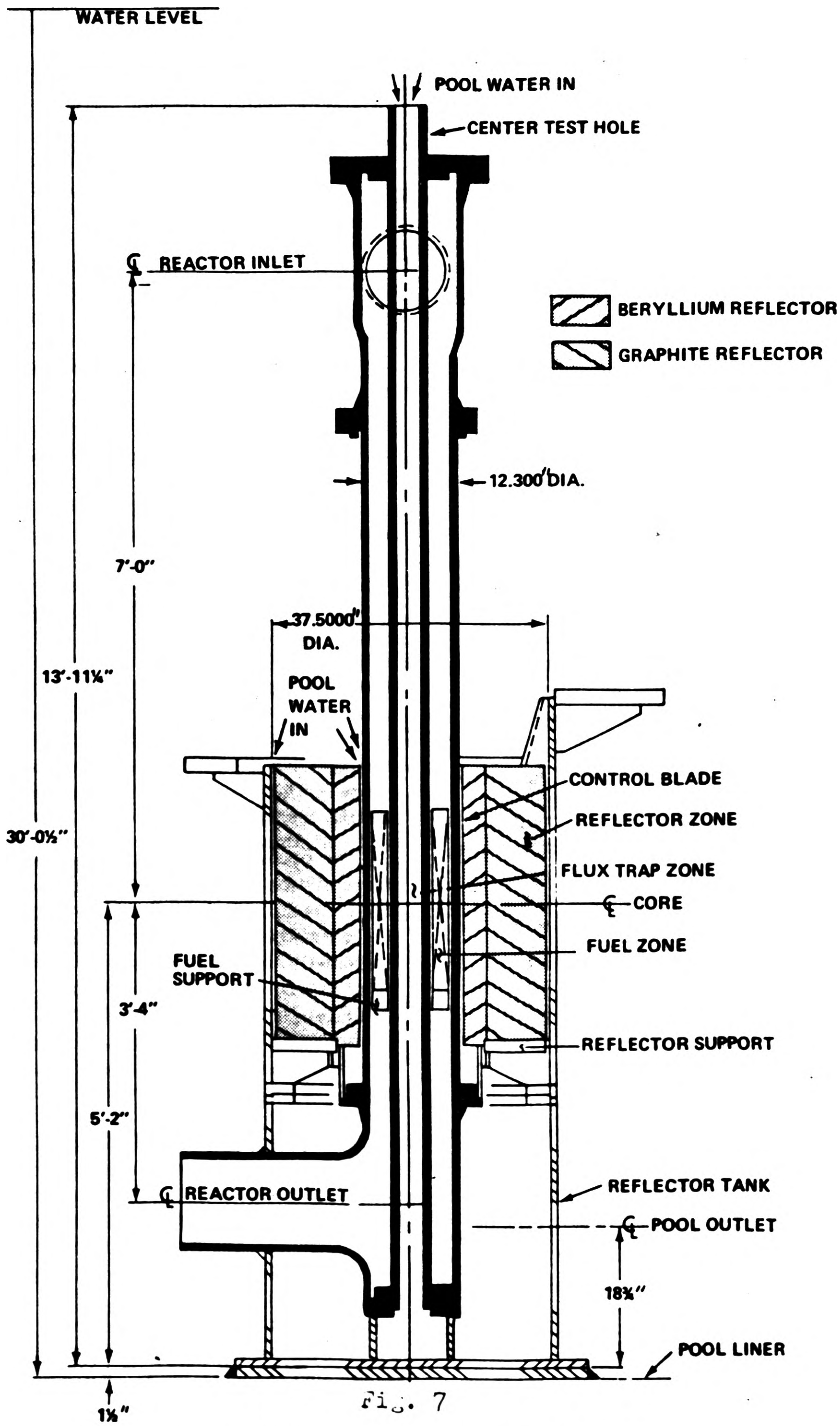

Fig. 7

Section of the Core and Reflector
MURR Columbia