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"RESEARCH ON FISSION INDUCED PLASMAS AND NUCLEAR PUMPED LASERS AT THE LOS ALAMOS SCIENTIFIC LABORATORY"*

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INTRODUCTION

A program of research on gaseous uranium and uranium plasmas is being conducted at The Los Alamos Scientific Laboratory under sponsorship of the National Aeronautics and Space Administration. The objective of this work is twofold: (1) to demonstrate the proof of principle of a gaseous uranium fueled reactor, and (2) pursue fundamental research on nuclear pumped lasers. The relevancy of the two parallel programs is embodied in the possibility of a high-performance uranium plasma reactor being used as the power supply for a nuclear pumped laser system. The accomplishments in the two above fields will be summarized herein.

GASEOUS CORE REACTOR

For many years the National Aeronautics and Space Administration has supported research and development programs on nuclear systems for space applications. One of these programs is an advanced reactor concept, a gaseous fuel nuclear reactor. The research branch of the U.S.-NASA, Office of Aeronautics and Space Technology, is conducting a program of research directed at developing the technology necessary for a multimegawatt uranium

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plasma core reactor. Although the basic goal of this work is for space application, other NASA-sponsored work suggests several attractive applications to help meet earth-bound energy needs.[1] Operation of a reactor core at uranium plasma temperatures opens the possibility of working systems with higher thermodynamic efficiencies than conventional reactors. Recent interest in the gaseous fuel reactor concept has expanded to include the use of uranium hexafluoride instead of uranium plasma as the fuel. With uranium hexafluoride as fuel, applications other than rocket propulsion are possible: the most significant is power, both in space and on earth.

The major design features of the gaseous core reactor are a reflector-moderated cavity containing fissioning plasma that is isolated from the cavity walls by hydrodynamic forces of an inert buffer gas. Reactor control is accomplished by rotatable control drums located in the reflector, and extraction of power may be accomplished by one of two methods. A heat exchanger of conventional concept can be used to cool the gases that are recirculated through the cavity. A second method is the removal of radiant energy (photon flux) through an optically transparent port. Attention is drawn to three fundamental features of the gaseous fuel reactor system which are: (1) gaseous flowing fuel, (2) the high neutron economy of the reflector-moderated cavity, and (3) the possibility of nonequilibrium optical radiation (i.e. optical radiation differing from the Maxwell-Boltzmann distribution of the characteristic core temperature). These features make possible some beneficial characteristics such as (a) small critical mass, (b) fuel circulation and on-site processing,

(c) burnup of transuranium actinides, (d) high fuel burnup, (e) high power generation efficiency, (f) breeding of ^{233}U from thorium, (g) low fission fragment inventory in reactor core, (h) high temperature for process heat, (i) optical radiation for photochemistry and space power transmission, and (j) high temperature for advanced propulsion systems.

early as 1955 consideration has been given to the possibility of producing nuclear energy by fissioning fuel in the gaseous state.[2,3] Following the detailed development of reflector-moderated reactors[4] significant confirmatory experiments were performed.[5] This sequence of work on spherical systems emphasized the importance of designing a system having a very high neutron economy. It demonstrated that benchmark experiments were very valuable accompaniments to the development of calculational methods needed to predict reactor performance. Additional research performed on cylindrical geometries is substantive for calculational verification.[6,7]

A program was instituted to demonstrate the feasibility of a gaseous ^{235}UF$_6$ reactor of cylindrical geometry.[8] The program is being conducted by investigation of critical configurations at The Los Alamos Scientific Laboratory and the development of uranium hexafluoride handling techniques and equipment by the United Technologies Research Center. Maximum utilization is being made of equipment and technology developed for the solid core nuclear rocket engine program (ROVER). Figure 1 is a schematic of the reactor experiment.

Initial experiments established the critical neutronic characteristics of the cylindrical gas core configuration. Zero power mockups were constructed using uranium foil to achieve the first criticality. Power distribution measurements were performed, control rod calibrations made, and reactivity worths determined for various structural materials. These initial scoping experiments were performed in a sequence of four steps. The first step was a configuration of the uranium foil arranged in a homogeneous distribution throughout the one meter diameter by one meter tall cavity of the reactor. The critical mass for this configuration was found to be 19 kg of 93.2% enriched uranium. The second step was a redistribution of the fuel to provide a uranium foil liner of the cavity. The critical mass remained about 19 kg as predicted by calculations. The third step was to add a beryllium flux trap resulting in a configuration which was critical with only 6.84 kg. The fourth, and final step, of this series was to provide a configuration whereby a canister containing uranium hexafluoride gas could be inserted in the center of the cavity region. This was accomplished by surrounding the beryllium flux trap annular ring with solid fuel.

The scoping experiments were followed by investigations using uranium hexafluoride gas. A canister was pressurized with uranium hexafluoride gas, inserted in the Be reflector, and critical measurements performed. The first phase is referred to as the static fill experiment and the equipment is diagrammed in Figure 2. Figure 3 shows the actual canister and gas handling system removed from the reflector assembly. A number of critical tests were made where additional uranium hexafluoride was added to the canister. Reactivity was adjusted by the removal of solid fuel from the exterior of the flux trap ring to compensate for the addition of gaseous fuel. Results of these experiments showed that no radiation induced chemical instabilities were produced by runs up to 1000 watts. In addition, experience was gained in the techniques required for the handling of uranium hexafluoride gas at somewhat elevated temperatures.

The next phase of work with the gas system was to perform experiments with recirculating uranium hexafluoride. A system was constructed to produce gas recirculation in race-track closed loop fashion. Its purpose was to investigate the effects on reactivity caused by fluctuations in either gas flow rate or in the gas pressure. The equipment used in the flowing gas experiment is shown in Figure 4. The canister is shown connected to the gas handling system by flexible lines and is raised into the reflector to perform the critical tests. As was the case on the static experiment, this system was equipped with double wall containment. Hot nitrogen gas circulated through the outer wall cavity and maintained the uranium hexafluoride gas at an appropriately high temperature.

The static experiments showed us that, from reactivity considerations, there would be an advantage in configuring the reactor design such that the gas would be contained in seven cells - a central cell surrounded by six others. Figure 5 illustrates this concept. The experiments are thus a mockup of the central cell. Monte Carlo calculations predict a critical mass for this configuration of approximately 4.9 kg. The target of the recirculating gas experiment was to have a uranium inventory of 700 g in the canister. For safety reasons, the initial tests of the recirculation systems were conducted with a uranium hexafluoride inventory of approximately 30 g and a mass flow rate of

1.2 g/second. The fuel loading mass flow was increased in a step-wise fashion to the final values of 700 g and mass flow rate of 50 g/second.

The final phase of the experimental program calls for the demonstration of buffer gas vortex flow confinement of the fissioning uranium hexafluoride fuel. The cutaway diagram shown in Figure 6 illustrates the flow pattern for this test, while Figure 7 is the gas handling system, and Figure 8 is the reactor core canister. Argon buffer gas is injected through the slot shown along the length of the fuel canister. Most of the argon flow exits through a perforated section in the canister wall after one sweep around the circumference of the canister. The remainder of the argon, along with the uranium hexafluoride fuel is removed from the canister through an exhaust port located at the center of the end wall. Injectors located just outboard of the exhaust port inject uranium hexafluoride continuously into the swirl pattern of the reactor core.

The effluent from the exhaust aperture is a mixture of buffer gas and gaseous fuel. Although initial critical tests will be made with gas flow in a blowdown mode, provisions are being made for continuous operation where the fuel and buffer gas will be separated on-line for loop operation.

A schematic diagram of the overall flow system, omitting cleanup devices for fission product removal, is shown in Figure 9. It consists of four major subsystems.[9] The first is the core canister with the vortex chamber, similar in size to the one used in the prior static and flowing uranium hexafluoride tests. The second is the argon buffer gas circulation system, the third is the uranium hexafluoride injection system, and the fourth is the uranium hexafluoride separation and reprocessing systems.

From the vortex chamber, most of the uranium hexafluoride fuel enters a separator and condensor in which the uranium hexafluoride will be desublimed and thereby separated from the argon and helium. Separated from the other gases, the uranium hexafluoride will be liquified and then pumped back to the injection pressure. The reclaimed uranium hexafluoride will then be reconditioned for reinjection into the core canister. The residual gases from the uranium hexafluoride separation will be stripped of any trace quantities of uranium hexafluoride by passing the gases through a NaF chemical trap. After the helium is separated from the argon in a cold trap, it is recompressed to injection pressures and is available to be added to the uranium hexafluoride for reinjection into the vortex chamber. In a similar fashion, the argon is reclaimed for continuous use as a buffer gas. The reprocessing of the uranium hexafluoride fuel stream with regard to separation of fission products and the handling of transuranium elements is not considered in this system. In the current uranium hexafluoride reactor experiments their quantities are too small for engineering studies. In addition, techniques for the reprocessing of nuclear fuel are well developed and only need to be optimized for gaseous-fuel reactor application.

NUCLEAR PUMPED LASER

One of the possible applications of the gaseous uranium core reactor is its use as a power supply for a nuclear pumped laser. The motivation for NASA's interest in the nuclear pumped laser is its potential future applications in space for transmission of power or long-range communications. Accordingly, research has been conducted to investigate the fundamental physics involved in the production of laser light output caused as a direct result of the fission process or other nuclear reactions. Although interests and activities were initiated in the early 1970s, experimental results did not become available in quantity until 1974. Table I is representative of the experimental nuclear pumped laser activities since that time.

The equipment shown in Figure 10 is the experimental apparatus used in early nuclear pumped laser studies at LASL. The LASL Godiva IV prompt burst reactor (bare U(93%) enriched) is seen at the right side of the picture, in close proximity to the nuclear pumped laser located at the left. Neutrons emanating from Godiva during a prompt burst (typically 3 MJ) illuminate the laser apparatus, causing fission of uranium foils or coatings located on the inner wall of the cavity. Initial experiments studied effects of fission fragments interacting directly with the lasant gas (He-He). Later studies were conducted on systems containing ^{3}He and no uranium. Subsequently, other systems were studied including liquid lasants,[10] and also a nuclear pumped flashlamp laser.[11] Figure 11 shows a schematic of the nuclear pumped flashlamp laser concept. Fissions produced in the UO_2 inner-coating of the flashlamp cavity provide efficient excitation of the He-Xe annular flashlamp. Photon excitation of the CF_3I laser results in substantial output from the iodine laser. Detailed results of this work is referenced.

A concurrent fundamental research effort is the performance of a gain measurement on a gas dynamic laser. The objective is to measure the absolute efficiency of fission fragment excitation of a cold gas dynamic laser. Figure 12 gives the schematic arrangement of the experiment. A GDL nozzle is depicted in close proximity to Godiva IV, where the lasant gas at ambient temperature enters the convergence side of the nozzle from the left. The gas is excited by fragments from induced fissioning of a uranium coating inside the nozzle. A transverse laser beam from a probe laser is used to measure gain in the downstream nozzle section. Lasant gases of interest are CO and CO_2. Reference 12 gives detailed status of this current work.

With regard to utilization of the plasma core reactor concept as a power supply for a nuclear pumped laser, two concepts can be pointed out. The first becomes apparent when one realizes the constituents of an inert buffer gas confined fissioning uranium plasma. At the uranium-buffer gas interface there is the condition of fission fragments interacting with the buffer gas. It is therefore attractive to optimize conditions in this interacting zone with the goal of producing efficient lasing action in the buffer gas.

A second concept arises with the realization of an intense photon flux produced by the fissioning uranium plasma. The concept is to utilize the photon flux for excitation of a laser. Figure 13 is the schematic of a seven-cell plasma core reactor. Each cell is contained within a transparent wall which isolates the working fluid annulus. The objective now becomes to produce a sufficiently efficient photon-pumped laser within the confines of the working fluid annulus. Consideration is being given to perform investigative work relevant to these concepts.

CONCLUSIONS

The gaseous fueled reactor system has the potential of several distinct advantages as an advanced power source. Because of these advantages it appears possible that this may be an ideal reactor for power production and for space propulsion. Characteristics such as high operating efficiency and low uranium inventory are particularly attractive. Advances in certain technology areas must be accomplished before it will be possible to produce an engineering design for a gaseous fueled power station. Corrosion problems of fluorine and uranium hexafluoride with materials must be solved, however, recent advances indicate these problems are not insurmountable. The vortex flow of buffer gas confinement obviates the most severe environment in the flow system. The feasibility of such confinement has been demonstrated successfully for small-scale devices and the present experimental activity is aimed at demonstration of the principle in the reactor environment at moderate power levels. Concurrently, efforts are being made to address the problems of adapting the gas core reactor concept to be used as a power supply for nuclear pumped lasers. Experimental and theoretical work is producing better understanding of fundamental phenomena, however further progress must be made before engineering problems may be addressed. Continued work in this field is particularly interesting to NASA because of the potentially important benefits in space applications.

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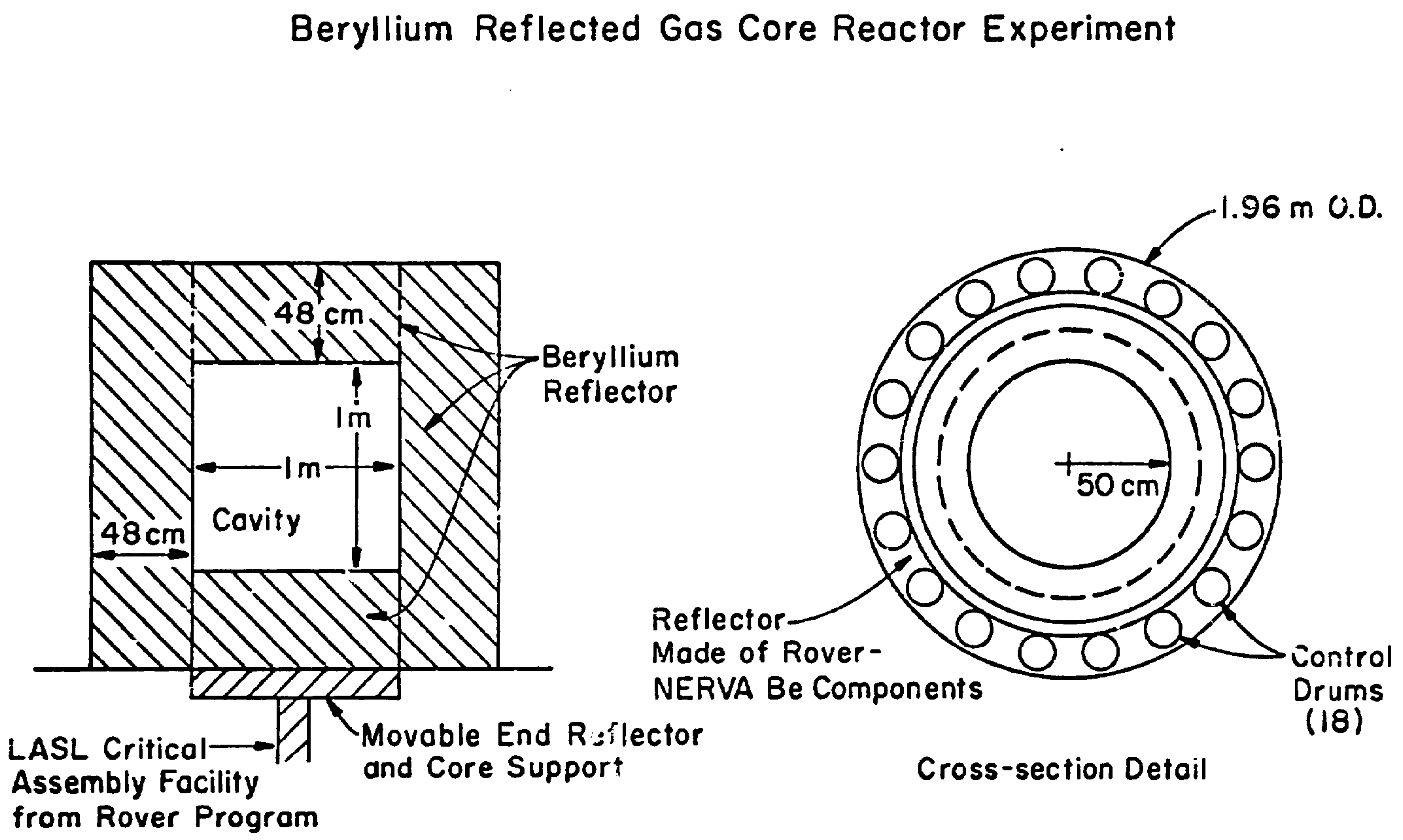

FIGURE 1

Beryllium Reflected Gas Core Reactor Experiment

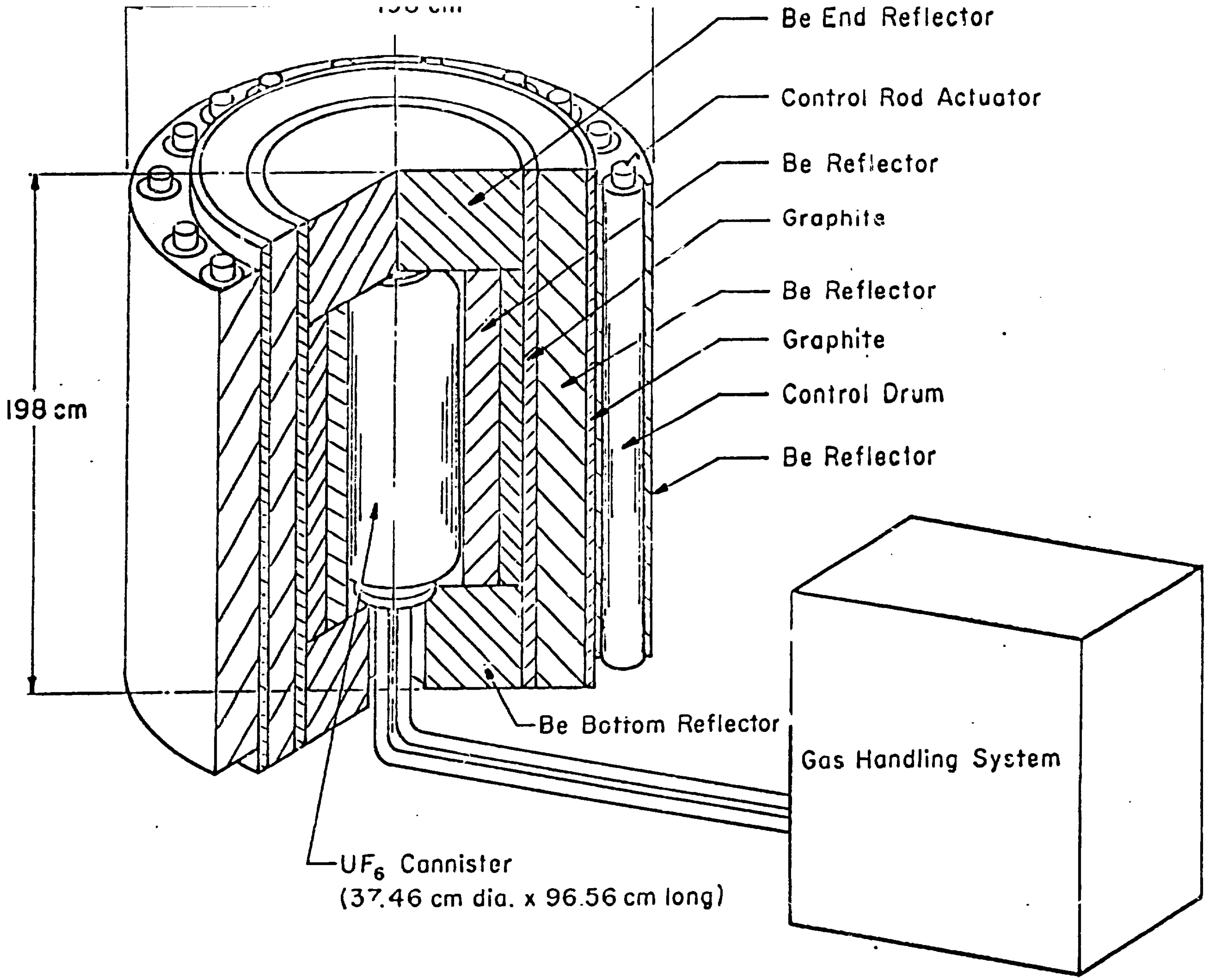

FIGURE 2

Gas Reactor Experiment

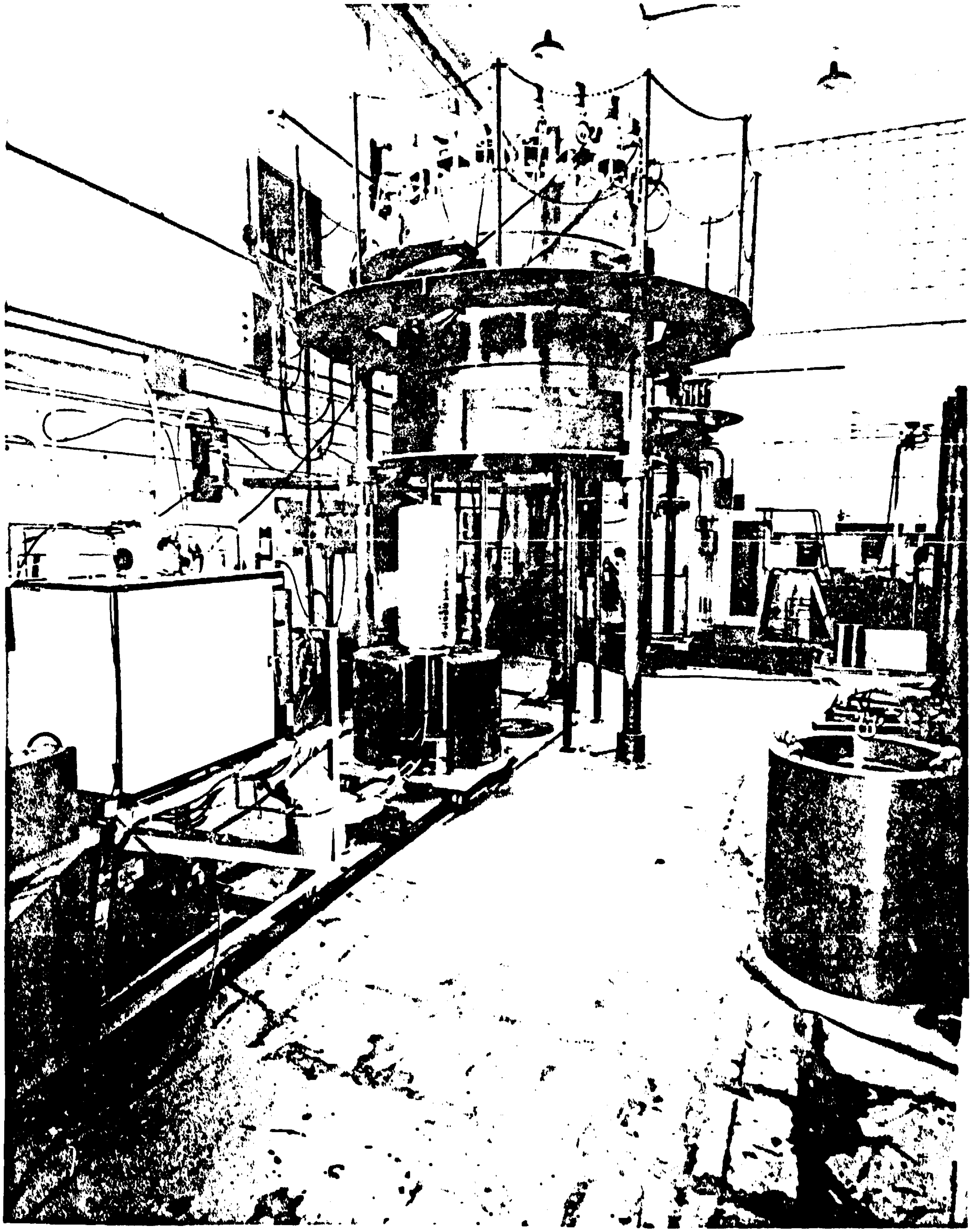

FIGURE 3

Canister and Gas Handling System

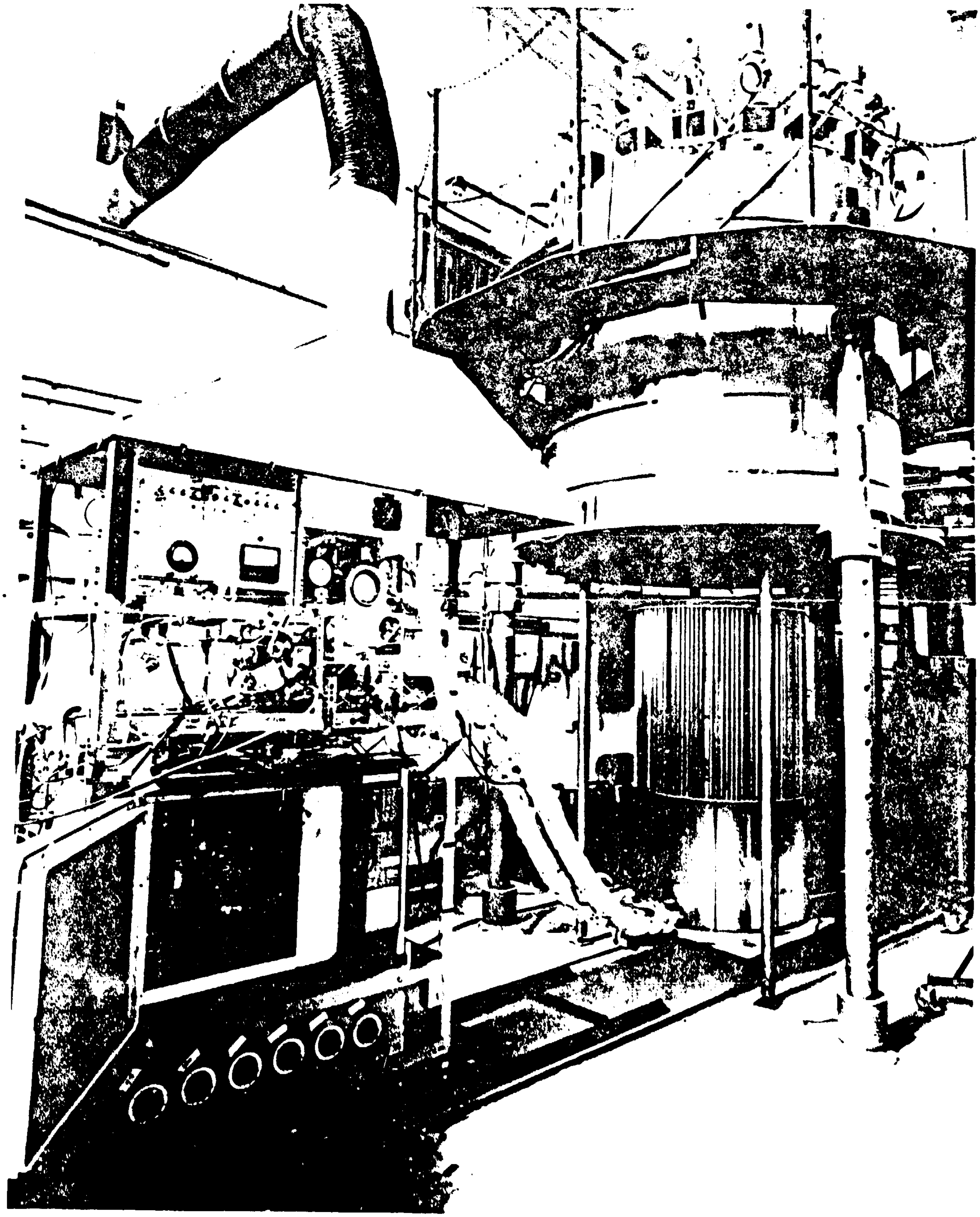

FIGURE 4

Flowing Gas Experiment Equipment

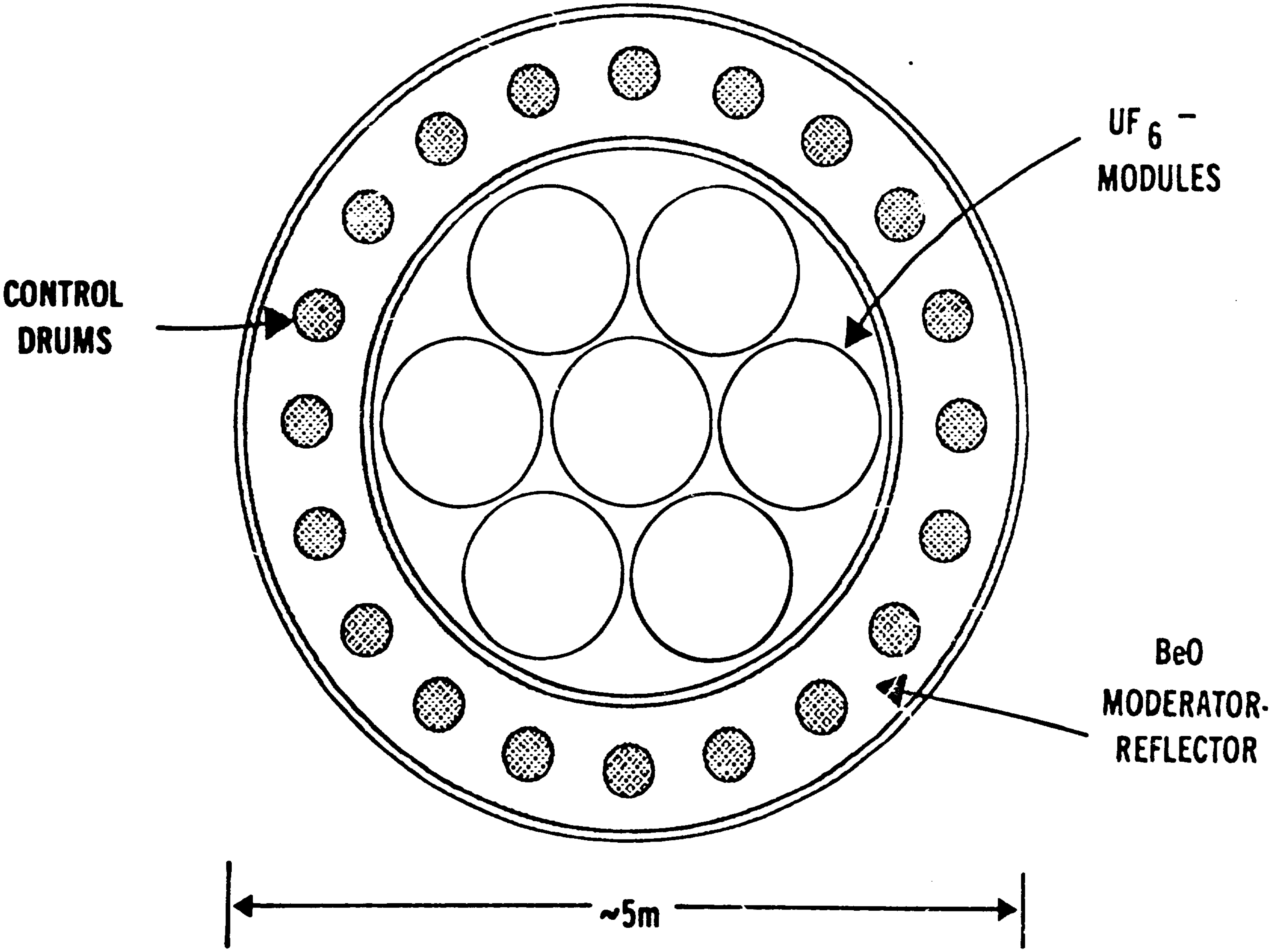

FIGURE 5

Self-Critical Uranium Hexafluoride Reactor Experiment

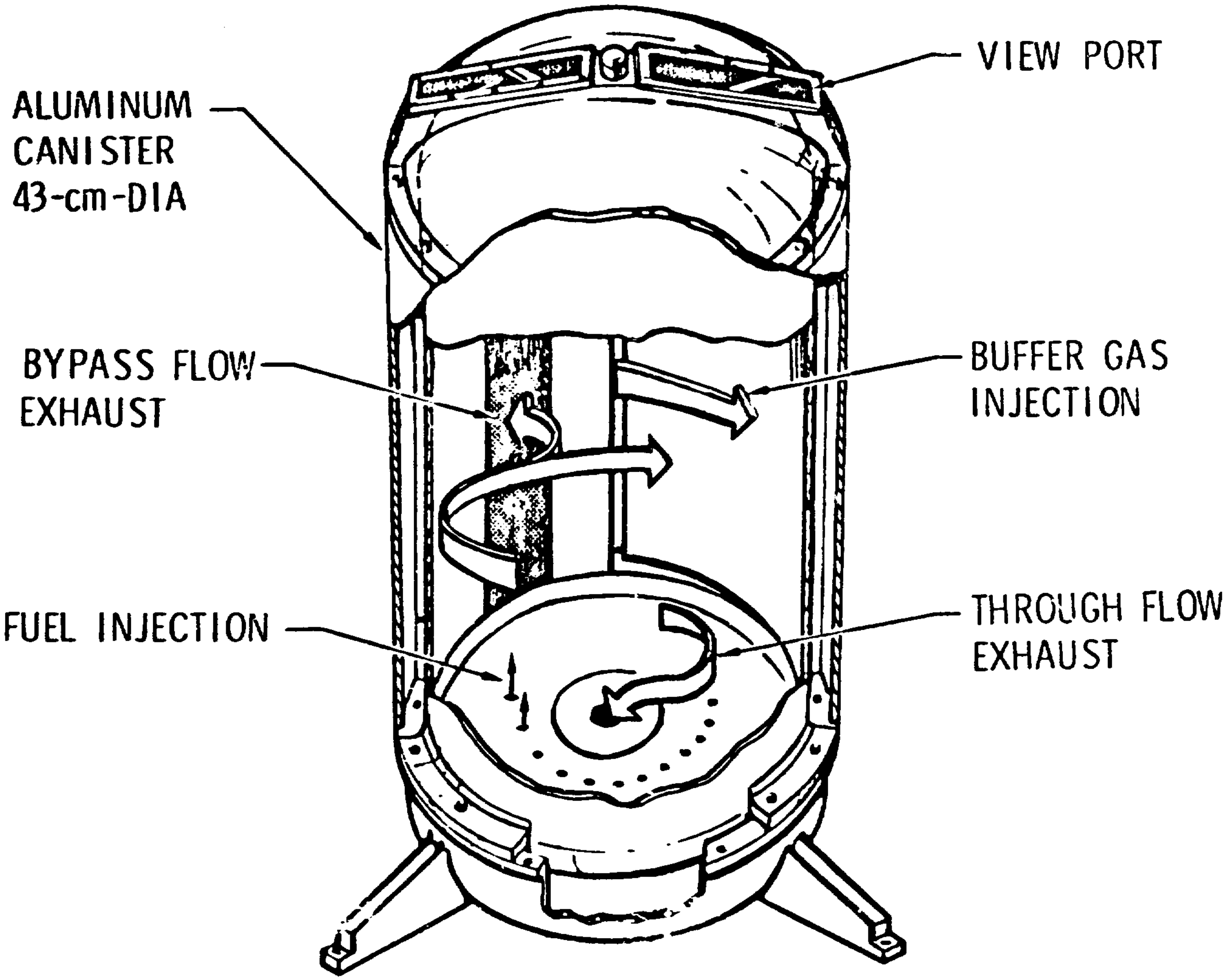

FIGURE 6

Fuel Canister with Buffer Gas Confinement

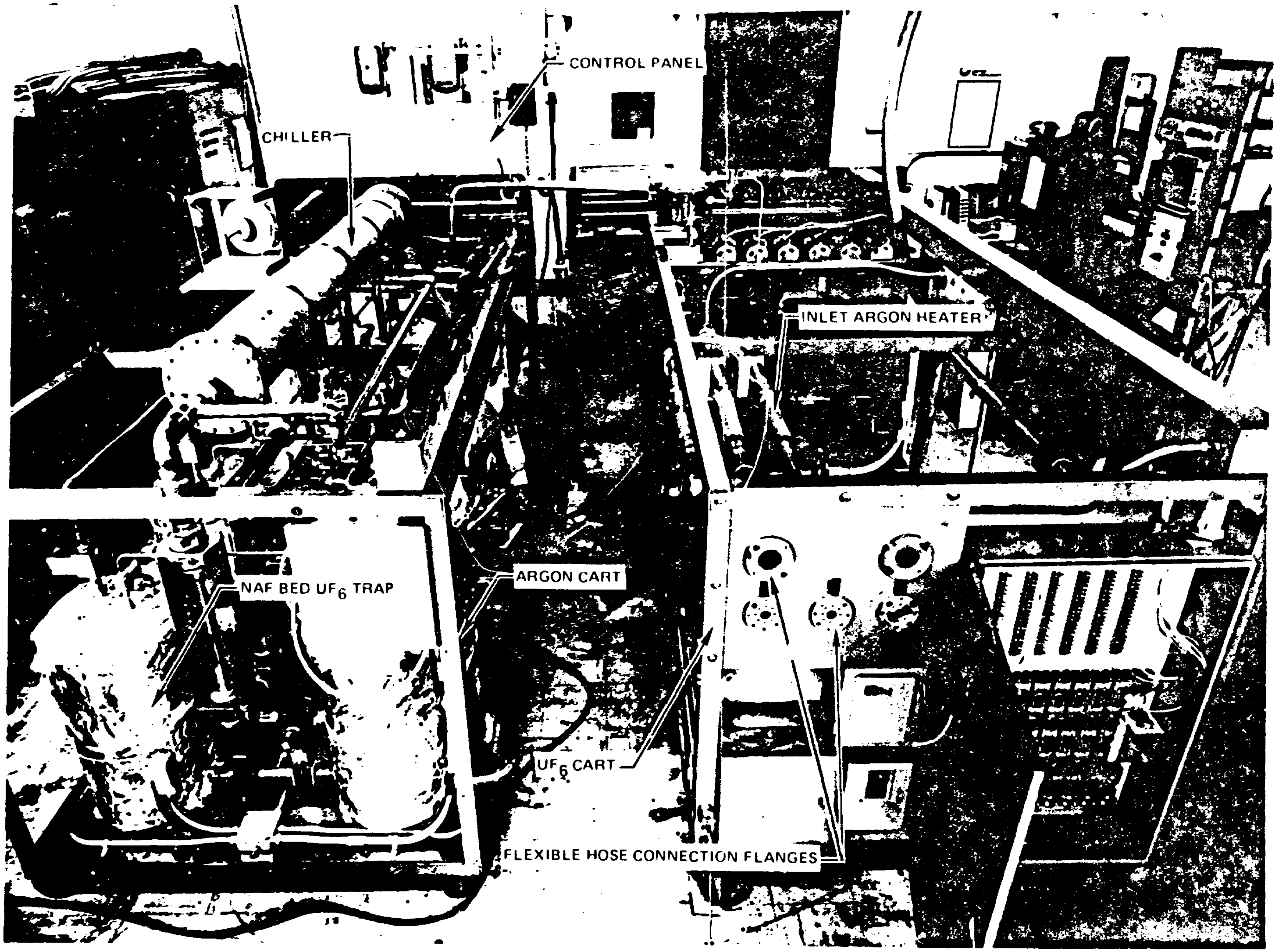

FIGURE 7

Vortex Flow System for Cavity Reactor Tests

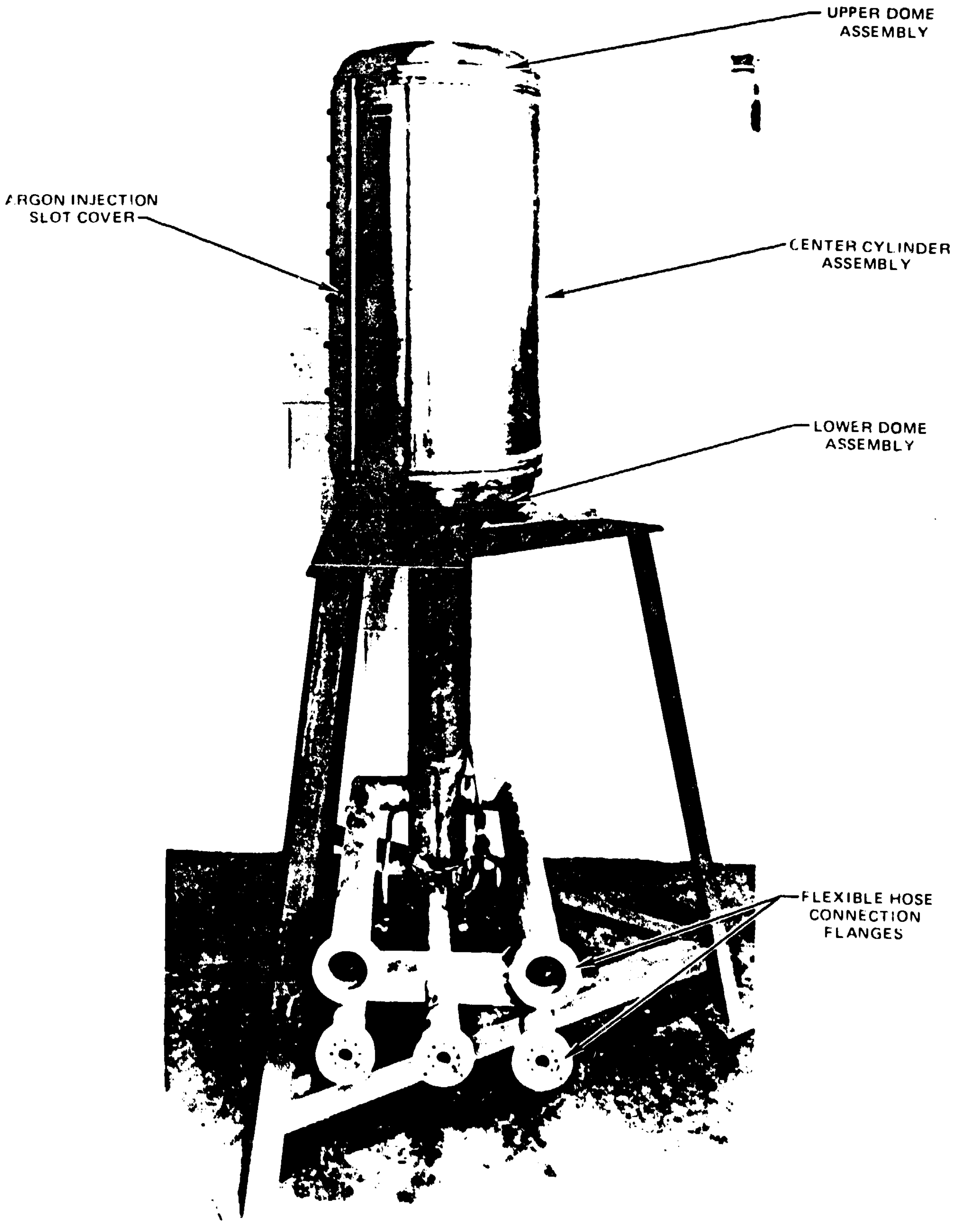

FIGURE 8
Vortex Flow Core Canister Assembly for Cavity Reactor Tests

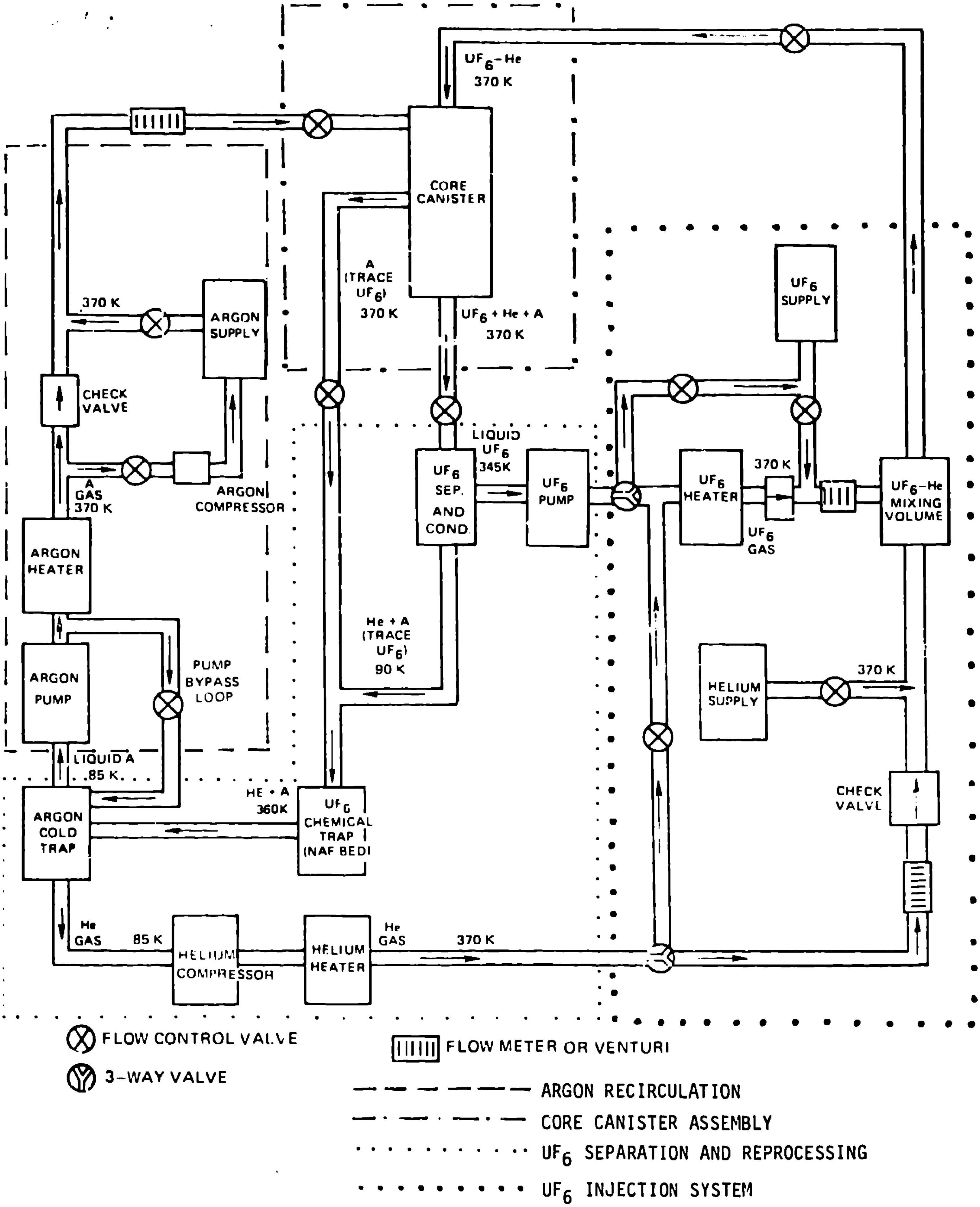

FIGURE 9

Schematic of Confined Argon/UF_6 Flow System

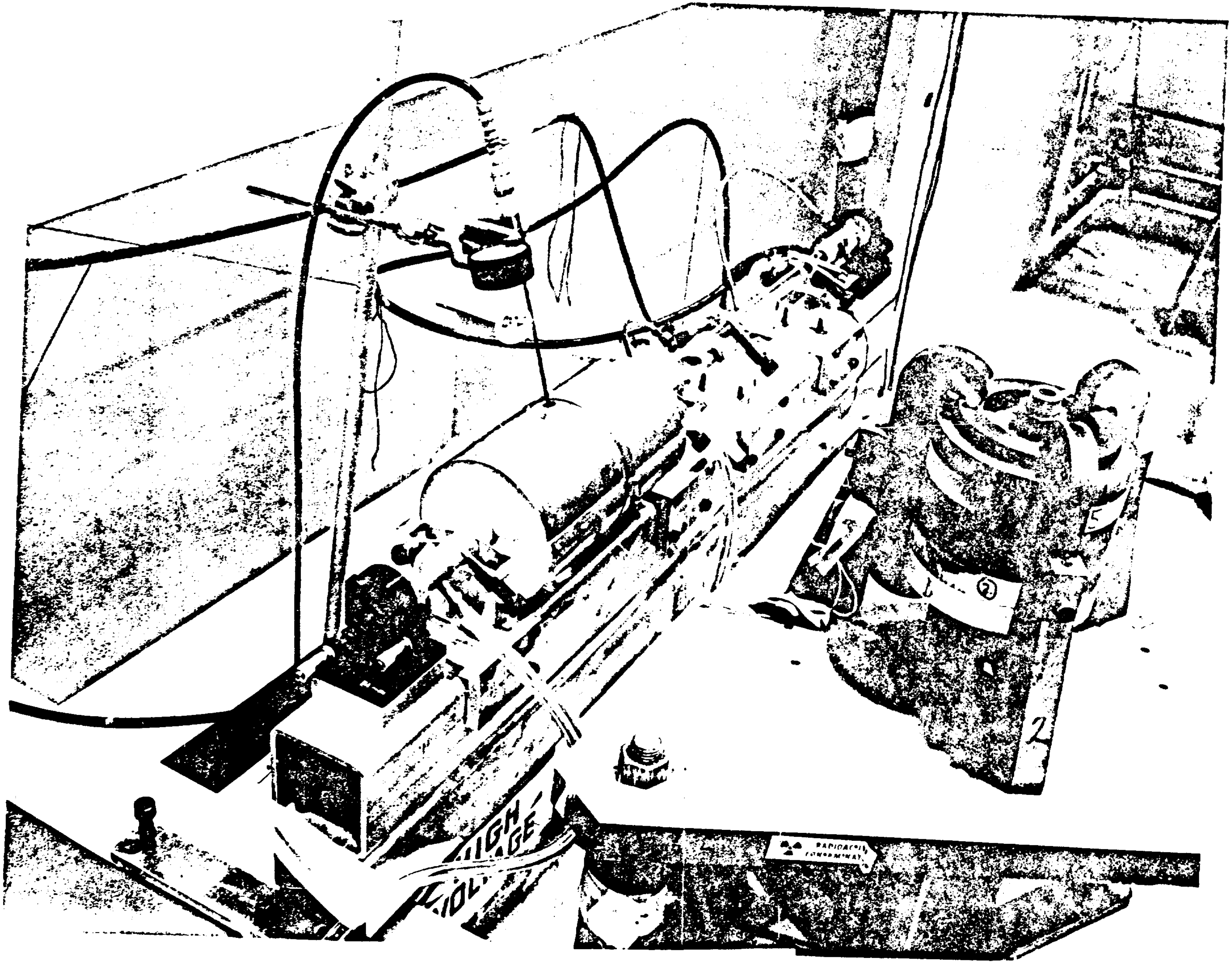

FIGURE 10

Nuclear Pumped Laser with Godiva IV

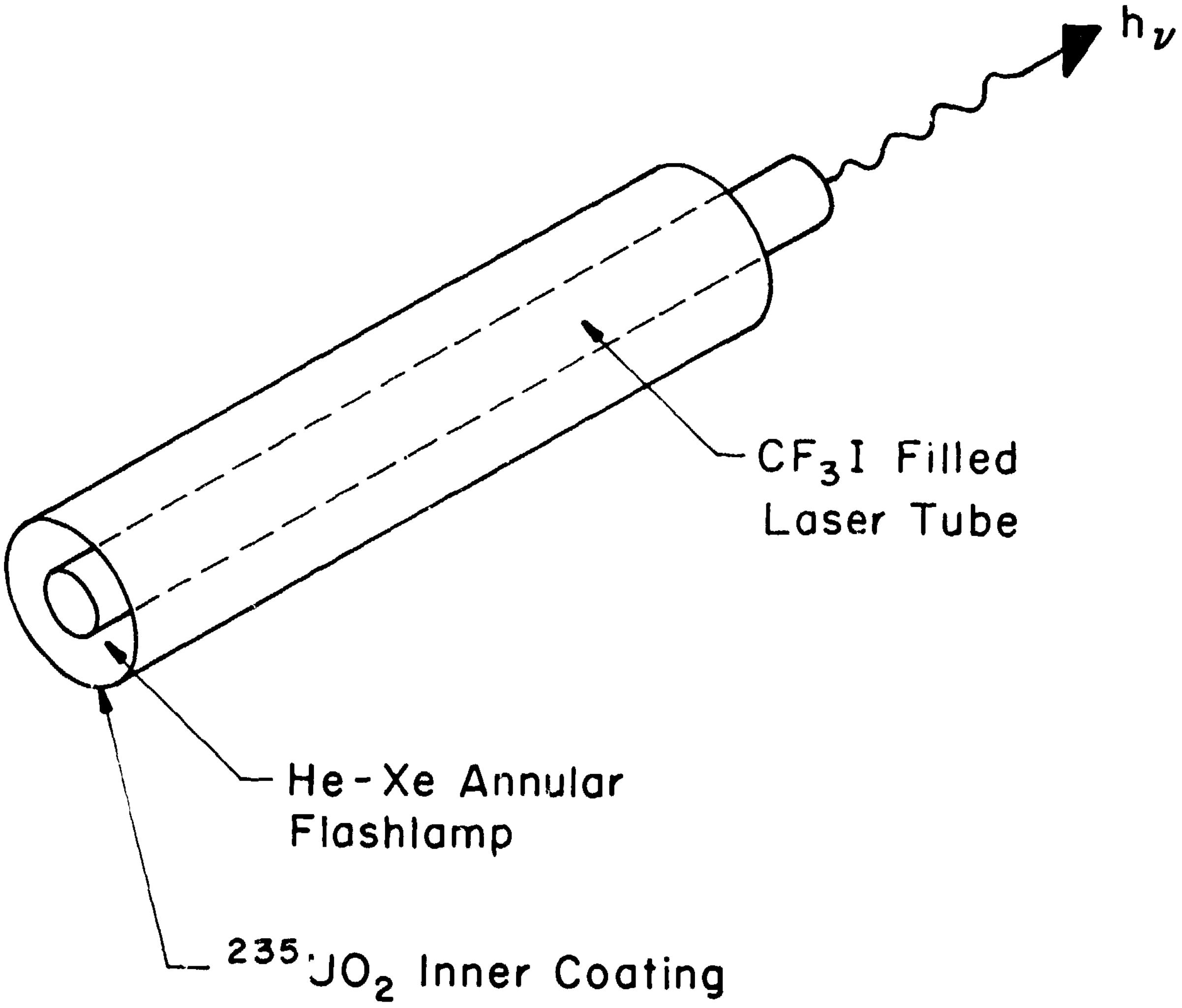

FIGURE 11

Nuclear Pumped Flashlamp Laser

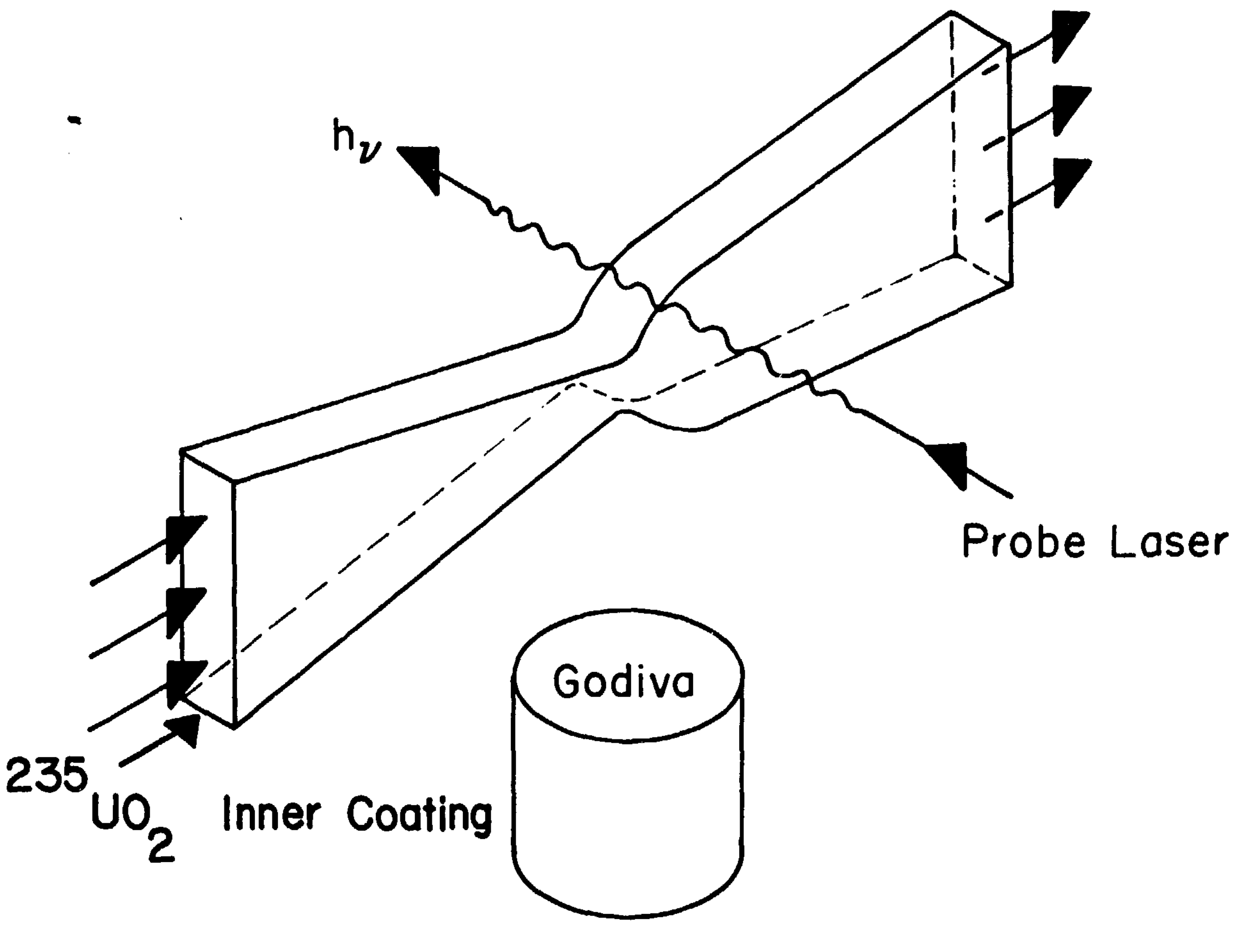

FIGURE 12

Gain Measurement of Nuclear Pumped Gas Dynamic Laser

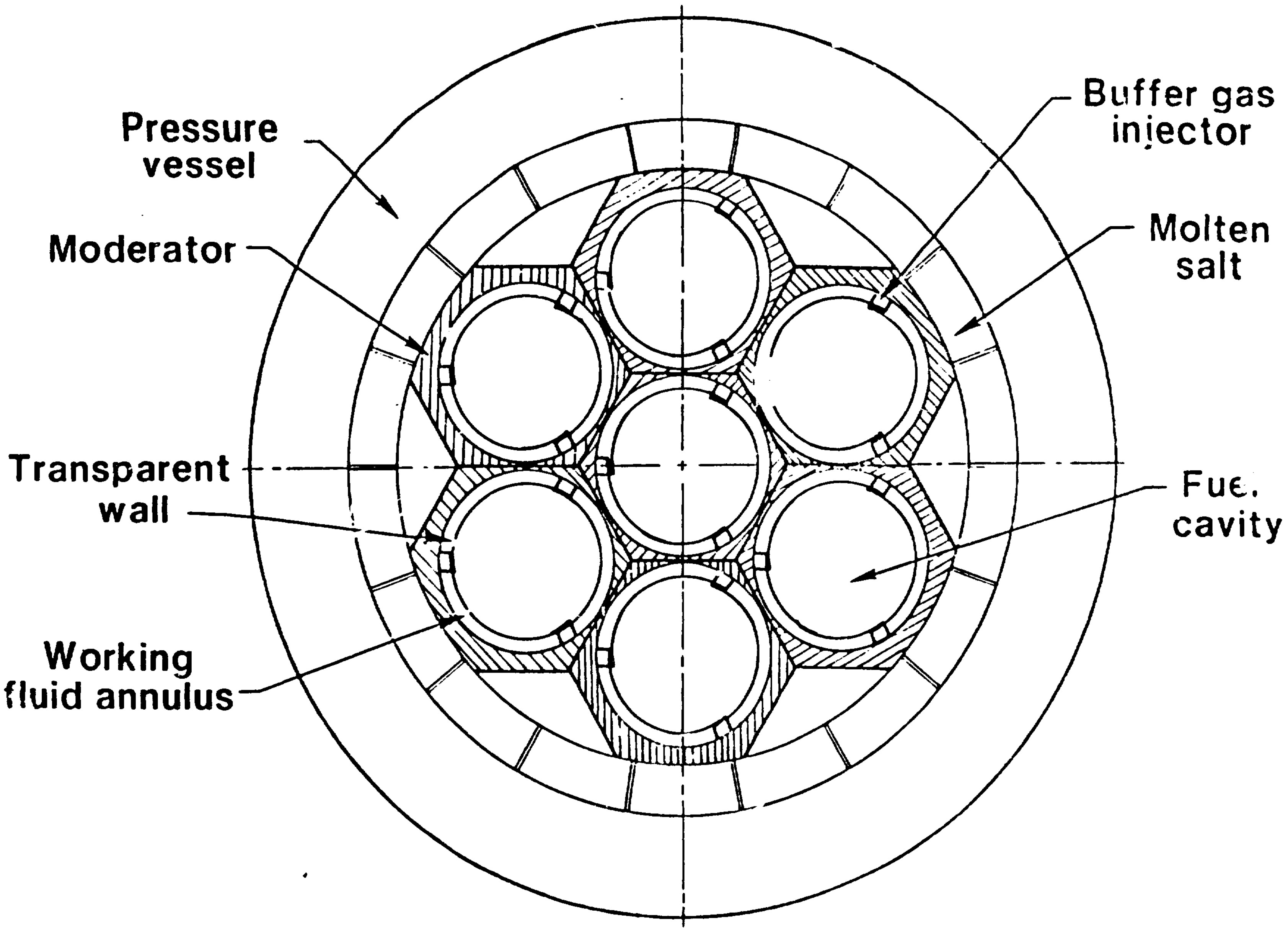

FIGURE 13

Schematic of Plasma Core Reactor

Significant Nuclear Pumped Laser Accomplishments

	Pressure (mm Hg)	Wavelength (μm)	Efficiency %	Remarks
1974				
Fission Fragment He-Xe Laser Los Alamos	200	3.5	<.005	Low power, proof of principle experiments.
Fission Fragment CO Laser Sandia Laboratory	100	5.1 - 5.6	0.1	
1975				
$B^{10}(n,\alpha)Li^{7}$ $Ne\text{-}N_2$ University of Illinois	75 - 400	.863 & .939	1×10^{-4}	Newly discovered laser system. Nuclear pumping is 22 times more efficient than electrical.
Fission Fragment Ar-CO Sandia Laboratory	400	5.1 - 5.6	1.0 - 5.0	Minor changes in system from 1974 experiments. Dramatic improvements in efficiency and a 50 time increase in laser output. Output power approximately 100 watts.
$He^{3}(n,p)T$				Large number of systems with volume excitation from Helium-3 mixed with lasing material. Moderate to high pressures. All systems are atomic transitions in the infrared and of low quantum efficiency.
He-Ne	400	1.117		
He-Ar	466	1.27	<0.01	
He-Cl	600	1.586		
He-Ar	200 - 3000	1.791		
He-Xe	200 - 3000	2.027		
He-Kr	200	2.52		
NASA Langley Research Center				

	Pressure (mm Hg)	Wavelength (µm)	Efficiency %	Remarks
1976				
$n(^{10}B,\alpha)^{7}Li$ He-Hg Sandia Laboratory	600	.615	10^{-6}	First nuclear pumped metal vapor system. Visible output at high pressures.
1976 - 1977				
$He^{3}(n,p)T$ Los Alamos	100 - 580	2.026, 3.5, 3.65	.013	Large series of precise experiments performed. Theory of charged particle excitation of system developed. Threshold and scaling parameters studied. Output power approximately 1 - 5 watts.
1977				
Fission Fragment Boosted Xenon Flashlamp to Pump CF_3I Los Alamos	580	1.315	→	Novel approach to nuclear pumping. Charged particles excite gas producing light to pump lasing material which is decoupled from fission fragment medium. Nuclear pumping is 2 times more efficient than electrical.
Fission Fragment UO_2^{+++} mixed in solution with lasants such as E^{+++}, Tb^{+++}, Pr^{+++}, Ce^{+++}	Liquid		>0.5	Shows promise for high power-small size systems. Uranly ion concentration of 10^{20} atoms/cc easily produced. Moderate fluxes will deposit 1-10j/cm^3.