CHAPTER 9

Areas for Break-Through

Closely related to high temperature gas reactor technology is the possible use of gaseous concepts for other purposes than the coolant alone. If we could do so, we might break through a number of technical barriers limiting reactor progress as we see it today. This is especially true in the area of fuel and its control. For example, nuclear enrichment plants usually produce UF_6 as an end product. This is a gas at moderate temperatures. If UF_6 gas could be used directly in a reactor as a fuel feed or make-up, then considerable savings in costly fuel fabrication would result. For example, also, if gaseous controllants could be used—in the form of pneumatic tubes, say—instead of mechanical-type control rods, then some of the limitations of present control rods might be overcome. If, somehow, the unwanted fission gases (namely: xenon, iodine, and krypton) could be bled off, reactor fuel life and power output would be appreciably extended. Should break-through success in any of these areas be attained, the possibility of rapidly advancing all types of nuclear ship reactors is encouraging.

9-1 Review of Gas Dynamics

Gases are the simplest form of matter. For this reason, it is desirable to review the basic properties of gases with the possibility in mind that some of their dynamic features may be applicable to marine reactors. In the long run, those reactor systems which are inherently simple in design and operation will be more prone to success. Admittedly, though, even where some of the gas principles appear attractive at this time, extensive research is required before their application can be advocated.

When we think of gases, we have to think in terms of molecules rather than in atoms as in the case of nuclear fission. A molecule is made up of one or more atoms. For example, helium is a mono-atomic molecule (one atom per molecule) whereas CO_2 is tri-atomic (three atoms per nolecule). In addition to atoms, molecules have electrons which help to naintain their molecular neutrality.

In the various concepts of gases, molecules are thought of as tiny spherical masses with elastic properties. These spheres are widely

separated from one another. They speed about with equal probability in any direction unless restrained by container materials or directionally changed by collision with other molecules.

The most characteristic property of a gas is pressure. The molecules tend to separate themselves (expand) indefinitely unless confined, in which case they exert a positive pressure upon the walls of the containing vessel. The pressure exerted is proportional to the density of the gas times the average velocity-squared of the molecules it contains (i.e., $P \approx \frac{1}{3}\rho v^2$). If several gases are mixed, the total pressure is the sum of the individual pressures exerted if each gas occupied the same volume by itself. The pressure of individual or of a mixture of gases can be increased (or decreased) by external work, with or without accompanying volume change.

For a fixed volume, the molecular pressure will increase (or decrease) directly with increases (or decreases) in temperature. This follows from the fact that molecular velocity is dependent on the temperature environment, called "thermal agitation" (i.e., $v \propto \sqrt{T}$).* Furthermore, the molecular velocity of a gas is inversely proportional to its molecular weight; that is, $v \propto 1/\sqrt{M}$. In other words, heavy molecules move slowly whereas light molecules move swiftly. This is true even if several gases are mixed. The net velocity effect is proportional to $\sqrt{T/M}$.

A gas experiences free expansion when it is allowed to effuse through a porous barrier where the pressure on one side is greater than that on the other. The term "porous" means: holes so small that molecules go through one by one. If gases are mixed, they will be separated by the porous barrier in inverse proportion to their molecular weights. That is, the light molecules moving faster will be separated from the heavy molecules by the factor $\sqrt{M_{(heavy)}/M_{(light)}}$ (recall Sec. 3-2). By the same token, if a mixture of gases enters a centrifuge, the heavier molecules will concentrate (separate) toward the outer portions of the container, whereas the lighter molecules will collect toward the axis.

When a gas contains two or more molecular species whose relative densities vary from point to point, a process called "diffusion" takes place to continually diminish the inequalities of composition. This is a consequence of thermal agitation alone (not pressure or volume). More molecules of a given kind travel from regions rich in that kind to regions of scarcity, thus tending to smooth out the inequalities. If, however, the temperature is raised high enough, the molecules will dissociate into lesser components. These components may be new molecules, atoms, or free electrons. The same dissociation effect also takes place under nuclear irradiation.

The above facts are a very brief review of the dynamic properties of gases in a more or less contained environment. Let us search now for

* The symbol "$\propto$" means "is proportional to."

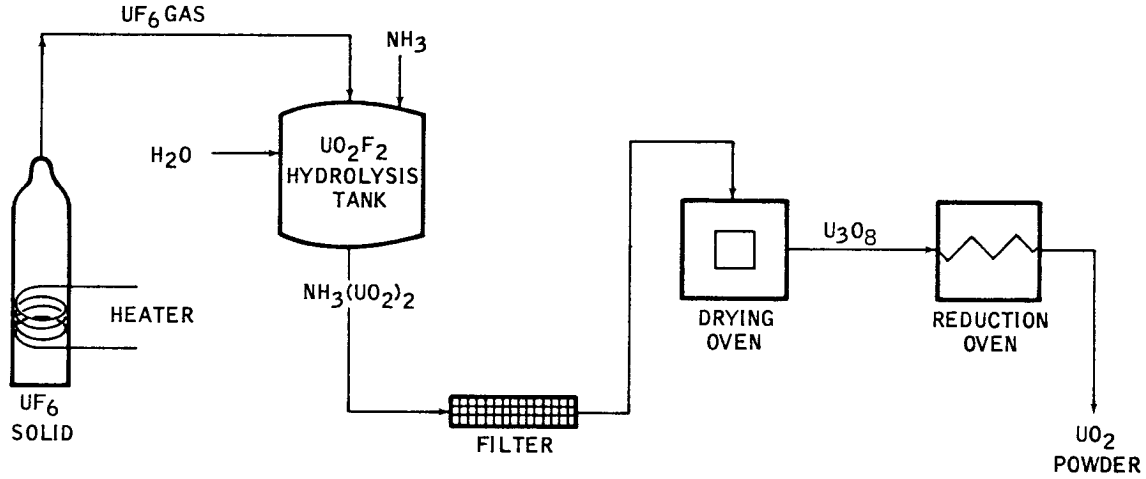

Fig. 9-1 Typical Method of Uranium Dioxide Preparation from UF_6 Gas

possible areas where these properties might be used. We shall do this first by looking at those areas of reactor technology where we should like to see break-throughs.

Remember, we are not now discussing gas as a coolant medium in a reactor or as an actuating medium in a turbine. Instead, we are considering only the inherent behavior of gas in a contained environment, such as in a fuel element.

9-2 Many-Stepped Fuel Fabrication

One of the first areas of desired break-through is to reduce the many fabrication sequences of fuel elements. To appreciate the numerous steps involved, a review of the fabrication of UO_2 fuel elements is of interest. These fuel elements are fairly typical . . . so much so that the use of UO_2 is rapidly becoming a standard nuclear fuel for power reactors.*

The first major step is the production of UO_2 powder . . . from UF_6 (uranium hexafluoride).† Cylinders of solid UF_6 are shipped from gaseous diffusion plants to UO_2 plants. Here, the UF_6 cylinders are heated by electric blankets which vaporize the UF_6 through pigtail pipes into a water tank (see Fig. 9-1). In water, UF_6 hydrolyzes into uranyl fluoride (UO_2F_2). From this liquid, the UO_2 is precipitated with aqueous ammonia (NH_3). The resulting ammonia diuranate compound is filtered, washed, and dried. It is then decomposed with steam to U_3O_8, and subsequently reduced to UO_2 in a hydrogen gas oven. The result is powder.

The second major step is to form the UO_2 powder—along with a matrix powder—into finished pellet shapes. This may be done by conventional powder-metallurgy techniques involving:

- cold compacting
- hydrostatic pressing
- hot pressing
- ceramic extrusion
- slip casting
- swaging

The shapes may be plain solid cylinders, circular-cored cylinders, star-cored cylinders, etc. (The cored holes serve as fission gas reservoirs.) The pellets are then sintered in a dry heat oven at around 3000°F. Sintering forces the powdered particles into intimate contact with one another, at temperatures below the melting point of the UO_2 (which is around 5000°F). Sintering is done in an oxygen-free atmosphere to avoid UO_2 picking up excess oxygen. Sintering improves density and strength, though it results in about a 1% weight loss.

Following the sintering process, the next step is to machine the pellets to close dimensional tolerances for fitting into the fuel rod tubes. Metallurgical assays and inspections are made to record fissionable content and to assure conformance to dimensional and mechanical specifications.

* Ref: "Uranium Dioxide Experience," J. C. Danko, *Nucleonics*, August, 1958, p. 90.

† Ref: "Steps in Preparing Uranium Dioxide for Fuel Elements," Hausner and Mills, *Nucleonics*, July, 1957, pp. 94 ff.

Chemical analyses are made to establish the impurity content and the alloy composition of the fuel material. This entire finishing and recording step is a major and tedious task.

9-3 Further Steps Required

The next major step is to load the fuel pellets into their tubular containers (jackets), leaving just sufficient room for bonding, growth gaps, and end closure welds. The most common jacket materials are zircaloy and stainless steel. The important fabrication difference between these two materials is the relative thermal expansion between the fuel and the jacket. The thermal expansion of stainless steel is *greater* than that of UO_2, whereas the expansion of zircaloy is *less* than that of UO_2. The bonding material, gas or liquid metal, is injected and the fuel is packed home by various techniques of pack rolling or coextrusion. If no bonding material is used, very close dimensional control of fuel and cladding components is required. The closure of the end weld requires the ultimate in precision and reliability.

Next comes another series of tests: nondestructive as well as destructive (see Table 9-1).* Following these tests and further accounting of the fissionable content, the fuel rods are assembled into fuel elements according to a specific design. The fuel elements then are shipped to the reactor core manufacturer, who is responsible for the proper nuclear, thermal, and physical sizing of the reactor core and its control rods. For the first core of a type-class, a model mock-up is made, and one or more of the fuel elements is tested for core cage fit, lock, and coolant flow. Subsequently, the fuel elements are installed—one at a time—into the real reactor core.

Installing a nuclear core into a ship reactor is a major step in itself. Precision-securing the core cage in place, inserting and locking in the fuel

Table 9-1. Typical Tests Performed on Fabricated Fuel Elements

NONDESTRUCTIVE - for determining fuel dispersion uniformity, imperfections in the fuel, bonding effectiveness, cladding cracks and defects, leak tightness, and integrity of closure weld:	DESTRUCTIVE - for determining by actual physical observation the integrity of the fuel-to-cladding bond, and general mechanical and thermal properties of specimen fuel elements over-all:
· Ultrasonic Test · Eddy-Current Test · Zyglo Test · Magnetic Test · Heat-Transfer Test · Radiographic Test · Corrosion Test	· Crush Test · Bend Test · Hydro-Pressure Test · Peel Test · Thermal Shock Test · Mechanical Shock Test · Metallography Test

* Ref: "Fabricating and Testing Tubular Fuel Elements," S. Storchheim, *Nucleonics*, January, 1957, pp. 85 ff.

elements, connecting control rod drive mechanisms, closing the top shield . . . and thousands of other details are involved.

And when this whole sequence of events—from UF_6 on—is done, we can only burn a few per cent of the total fissionable content! Then we have to take out the fuel elements, send them to reprocess plants to reclaim the unburned fuel atoms, then repeat the fabrication cycle all over again.

9-4 Short Cuts with UF_6 Gas

Many minds have wondered about ways and means to short-cut the many fuel element fabrication steps above. For, obviously, if reliable short cuts could be found, there would result appreciable savings in time, cost, and complexity of fuel fabrication. Most efforts, however, fall into the category of technical refinements rather than specific break-throughs. Some entirely new approach is needed . . . possibly using UF_6 directly?

The technology of UF_6 production is well developed and virtually any degree of enrichment desired could be bled off from Government gaseous diffusion plants without further processing. Accordingly, UF_6 represents the basic nuclear fuel form and, therefore, it should be the most economic. It is in this form that the Government-controlled price is prescribed (recall Table 3-2).

A few words about the properties of UF_6: It is solid at ordinary temperatures, but sublimes (vaporizes) completely at 135°F, atmospheric pressure. It is one of the heaviest gases known. Its thermal conductivity is about on a par with CO_2, which is about ¼ the value of helium. UF_6 gas is thermally stable up to about 1800°F after which it begins to dissociate. Under irradiation it will dissociate fairly easily, breaking down into UF_4 (solid) and F_2 (gas) for every 20 ev that the gas molecules absorb. The carrier agent, fluorine, is a single isotope with a very low thermal neutron capture probability (i.e., 0.009 barn). Thus, the fluorine offers negligible competition to uranium for neutron capture. UF_6 gas has a marked corrosive action on all metals except gold, platinum, and nickel.

Recognizing the possibilities with UF_6 gas, one researcher has proposed that it be used directly as a circulating fuel-coolant.* He would pressurize the gas to about 500 psi and operate at close to 1000°F. He points out, however, that such a scheme would have similar advantages and disadvantages of other circulating fuel systems. Advantages: continuous fuel feed without fabrication difficulties; continuous removal of fission products; and significant temperature-safety consequences. Disadvantages: large circulating fuel inventory ($4½ million estimated); large reactor size (20% void space); serious radiocontamination problems external to the core; and generally poor heat transfer and heat exchange characteristics of the gaseous fuel-coolant. For all of these and other reasons, circulating fuel reactors have been discounted as candidates for nuclear merchant ships (recall Sec. 7-3).

* Ref: "Gaseous Fuel Reactor," S. Baron, *Nucleonics*, August, 1958, pp. 128 ff.

But, possibly, the advantages could be salvaged and the disadvantages minimized by **not circulating** the UF_6 gas: by using it only as a **fuel feed.** In other words, it would be substantially a one-way feed scheme—somewhat analogous to an oil-fired boiler. Regular fuel elements could be fabricated in the ordinary way, but without adding in fuel in excess of criticality. Then the reactor could be started up in the normal way, and the UF_6 gas could be fed in to replenish the U-235 fuel atoms that are burned.

This fuel feed concept might not eliminate all of the fuel element fabrication techniques, but it would extend the life of the fuel elements considerably. An extension of fuel element life has the same economic effect as fabrication short cuts. If such a scheme could be made technically feasible, the life of a fuel element would depend solely on the integrity of its cladding material and not upon the burnup and poisoning of its fuel species.

9-5 Possible Scheme for UF_6 Feed

The use of UF_6 gas as a fuel element feed might be as schematized in Fig. 9-2. UF_6 bottles could be mounted around the outside of the reactor, that is, outside of the primary shielding. There could be small-diametered, short-run piping from the bottles through the shielding and the reactor vessel to the various fuel elements. There could be limited access to the bottles for installation, inspection, and replacement.

Design care must be taken, of course, not to get the UF_6 bottles too close together, nor to construct them of such shapes that nuclear criticality could exist outside of the core. But this is the same safety design problem that confronts all nuclear fuel process and fabrication plants. At these **sh**oreside plants, premature criticality is prevented by designing the process fuel containers in an "always safe" configuration. In addition, solid neutron absorbing shields (cadmium, boron) are used. Similar safety arrangements could be designed for shipboard UF_6 bottles and rack mounts (see Fig. 9-3).

The UF_6 bottles could be heated by automatically controlled electric heaters. A gas supply pump, tied-in to a pressure regulator and neutron flux control, could maintain positive feed pressure on the UF_6 gas. The gas could enter the fuel elements via special tubing and connections designed as part of the top grid plate. Mating top end fittings of the fuel elements could be combination orifices and locking devices. All tubing could be appropriately manifolded to all bottles . . . to give uniform fuel feed. The feed manifolds could be adequately contoured to permit streamline flow of the normal coolant. The coolant could be any of the materials previously discussed: water, organic, liquid metal, or gas.

The UF_6 gas would enter the interior of the fuel elements via the circular or star-shaped holes throughout each fuel element length (recall Sec. 3-9 and Fig. 3-6). Diffusion of the feed gas to all parts of the fuel element interior would take place as the normal consequence of gas

dynamics, assisted by pressure and temperature effects. Few ceramic fuels are fabricated with a compaction density in excess of 90%, which is 10% porosity. This porosity, together with the center hole, would provide, perhaps, 15 to 20% void space in each fuel element. This amount of void would be sufficient for uniform diffusion of the UF_6 gas.

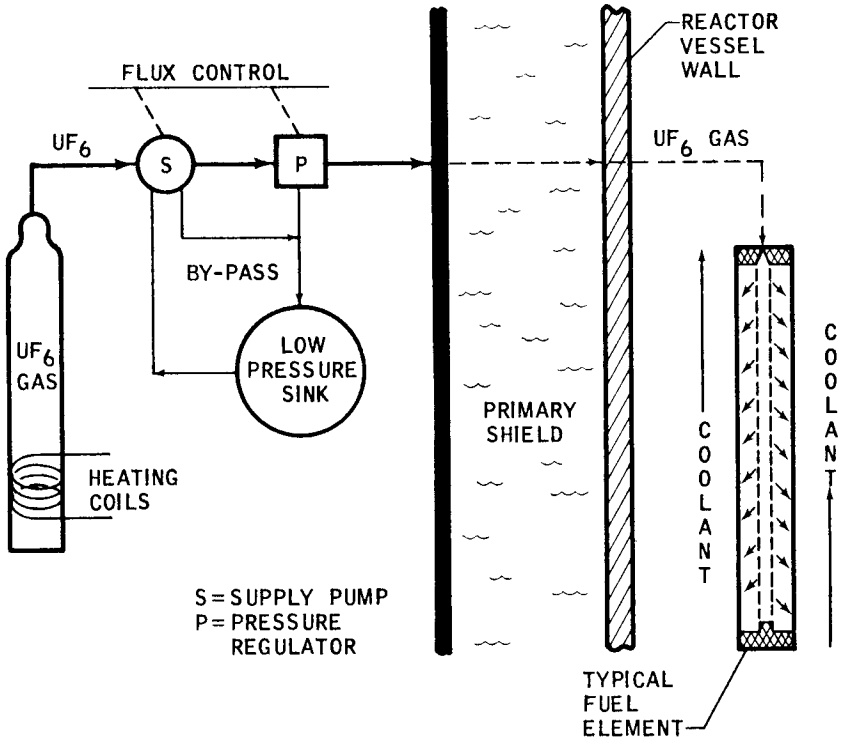

Fig. 9-2 Possible Scheme for Direct UF_6 Feed to Reactor Fuel Elements

Any adverse temperature rise in the fuel element would simultaneously create a pressure rise ($P \bullet V = R \bullet T$ = constant: V and R are fixed). The excess pressure would override the pressure regulator and dump the excess UF_6 gas into a low pressure sink (Fig. 9-2 again). At the same time, the supply pump pressure could be bypassed to the sink, if necessary. With adversely low temperatures, the pressure regulator would permit the supply pump to pump in more UF_6 gas. The system would be "fail safe" because in the event of pump failure, new feed gas would not enter the fuel elements.

To get some idea of the amount of UF_6 gas needed, the data in Table 9-2 are presented. It is assumed that the pressure regulation is set for 500 psi, with a central gas temperature of about 2000°F. The U-235

content in the UF_6 is, say, 66.6%.* Under these conditions, one liter of UF_6 gas would supply about 6.5 MW of fission heat per day, or about 15 liters per 100 MW-day. This is about one-half cubic foot of UF_6 gas at 500 psi.

Table 9-2. Approximation of UF_6 Gas Requirements Per 100 MW-Days

Fissions Per MW-Day

3.1×10^{10} fissions/watt-sec*

$= 2.68 \times 10^{15}$ fissions/watt-day

$= 2.68 \times 10^{21}$ fissions/MW-day

UF_6
Temp. 2,000°F
Press. 500 psi
U-235 66.6%

Number UF_6 Atoms Per Liter

$$N_{(UF_6)} = \frac{\rho A_0}{M}$$

where $\rho = 13.28 \times \frac{323.2}{T^{\circ}K} \times P_{(atm)}$ g/liter**

$\left[T = 273 + (2{,}000^{\circ}F \times \frac{5}{9} - 32) = 1{,}350^{\circ}K\right]$

so, $\rho = 13.28 \times \frac{323.2}{1350} \times 34.4 = 112.5$ g/liter

$M = (2/3 \times 235 + 1/3 \times 238) + 6 \times 19 = 350$

So, $N = \frac{112.5 \times 6 \times 10^{23}}{3.5 \times 10^{2}} = 1.93 \times 10^{23}$ UF_6 atoms/liter

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Number U-235 Atoms Per Liter

UF_6 consists of 1 atom U + 6 atoms F

So, $N_U = 1/7 \times 1.93 \times 10^{23} = 2.75 \times 10^{22}$ U atoms/liter

$N_{U-235} = 2/3 \times 2.76 \times 10^{22} = 1.84 \times 10^{22}$ fissionable atoms/liter

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Liters Per 100 MW-Day

1 liter UF_6 (U-235 at 66.6%) will produce

$$\frac{1.84 \times 10^{22}}{2.68 \times 10^{21}} = 6.85 \text{ MW-days}$$

$\therefore$ 14.5 liters required per 100 MW-days

1 cu ft = 28.32 liters

So, 1/2 cu ft UF_6 gas (at 500 psi) will produce 100 MW-days

*Standard conversion factor.
**The Chemistry of Uranium, Katz and Rabinowitch, McGraw-Hill, 1950, p. 429.

* Note that this is a significantly higher enrichment than the 5% U-235 *SAVANNAH* fuel. In gaseous fuel form, we want every possible U atom to be fissionable . . . because we can't pack into a given gas volume as many fissionable atoms as we could otherwise do in solid fuel form.

Using commercial standard 200 cu ft (1 atm) gas bottles, one such bottle would last about 12 days per 100 MW of operation. For a 75 MW reactor ship operating, say, 300 days per year, about 20 UF_6 standard gas bottles would be required. Spares and replacement bottles could be handled without shielding, almost as readily as the handling of helium, oxyacetylene, Freon, and other gas bottles on merchant ships today.

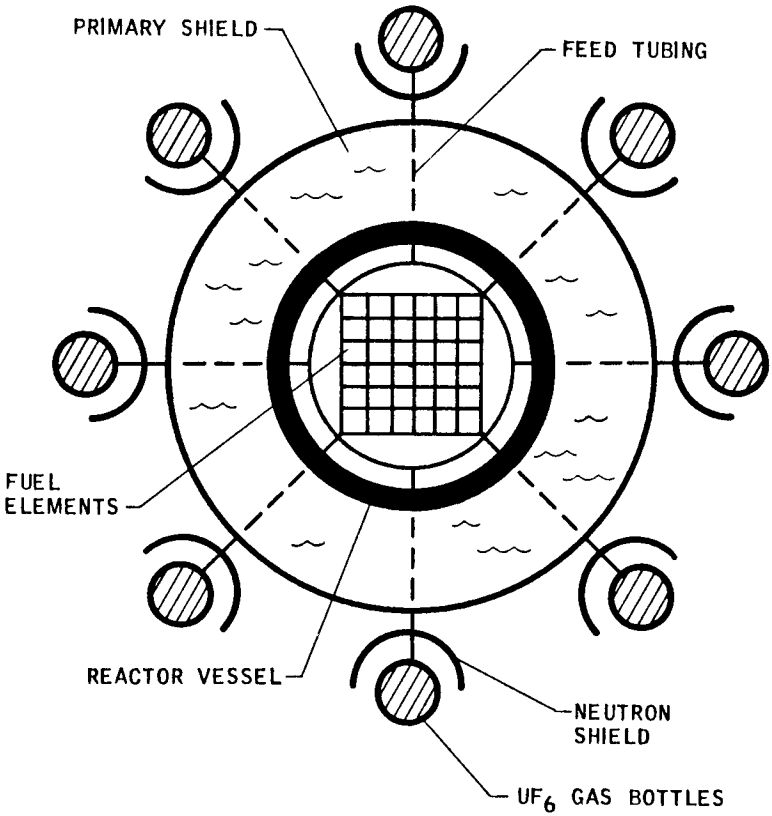

Fig. 9-3 UF_6 Gas Bottles Arranged for Direct Fuel Feed to Reactor

9-6 Behavior of Fission Gases

The question next arises: what about the fission gases? Will they not affect the dynamics of the direct UF_6 feed scheme just described? Yes, but possibly here, too, is a potential break-through area. First, a few words about fission gases and their behavior.

For every five atoms of U-235 fissioned, there result 10 atoms of fission residues . . . approximately two of which are gases. At atmospheric

pressure, when 1% of the fuel atoms is fissioned in a unit volume of fuel matrix, there results four times the volume of fission gas.* Consequently, it is easy to see that fission gases soon reach a point where they are cause for concern. This concern takes the form of fuel element swelling, cracks, degraded heat transfer, and poison buildup.

Table 9-3. Principal Gases from U-235 Fission

Fission Gas	Radioactive Isotope	% Yield	Half-Life
Kr	85	1.5	4.4 h
I	133	6.5	20.5 h
Xe	133	6.5	5.2 d
	135	6.4	9.1 h
		Total 20.9 %	

The fission gases are principally krypton, iodine, and xenon (see Table 9-3). Normally, an effort is made to contain, or lock in, these fission gases in the interstitial bonds of the fuel matrix atoms. In UO_2, for example, this containability is a function of the fuel matrix porosity and the central fuel temperature. At 30% porosity, for example, about 50% of the fission gases are self-released, whereas at 10% porosity 3% of the gases are released. At 5% porosity, only 1% of the gases is released. However, if we heat the 5% porosity fuel to around 2500°F, then 20% of the fission gases are released.† It should be stressed that this fission gas release is from the fuel matrix only; it is *not* from the fuel element cladding.

When the released-from-fuel fission gases accumulate to about 50% of the bonding volume of the fuel element, there results a serious degradation of heat transfer from the fuel across the cladding to the reactor coolant (recall Table 3-4). To overcome this effect, the central fuel temperature has to be increased by about 600°F for every 0.001 inch of fuel element cladding. Thus, thermodynamically, the buildup of fission gases limits the useful heat that we can get out of a reactor.

Other adverse effects of fission gases have been discussed in Sec. 8-4 and 8-5.

9-7 Gases from UF_6 Fission

The krypton-iodine-xenon gases are the direct consequence of fissioning U-235 atoms. That is, these gases are produced directly from the U-atom in a molecule of UF_6 gas. When the U-atom is fissioned, the gas molecule is destroyed, thereby releasing six atoms of fluorine. Now, fluorine is a highly reactive chemical agent. As the free fluorine atoms sweep by the area of fission, they "fluoridize" many of the nongaseous fission product residues into volatile (gaseous) forms. The more important of these gaseous fission product fluorides are give in Table 9-4.

* Ref: "Fission Gas Behavior in the Uranium-Aluminum System," M. B. Reynolds, *Nuclear Science and Engineering*, April, 1958, p. 428.

† Ref: "Fission Gas Release," *Power Reactor Technology*, USAEC, Jan., 1958, pp. 32 ff.

It is significant to mention at this point that one of the more promising processes for recovering unburned fuel from used fuel elements is the so-called "fluorination process."* This process consists of dissolving solid fuel elements in a fluoride salt followed by gas fluorination to produce UF_6. In the process, also, radioactive fission product fluoride gases are produced. All gases are mixed together when they leave the fluorination still. Since all of these gases have different sublimation temperatures, they are easily separated from each other by gaseous chromatography and distillation methods. The UF_6 gas is the reclaimant sought. The fluorination process offers much in the way of simplicity and compactness, and permits the radioactive wastes—after being cooled—to be collected in solidified fluoride salt form. The principles of shoreside fluorination can be applied to shipboard fuel elements.

Most of the fission fluorides in Table 9-4 are solid at ordinary temperatures. But they are all well volatilized at 500°F, which is *considerably below* the center temperature of the fuel element. Consequently, it is rather interesting to find that in our UF_6 fuel feed case we have a fluorination process automatically built in!

Note that we have three (Table 9-3) direct fission gases and five (Table 9-4) fission gas fluorides. What can we do about them? Could we possibly bleed them off?

Table 9-4. Most Probable UF_6 Fission Product Fluorides

Volatile Fluoride	Radioactive Isotope	% Yield	Half-Life
NbF_5	95	6.3	35 d
MoF_6	99	6.1	67 h
RuF_5	103	2.9	42 d
	106	6.4	1 y
TeF_6	127	0.25	110 d
	129	1.0	32 d
IF_7	131	2.9	8 d
		Total 25.8 %	

9-8 Possible Bleed-Off Scheme

Under present concepts of marine reactor technology, effort is devoted to containing all fission gases in the fuel matrix. In doing so, we accept the fuel burnup limitations resulting therefrom. Rarely does this burnup exceed 20% of the fissionable content, which represents about 1% of the total fuel matrix material (U-235 plus U-238). If we were to use the

* Ref: "Uranium Recovery from Spent Fuel by Dissolution in Fused Salt and Fluorination," G. I. Cathers, *Nuclear Science and Engineering*, Nov., 1957, pp. 768 ff.

UF_6 feed scheme, without some form of fission gas bleed-off, we could do no better than the solid fuel burnups. We might not even do as well, due to the added pressure buildups from the fission product fluorides.

The ability to bleed off fission gases is one of the more successful features of circulating fuel technology (recall Sec. 3-7 and Fig. 3-5). When a liquid fuel and fission product slurry is pumped outside of the reactor core, the fission gases escape very simply on their own. An off-gas collection system is provided to hold up these gases to allow radioactive decay; then they are released to the atmosphere. The bleed-off

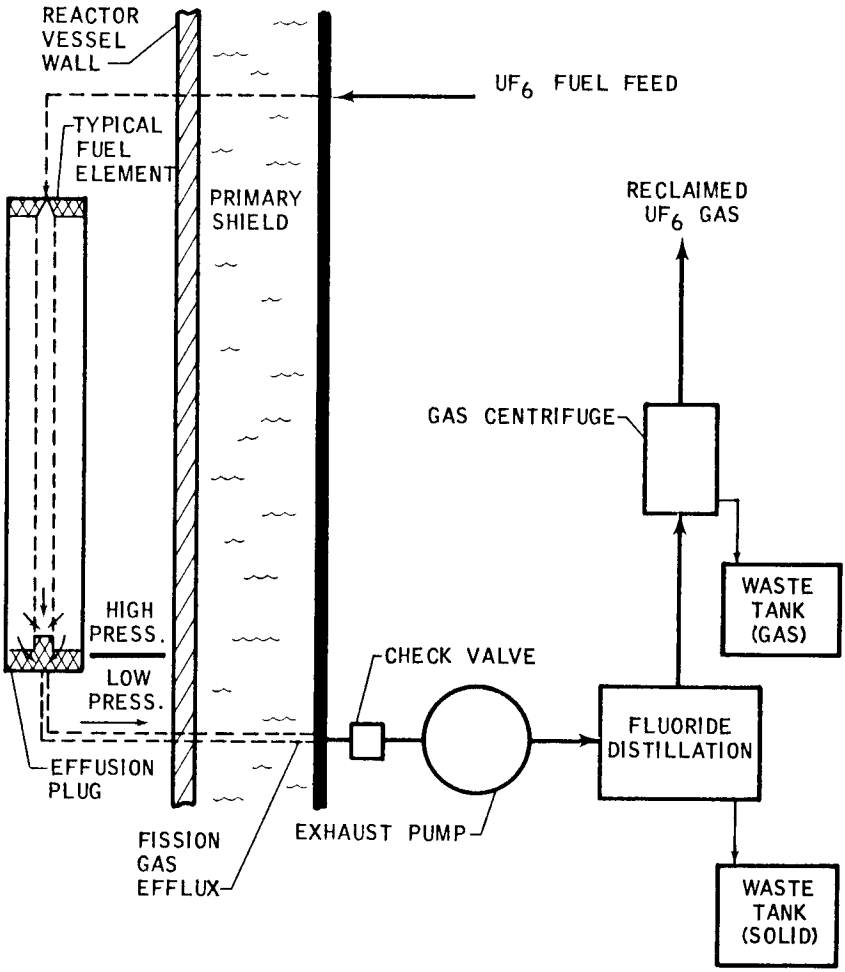

Fig. 9-4 Possible Scheme for Bleed-Off of Fission Gases from Reactor Fuel Elements

arrangement is simple because of the inherent capability of gases to separate from liquids, and the fact that the fission gases themselves are low-level radiation sources. Xenon, our predominant poison, for example, gives off 0.34 Mev beta rays and 0.08 Mev gamma rays. These radiations are very "soft" as nuclear hazards go. So, possibly, we could borrow some of the fission gas bleed-off principles from circulating fuel technology.

In our case, we are considering using UF_6 gas as a fuel feed only (recall Fig. 9-2). That is, we do not have any circulating mixture of fuel and fission products as in the circulating fuel-coolant sense. It is possible, nevertheless, that we could bleed off the fission gases directly from the fuel elements themselves.

Conceivably, this bleed-off could be done by using the effusion barrier principle previously discussed (Sec. 9-1 and 3-2). Possibly, a small effusion plug could be designed into the lower ends of each fuel element, as typified in Fig. 9-4. Each of these plugs would mate with a bleed-off line smaller in size, and at lower pressure, than the UF_6 supply line at the upper end of the fuel elements. The bleed-offs could be integrally manifolded into the bottom grid plate of the reactor core, from which one or more common lines could lead through the reactor wall and primary shield.

It is anticipated that some of the UF_6 gas would also effuse out. But the relative effusion of the fission gases—since they are lighter—would be significantly greater. The ideal effusion (separative) factors follow from the gaseous effusion relationship, namely

[Eq. 9-1]

$$\frac{\text{F.G.}}{\text{UF}_6} \approx \frac{\text{M (UF}_6\text{)}}{\text{M (F.G.)}}$$

where F.G. stands for fission gas and M, the molecular weight. Using this relationship, the effusion of the fission gases (including the volatile fluorides) is given in Table 9-5. Note the natural division of the two types of gases into short-lived and long-lived radioactive categories. Note, too, that all of the fission gases will effuse out of the fuel element *faster* than the UF_6 itself . . . the slowest being 16% faster.

9-9 Efflux Reclamation of UF_6

Instead of a single-effusion plug, if we used multi-staged effusion plugs in the lower end of the fuel elements, it might be possible to strip down the amount of UF_6 that gets into the fission gas efflux. It is doubtful, though, if the efflux would ever be completely free of UF_6. It would be necessary, therefore, to reclaim the UF_6 and cycle it back to the fuel feed supply system (see Fig. 9-4 again).

Reclamation methods could involve a small-scale combination of the fluoride distillation process and the gas centrifuge. Fluoride distillation techniques could be used to trap the long-lived fission fluorides, and send them to a waste collection holdup tank . . . where they would be

cooled and solidified. The gas centrifuge could be used to trap the short-lived fission gases, and let the UF_6 on through.

The gas centrifuge is one of the more successful methods for separating heavy gases of differing molecular weights. This device (see Fig. 9-5) was developed for the enrichment of $U^{235}F_6$ from $U^{238}F_6$. It was found versus 1.004) discussed in Sec. 3-2.* Though it has not been used in the production of mass quantities of the fissionable U-235, it would serve shipboard service well. It would be analogous to fuel oil centrifuging with differences, of course, in design details and safety features.

Table 9-5. Effusion Probabilities of Fission Gases from UF_6 Fuel Elements

	Molecular Weight	Effusion Factor
Fission Gases		
(short-lived radioactivity)		
(hold-up ~ 10 days)		
Kr	85	2.06
I	133	1.64
Xe	135	1.62
Ce	137	1.60
Volatile Fluorides		
(long-lived radioactivity)		
(hold-up ~ 60 days)		
NbF_5	190	1.36
RuF_5	200	1.32
MoF_6	215	1.27
TeF_6	245	1.20
IF_7	264	1.16

Following appropriate holdups and radioactive decay, the fission gases could be released to the atmosphere, and the solidified fluorides could be sealed and dumped overboard. More on the disposal of fission product wastes in a later chapter.

9-10 Disadvantages of Control Rods

Another important area where break-throughs might be explored pertains to avoiding the use of mechanical control rods in marine reactors. These rods are long-shaft devices at the end of which are absorber elements, which move in and out of the reactor core. When there is a large number of mechanical control rods, system complexities result.

* Ref: "The Gas Centrifuge," Benedict and Pigford, *Nuclear Chemical Engineering*, McGraw-Hill, 1957, pp. 510 ff.

On the *SAVANNAH*, for example, there are 21 control rods (recall Sec. 6-7). Each of these rods has its own electro-mechanical drive motor and hydraulic trip. Each shaft extension passes through a buffer seal with special fittings, cooling—and attention—in the reactor head. Each absorber element in the core has its own upper and lower guide tubes and coolant flow baffling. And each control rod has its own electrical circuit and rod position indicator. Since the *SAVANNAH* is expected to operate more than three calendar years (or about 350,000 nautical miles) without refueling, her control rods must be the ultimate in electro-mechanical reliability. There are numerous practical factors which could upset this ultimate-in-reliability.

Among the foremost disadvantages of mechanical control rods is their "lengthiness" (see Fig. 9-6). The over-all rod length is from 3 to 4 times

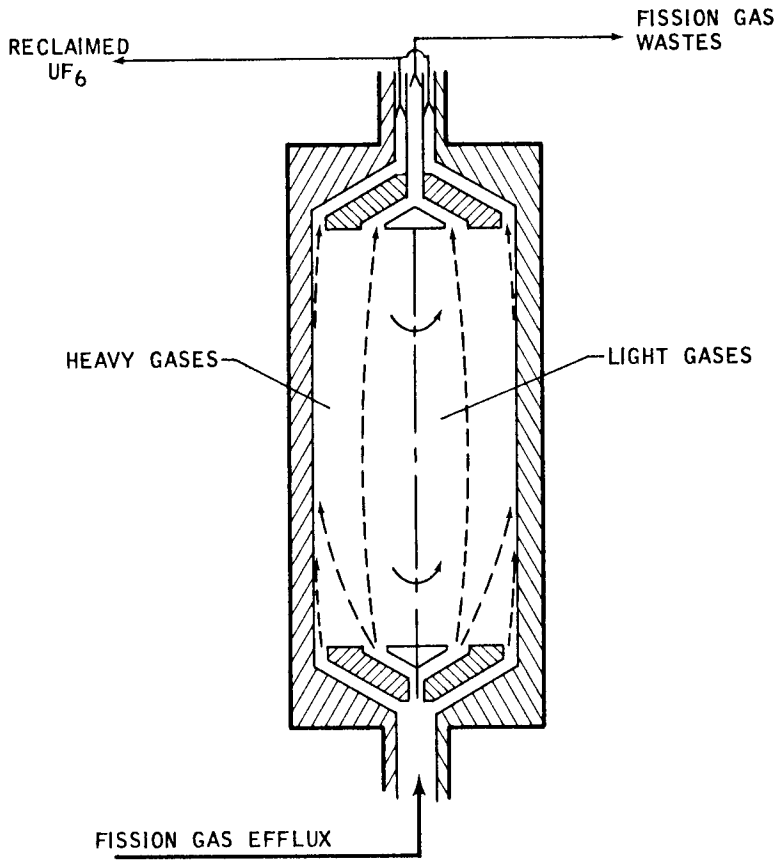

Fig. 9-5 Simplified Schematic of the Gas Centrifuge

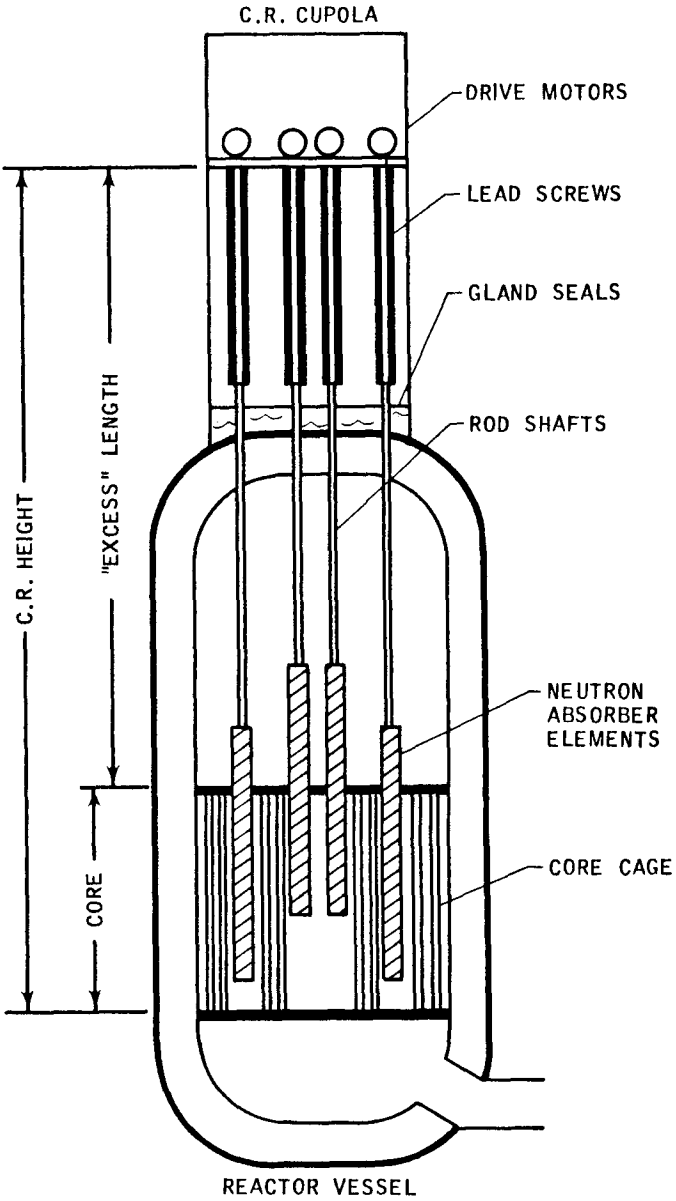

Fig. 9-6 Typical "Lengthiness of Mechanical Control Rods

the length of the absorber elements in the reactor core.* Nuclearly, only the absorber elements control the fission multiplication and the rest of the rod is excess length necessary to move the absorber elements up and down. This excess length poses added materials, corrosion, and warpage problems which we would like to avoid. The shaft bearings, seals, and couplings are of precision design. Internal fouling in the reactor or external mechanical shock could misalign these rods and cause them to jam. The excess length also poses added cooling, flow baffling, and hydraulic vibratio al problems in the reactor internal design. If there were some way to shorten these control rods—and still perform the same nuclear function —the reactor vessel could be simplified. Its over-all height could be much reduced.

A further disadvantage of mechanical control rods is the distortion they cause to the power profile in the core. Since the absorber elements absorb neutrons, the absorption takes place only where the elements are located. As a result, the neutron (power) profile "dips" at the absorber elements . . . and "peaks" in the regions in between. Where there are a multitude of absorber elements, the neutron profiles become much distorted (see Fig. 9-7). The distortion appears axially and radially, and changes with operating time. This accelerates local burnup of the fuel, and necessitates refueling at more frequent intervals. There is left much unburned fuel in the unpeaked regions of the core.

The absorber elements are nonproductive, powerwise, and they take up valuable space in the active core. They also distort the neutron moderation and coolant flow. Extra structural material is required to support and protect them. This increases the volume of the core, its cost, and its complexity. Some scheme for structurally combining the absorber elements with the core cage structure certainly would simplify the situation. Such a scheme might conceivably involve using a controllant gas.

9-11 Control with BF_3 Gas

Another member of the fluoride gas family is BF_3: boron trifluoride. This is a gas at ordinary temperatures. It is a well-behaved gas and therefore follows the principles of gas dynamics previously discussed (Sec. 9-1). It is entirely conceivable that BF_3 could be injected into fixed tubes or shells directly in the reactor core. If so, the controllant gas could control the excess fission neutrons just as readily as the absorber elements of mechanical control rods.

The principal ingredient of BF_3 that gives us the neutron control-by-absorption is boron. Boron has long been used in reactor technology as a control rod and shielding material, mostly in the solid state (recall

* On the *SAVANNAH*, for example, the neutron absorber elements are approximately 5½ ft long. The reactor vessel height is approximately 26½ ft, above which there is a control rod cupola extending approximately 24 ft. Thus, the total over-all rod length is almost *ten times* the useful nuclear length of the absorbers!

Sec. 6-7). Boron is favored because it has a linear neutron absorption pattern which permits reasonably predictable behavior with operating time.

Boron in its natural state consists of two isotopes; namely: B-10 and B-11. Their isotopic abundances are 19% and 81%, respectively. Principal interest is in B-10. It has a thermal neutron absorptivity of about 4000 barns compared with virtually zero absorptivity for B-11. Consequently, when considering BF_3 gas as a reactor controllant, we are thinking in terms of $B^{10}F_3$. However, we shall drop the superscript 10.

The concept of using BF_3 gas as a reactor controllant is not new. One researcher was successfully able to control a low power reactor by such

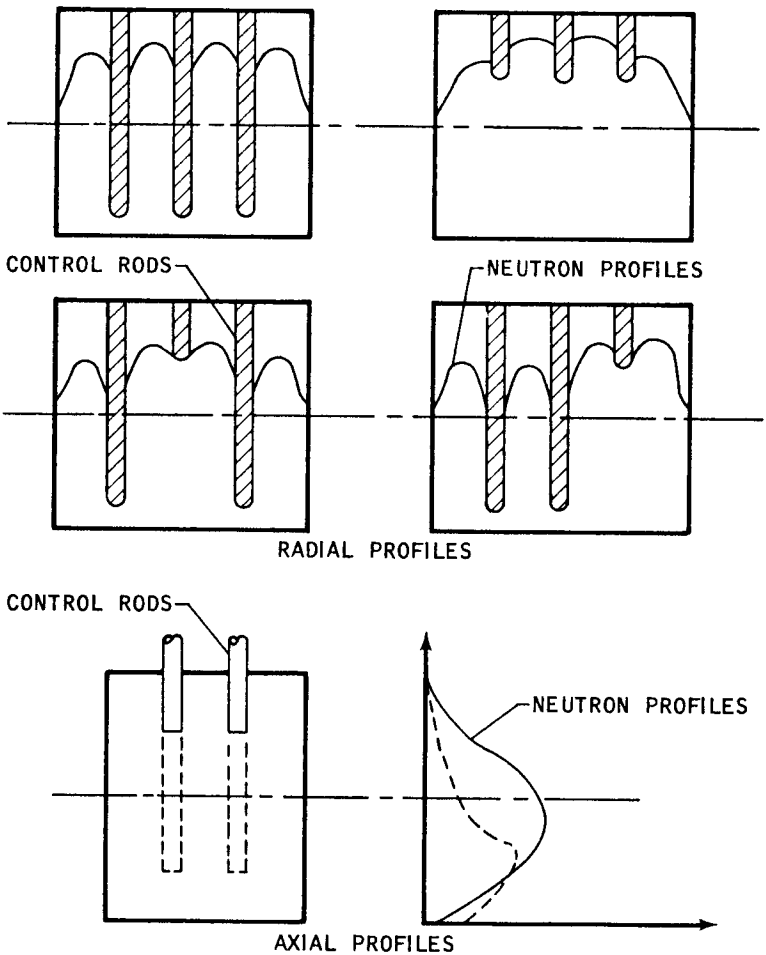

Fig. 9-7 Distortion of Neutron Profiles with Mechanical Control Rods

means.* He inserted a gas-filled tube in the reactor core, and used an external means for varying its pressure (Fig. 9-8). He found that "fine control" of the reactor—in contrast to coarse or large control—could be accomplished by varying the gas pressure. Variations in gas pressure, in turn, varied the number of boron-10 atoms in the core. He recognized that "a gaseous control system would be much less expensive than a system using control rods." But he concluded that such control would not be possible for high power reactors where a large amount of solid excess fuel is built in. The number of gaseous atoms of B-10 to overcome the solid excess atoms of U-235 would be prohibitively great.

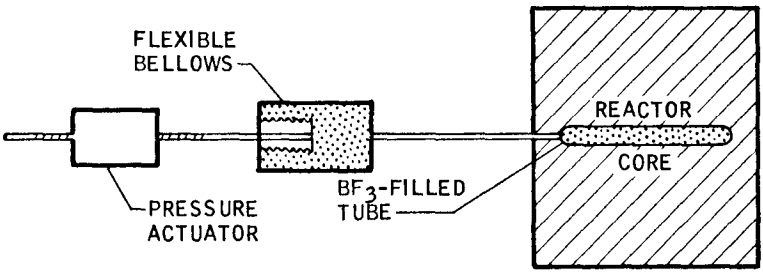

Fig. 9-8 BF_3 Gas Control System Used on Test Reactor

But in our case, if UF_6 gas were used as a fuel feed only, we would never have any substantial excess fuel in the reactor. The UF_6 fuel principle is one of positive feed to continuously compensate for the fuel burnup as it occurs. This is an entirely different concept from present-type reactors where all of the fuel for a year or two's operation is built in at one time. With UF_6 at operating power level, there could be only small transient excesses of fuel atoms. It would seem, therefore, that these transient excesses could be fine-controlled with BF_3 gas.

A possible scheme for using BF_3 gas to control a reactor is shown in Fig. 9-9. A system of hollow, concentric shells ("window shades") could be designed as an integral part of the core cage structure. These shells would conform to the geometry of the fuel and moderator elements, which may be circular, square, or hexagonal in shape. Or there could be special controllant tubes strategically located around the core to give uniform gas distribution. The shells or tubes would be appropriately manifolded and connected to a regulated gas supply, external to the reactor vessel and its shielding. There could be separate means to pump off any excess BF_3 gas.

* Ref: "Using Boron-Trifluoride Gas for Reactor Control," W. E. Cawley, *Nucleonics*, Aug., 1955, pp. 30 ff.

With any variant of the above gas controllant scheme, there would result very significant reductions in over-all reactor vessel size, and in the total amount of primary shielding required. Too, the improved uniformity of fission control—due to self-compensation (diffusion) of the BF_3 gas molecules—would permit greater power output from a smaller reactor size. These possibilities suggest that gas controllants may be one of the more promising break-throughs for all reactor designs.

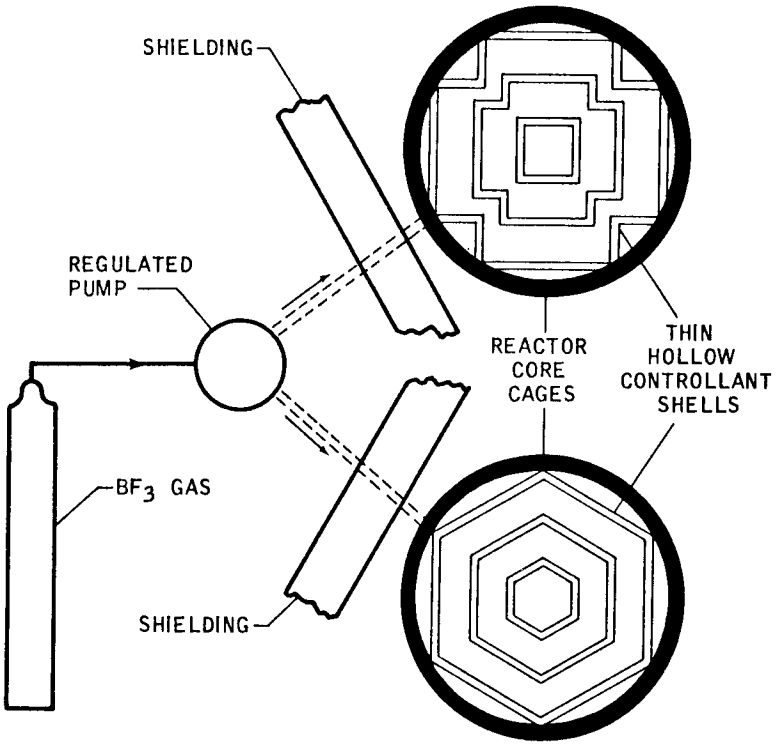

Fig. 9-9 Alternate Geometry for Gas Controllant Shells in Reactor Core

SUMMARY

We would like to go beyond presently conceived marine reactor features, and determine possible areas for technical break-throughs. If successful, we could advance all future nuclear ship reactors. The direction in which we would like to advance is toward simplicity and safety. In this regard, there exists a vast field of maritime research, if we consider the dynamics of gases for other purposes than reactor coolants.

Gases are the simplest forms of molecular matter, and they respond very sensitively to pressure and temperature changes. A mixture of different gases, when in a constrained environment, will diffuse (spread out) and effuse (pass

through barriers) in a characteristic behavior which has been long known. The response to temperature is a function of molecular weight which is characteristic of each type of gas.

The basic nuclear fuel produced by Government-owned gaseous diffusion plants is UF_6: uranium hexafluoride. This material is solid at ordinary temperatures but sublimes (vaporizes) readily at 135°F. In gaseous form, UF_6 would appear to be the most economic nuclear fuel form available. Yet, this UF_6 gas is converted into solid fuel, typically UO_2, by a multitude of chemical, powder-metallurgy, and mechanical fabrication steps that are costly . . . and complex.

As a short-cut fuel fabrication concept, we possibly could use the UF_6 gas as a one-way fuel feed . . . directly into ceramic-type fuel elements. The reactor coolant could be any other medium chosen for its superior heat transfer capabilities. If a direct UF_6 fuel feed scheme should prove feasible, nuclear fuel supply and replenishment would then be a simple matter of exchanging gas bottles like other gas bottles on merchant ships today.

When a $U^{235}F_6$ gas molecule is fissioned, two types of gases are generated: fission gases and volatile fluorides. The fission gases (about 20% yield) come from the U-235 atom split up. At the same time, six fluorine atoms are set free but they soon fluoridize nearby solid fission products into gaseous forms.

It is conceivable that both types of fission gas could be bled out of the fuel elements by effusion barrier techniques. There could be "effusion plugs" designed into the lower end of each fuel element whereby a pressure differential (greater on the inside of the fuel element) could be maintained. In the bleed-off efflux, however, there would be some unburned UF_6. But the fuel gas could be reclaimed by small-scale combinations of fluoride distillation techniques and the gas centrifuge.

It is also conceivable that gases could be used to nuclearly control a fission reactor and, in fact, this already has been done on a low power test reactor. The gas used was $B^{10}F_3$: boron trifluoride.

When using UF_6 gas as a continuous fuel feed, there would be only transient excesses of fissionable fuel in the reactor. These excess fuel atoms could be fine-controlled with BF_3 gas. Means could be provided for injecting the gas controllant into concentric hollow shells forming part of the core cage structure or into strategic controllant tubes throughout the core. The use of gas controllants would nullify the excessive lengths of mechanical control rods and shafts, and would permit a more uniform power profile in the reactor core. The net consequence would be a smaller reactor (therefore, less shielding, too) of higher power capabilities. Such a possibility is attractive for all types of nuclear merchant ships.