CHAPTER 8

Gas Reactor Turbines

The "ultimate" nuclear plant for merchant ship propulsion appears to be some form of direct cycle reactor-turbine, eliminating steam and other forms of intermediate heat exchange. There are indications that such a cycle may be a pressurized gas reactor coupled directly to a gas turbine. The turbine, in turn, may be coupled to a controllable-pitch propeller (for reversal). A ship propulsion plant of this type offers a number of advantages in terms of increased nuclear, thermal, and mechanical efficiencies. Temperature, however, appears to play the key role. For example, at 1800°F a simple gas turbine will develop 60% more (1250 K) power than at 1200°F. But reactors cannot yet attain these tem- (925 K) peratures. The only hope of doing so appears to be with gas cooled reactors, possibly using helium. However, since numerous developmental problems exist, the ultimate nuclear ship is some years away.

8-1 The Ultimate Simplified

The direct reactor-to-turbine gas cycle is referred to as a "closed cycle" system because the gas coolant is recirculated continuously. It is like the primary loop of any of the reactor systems previously described (Ch. 7). In lieu of the heat exchanger we have a gas turbine and cooler, and in lieu of the pump, a compressor (see Fig. 8-1). In the closed loop, the fission heat generated in the reactor is converted directly into mechanical rotational torque on a propeller shaft. What could be more direct or more simple than this?

The direct conversion of reactor heat into rotational torque is a form of "bootstrap" operation. The compressor pressurizes the gas, thereby imparting to it the driving force through the reactor. The reactor heats the gas at near-constant pressure, thereby causing its volume to increase. This increased volume of high-pressure gas enters the turbine which is primarily a pressure sink. The gas expands; its velocity accelerates, imparting high speed to the turbine rotor. This rotor in turn rotates the compressor which pressurizes the gas in the first place.

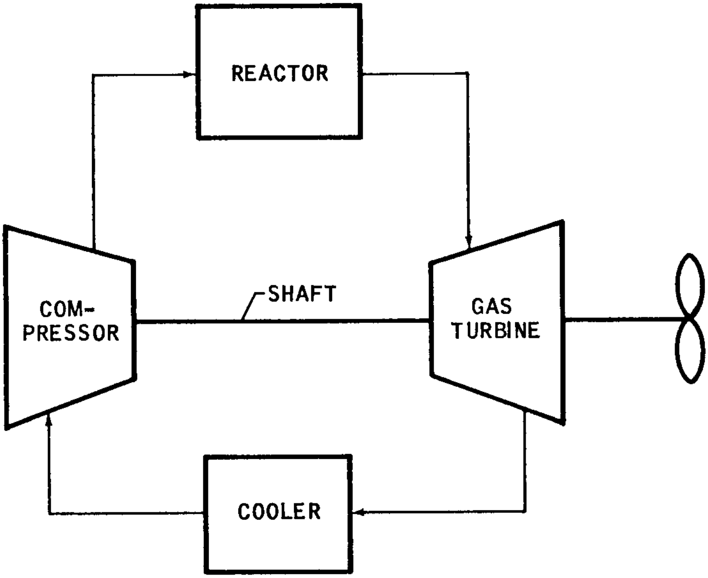

Fig. 8-1 Simplified Loop of Closed Cycle Reactor-Turbine System

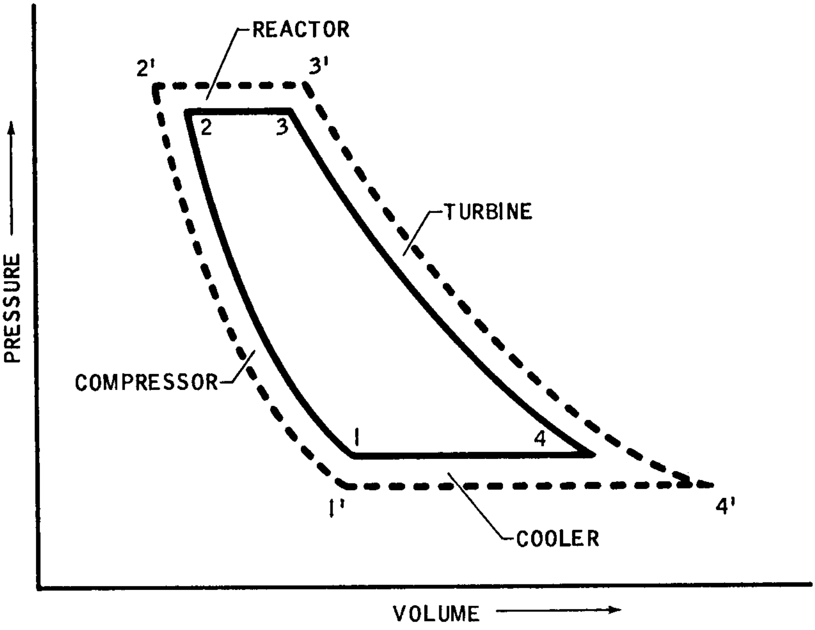

Fig. 8-2 Idealized P-V Diagram for Simple Gas Turbine

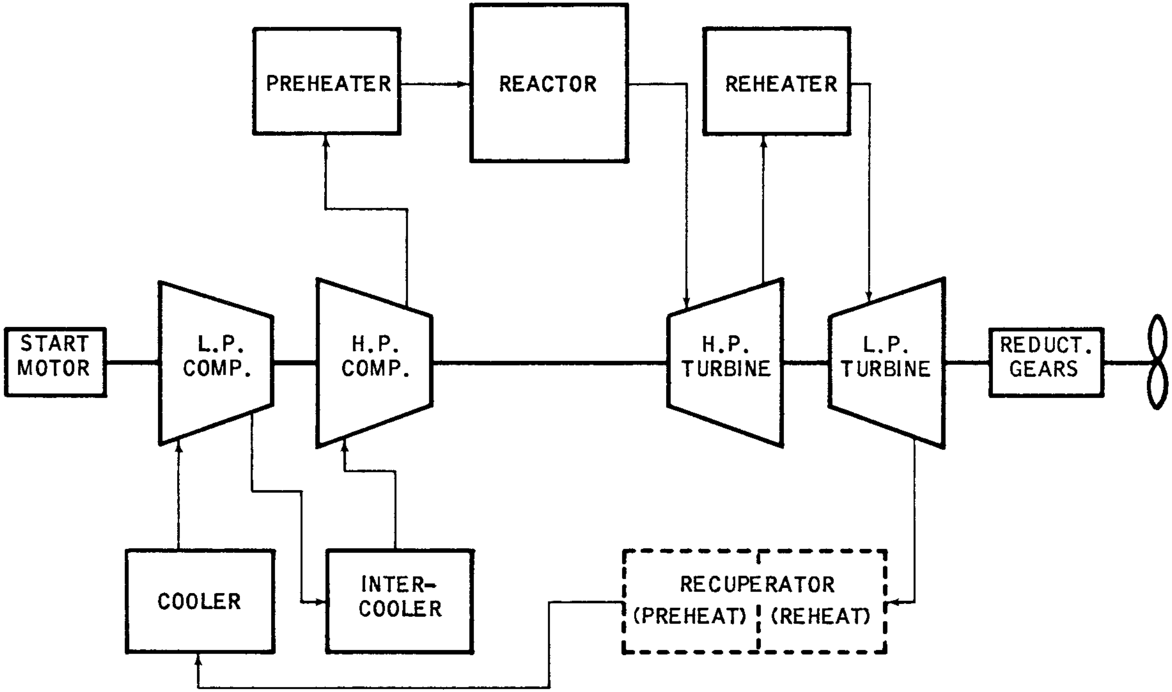

Fig. 8-3 Possible Arrangement for Nuclear Ship Gas Turbine Propulsion

When the gas leaves the turbine, its volume has increased considerably, and its pressure has decreased . . . also considerably. Its temperature is still high. A cooler is used to reduce this temperature before the gas re-enters the compressor. Otherwise, re-compression would be difficult if not impossible.

This simple gas turbine cycle has its origin in the ideal gas laws of physics, namely:

$$P \cdot V = R \cdot T = \text{constant}$$

That is,

$$\text{pressure} \times \text{volume} = \text{gas} \times \text{temperature} = \text{constant}.$$

This idealism tells us that, for a given gas, we can alter two of its three physical properties (pressure, volume, temperature) while holding the third property constant.

In the compressor, we try to hold the temperature constant; we increase the pressure and reduce the volume. In the reactor, we try to hold the pressure constant; we increase the temperature and increase the volume. In the turbine, we try to hold the temperature constant; we decrease the pressure and increase the volume. And in the cooler, we try to hold the pressure constant; we decrease the temperature and decrease the volume. These relationships are more evident in the P-V diagram of Fig. 8-2.

8-2 Refinements to the Cycle

The area enclosed by the 1-2-3-4 cycle in Fig. 8-2 is the net amount of power produced by the gas turbine. Unfortunately, this represents only about ⅓ of the total power. This is all that is left over after the compressor takes its share. In other words, the compressor takes ⅔ of the turbine power, leaving only ⅓ for the propeller shaft. These are facts of gas turbine life.

The area of Fig. 8-2 can be increased in one or more of the following ways:

(1) Increasing gas compression
—in which case Point 2 moves up to 2′;
(2) Increasing reactor temperature
—in which case Point 3 moves over to 3′;
(3) Increasing pressure drop across turbine
—in which case Point 4 moves down to 4′;
(4) Increasing temperature drop across cooler
—in which case Point 1 moves back to 1′.

The greatest single area-increase comes from increasing the reactor temperature. But as we shall see later, there is a limit in this regard. Consequently, other refinements have to be made. These take the form of multi-stage compressors, multi-stage heaters, multi-stage turbines, and multi-stage coolers.

Since the turbine exhaust is quite high in temperature, as much of this heat as possible is recuperated (recovered). This is done in the form of preheating the inlet gas to the reactor, and reheating the gas between turbine stages. The residual heat is dumped overboard.

There are many possible arrangements of multi-staging and compounding of turbines, coolers, and compressors. The most probable for nuclear ships may be a two-stage system much as schematized in Fig. 8-3.* A corresponding P-V diagram is shown in Fig. 8-4.

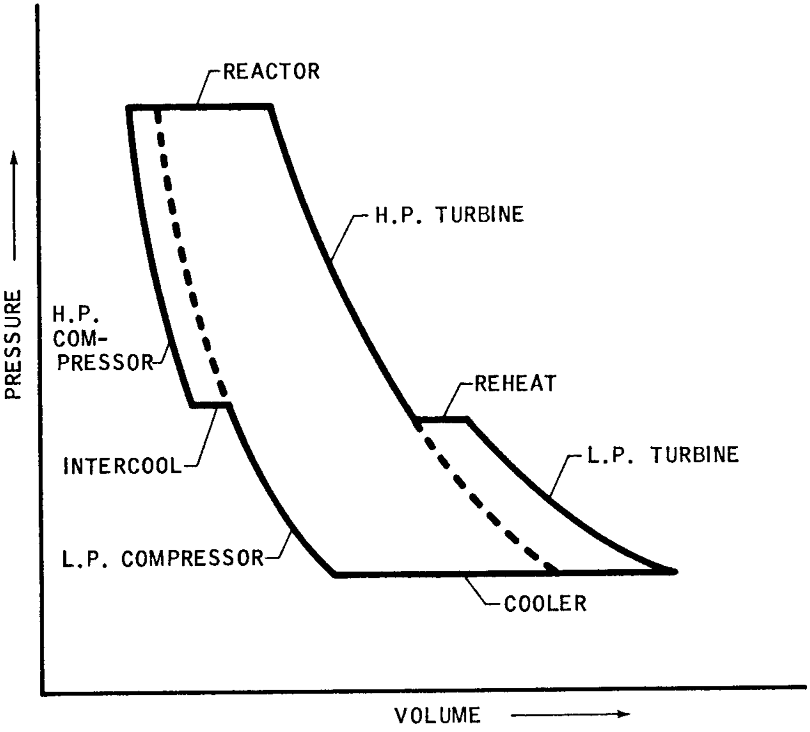

Fig. 8-4 Idealized P-V Diagram for Two-Stage Gas Turbine

8-3 Competition from Steam

The gas turbine cycle described is similar to that of the steam turbine cycle so well standardized on merchant ships today. The principal difference is that gas is used instead of steam. The P-V-T relationships are more nearly ideal for a gas than they are for steam, and hence there is a better possibility of getting more useful work out. Another feature is that the gas does not undergo a phase change as in the case of water to steam, or of its condensate: steam to water.

In practice, both the gas and steam cycles are nearly on a par, considering the net useful mechanical work produced. The gas cycle uses most of the energy stored in the gas to drive the compressor, and a certain propor-

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* Note the necessity for a starting motor to get the compressor-turbine "bootstrap" going.

tion is lost in the coolers. The steam cycle, on the other hand, gives away the great bulk of its energy nonproductively to the condenser. However, the condensate—which is the reactor coolant—can be pumped back through the primary loop at far less a power consumption than required by gas compressors. This gives the steam cycle the edge in over-all plant efficiency. This competitive edge holds true up to a "cross-over" temperature of about 1400°F (see Fig. 8-5).[*]

(1000 K)

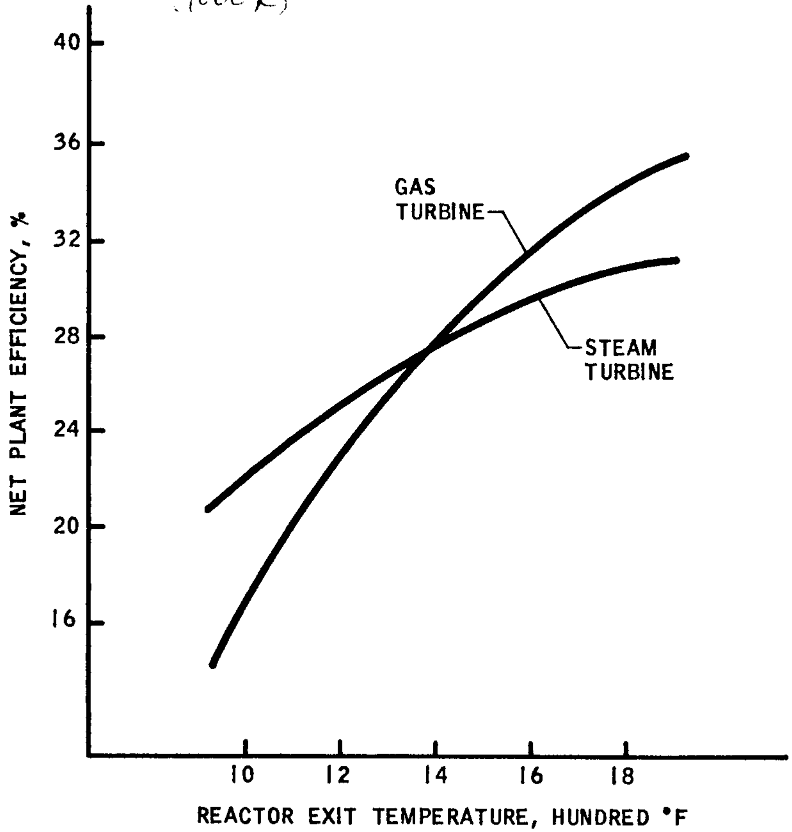

Fig. 8-5 The Temperature "Cross-Over" of Turbine Efficiencies

Another factor of competitive interest between the two cycles is performance at startup and low speeds. A gas turbine, because of its compressor, doesn't become self-sustaining until up to about 25% of its design speed.[†] Consequently, at speeds less than this amount, a starting motor

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[*] Ref: *The Reactor Handbook, Vol. II, Engineering,* AECD 3646, March, 1955, p. 377.

[†] Ref: "Gas Turbines," *Mechanical Engineers' Handbook,* L. S. Marks, Fifth Edition, McGraw-Hill, 1951, p. 1257.

is required to get the turbine-compressor going. Here again, (i.e., at low turbine speeds), the efficiency of the steam turbine has the edge over gas turbines.

Still another factor in favor of the steam turbine is its long developmental history of successful marine applications. Single steam turbine units (high- and low-pressure compounded) of 20,000 HP are common . . . and some go up to as high as 60,000 HP (in the case of the S.S. *UNITED STATES*). In contrast, the largest installed marine gas turbine (single unit) is 3000 HP. Two such gas turbine units have been installed on each of the Liberty Ships *JOHN SERGEANT* and *WILLIAM PATTERSON*.* These two gas turbine ships are considered to be an outstanding technical success. But since, from the nuclear point of view, we are only interested in large ships—in excess of 20,000 SHP, marine gas turbines have a long way to go to overcome the competition from steam. Indeed, the competition from the steam turbine is the major "problem" facing the ultimate nuclear plant for merchant ships.

8-4 Temperature Difficulties in Reactor

From Fig. 8-5, it is evident that the temperature range of interest to gas cooled reactors—driving either steam or gas turbines—is 1000° to 1800°F. What is not so evident is that the attainment of even 1000°F in a reactor meets with difficulty.

When we realize that the temperature of combustion gases in the furnace of a standard marine boiler attains the order of 3500°F, we ask (2200K) ourselves: Why is 1000°F so difficult in a gas reactor? Let us look at the situation in reverse. Let us start with a reactor exit gas temperature of 1000°F and work uphill (recall Sec. 5-1) to explore the temperatures involved. Let us ignore thermal stress.

When the 1000°F gas coolant comes in contact with the surface of a nuclear fuel element, a film barrier called "boundary layer" builds up. This film shuts out intimate contact of the fast-moving gas with the fuel element surface. This film is made up partly of gassified atoms of the metallic cladding material, and partly by the coolant gas atoms trapped by the frictional roughness of the cladding surface. To drive across this film barrier, a temperature difference on the order of 300 to 500°F is required. Taking into account the temperature drop across the cladding wall itself, and hot-spot uncertainties, we are up to a temperature of around 1500-1600°F on the fuel-side of the fuel element cladding.

If we consider type 310 stainless steel as a standard high-temperature cladding material, as used in the *SAVANNAH* reactor, we note a drastic fall-off in its tensile properties in the range of 1200 to 1600°F (see Fig. 8-6). But even so—up to 2000°F—there is adequate structural strength (around 10,000 psi) for the fuel elements if no other forces came into play.

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* Ref: "Technical Progress in Marine Engineering During 1957," *Journal of the American Society of Naval Engineers*, May, 1958, pp. 245 ff.

Inside the fuel element, where the actual fissioning is taking place, the temperatures are higher still. We have already acknowledged (Sec. 3-5) that the central temperatures may be as high as 5000°F without any consequences to the fuel itself. But, what about those fission residue gases? They are gases, and they behave PVT-wise just like the gas coolant.

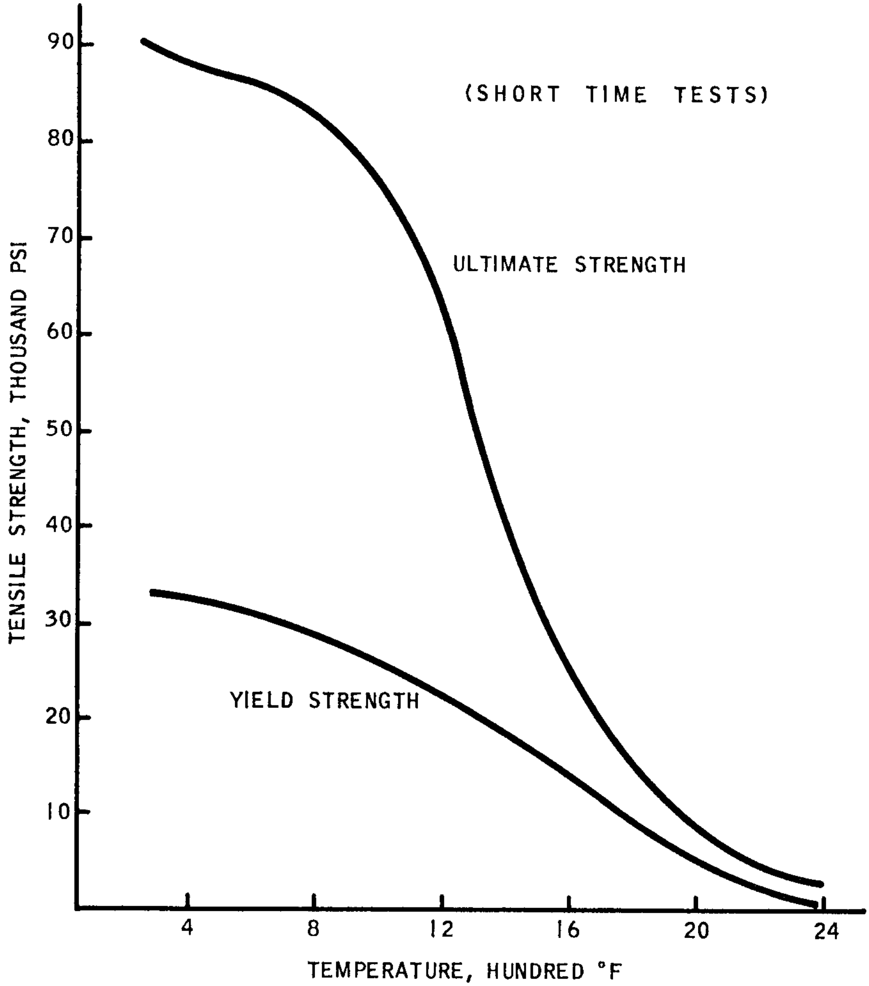

Fig. 8-6 Typical Temperature Strength of Stainless Steel

When we hold their volume constant (as we do when we try to contain them in the fuel element) and increase their temperature, their pressure builds up . . . very significantly. The longer the reactor operates, the greater the amount of fission gases generated and the greater the pressure forces built up.

Thus, at high temperatures we have a continually increasing internal force acting against a diminishing restraining force: the fuel element walls. Sooner or later, the fuel elements will rupture.

We could avoid fuel element rupture altogether if we used tungsten, say, which has the highest high-temperature strength of any known material. At 2000°F, for example, tungsten has an ultimate strength of about 70,000 psi . . . as against about 10,000 psi for stainless steel. But unfabricated tungsten sheet costs about 30 times that of stainless steel! And, even worse, tungsten captures about 10 times more thermal neutrons than does stainless steel. This means that more high-cost nuclear fuel has to be added to each fuel element to compensate for the neutrons that would be lost to the tungsten. The same situation, to a lesser degree, holds true for other famous high-temperature materials.

So, we try various materials back and forth, and spend years of research trying to find a satisfactory cladding material for fuel elements in a gas reactor.

8-5 Nuclear Consequences of Temperature

Even with the right combination of materials for high-temperature fuel elements, nuclear factors impose a limit on how high in temperature we can go.

Table 8-1. Fission Probability of U-235 at Selected High Temperatures

Fuel Temp. °F	Neutron Energy ev	Fission Probability barns
100	0.026	565
1,000	0.070	315
1,250	0.082	100
1,500	0.094	260
1,750	0.108	250
2,000	0.118	240
2,250	0.130	220
2,500	0.142	210
2,750	0.153	205
3,000	0.166	200

Ref: "Uranium-235 Neutron Cross Sections", D. L. Kavanagh, Nuclear Science and Engineering, August, 1958, pp. 161 ff.

(1400K)

For example, assume that the average temperature inside of a fuel element is 2000°F. At this temperature, the "thermalized" energy of neutronic fission is 0.118 ev. By reference to nuclear tables on the fission cross section of U-235 (see Table 8-1), we note that at 2000°F the fission probability is 240 barns.* This is about 25% less than at, say, 1000°F. This means that we have to add additional fuel to compensate for the diminishing fissionability of the fuel . . . at increasing temperatures.

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* Recall Sec. 1-11 for the definition of a "barn" (i.e., 10^{-24} cm^2).

An even more drastic nuclear situation occurs in the fission gases, particularly xenon-135 This is the predominant fission-generated poison discussed in Sec. 1-11.[*] In a way, xenon poison is a built-in safety feature at temperatures below about 1250°F, where the neutron absorptivity is on the order of 3×10^6 barns. At these temperatures, xenon-135 functions as a burnable poison much in the same way as if we deliberately put it there to control the fuel in excess of criticality. It saves on the number and size of control rods that we need. Now, if the temperature at which the xenon is being accumulated and burned is increased beyond 1250°F, a sharp drop in its poisonability occurs (see Fig. 8-7). At 2000°F, the poison capability falls to 0.75×10^6 barns which is a drop of 2.25 million barns. This is equivalent to adding 10,000 atoms of U-235 for every atom of xenon in the fuel element. In other words, the higher the temperature the greater the fall-off in xenon poison; simultaneously, the core fission multiplication increases . . . markedly.

This poison fall-off may be thought of as desirable, since we are effectively adding fuel. But this imposes stringent requirements on the control system. The effective fuel added has to be compensated by control rod poisons; otherwise the fission process will run away. However, the poisons built in to the control rods *also decrease with temperature!* Soon there arises a practical limit to the size and number of control rods that can be used.

Furthermore, at high temperatures, it is necessary to determine *new* nuclear constants that go into the criticality calculations of Ch. 4 (e.g., f, p. τ, L^2). Neutron absorption, scattering, and diffusion data all have to be redetermined at high temperatures. Extensive—and costly—laboratory equipment is required in order to do this.

8-6 Aerodynamics in Gas Reactors

As we push toward higher temperatures in gas cooled reactors, we have also to deal with the aerodynamics of the coolant flow. This involves a study of flow profiles induced by high velocities through the reactor core.

The coolant velocity is directly related to temperature in the form of $v = \sqrt{C_1 T}$ where C_1 is a coefficient based on the properties of the particular gas coolant (assuming pressure and volume constant), and T is temperature. In gas reactors, we are dealing with velocities approaching the order of 250 ft/sec . . . or approximately 150 knots! This is a sharp contrast to the flow velocities in liquid cooled reactors where the coolant flows on the order of 25 ft/sec . . . 10 ft/sec in the case of the *SAVANNAH*.

The consequences of high gas velocity through a reactor are many-fold. One of the foremost is boundary layer, again. In each coolant channel, the

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[*] The fission yield of xenon-135 is 6.2%. That is, for every 100 atoms of U-235 fissioned, we get 6 atoms of Xe-135. Ref: "Uranium-235 Fission Product Production," Blomeke & Todd, Oak Ridge National Laboratory (ORNL-2127), p. 35.

flow builds up in a long wedge-shaped manner, on top of the film barrier previously mentioned (Sec. 8-4; see Fig. 8-8). This velocity wedge keeps the coolant farther away from the heated surfaces of the fuel element, thereby reducing the effectiveness of heat transfer. If the wedge builds up too much, as it would in long, small-diametered tubes, the wedge will choke and thereafter block any further passage of the gas coolant (called "thermal choking"). This would starve a tube . . . then burn out.

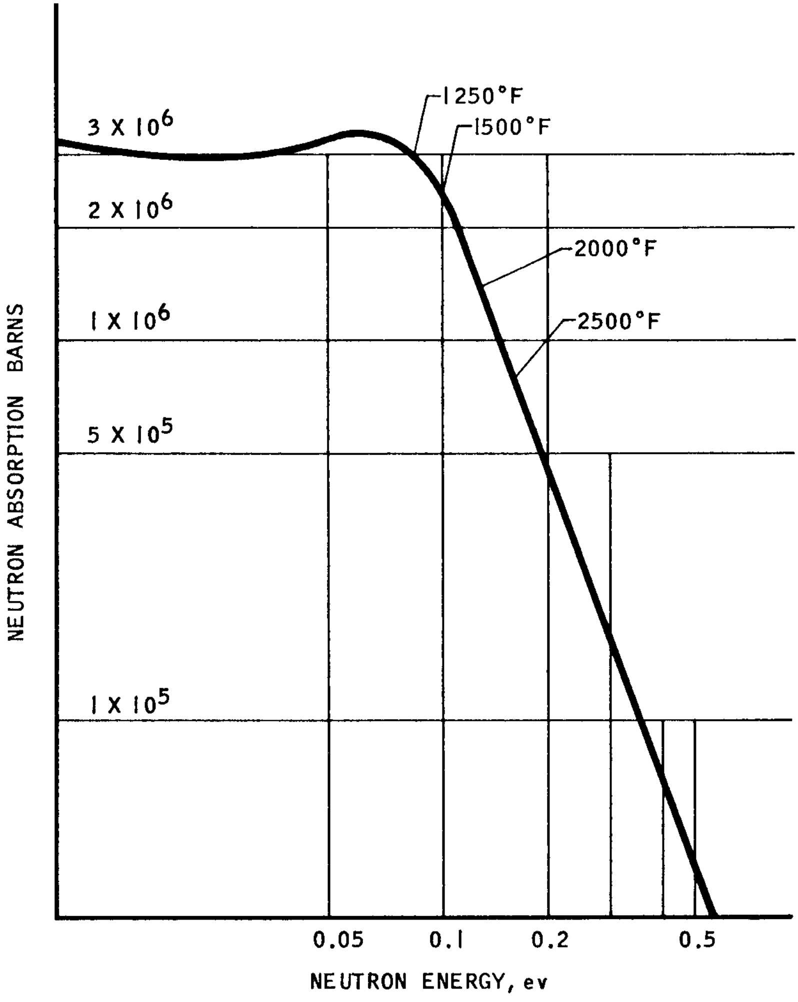

Fig. 8-7 Fall-Off of Xenon Poisoning at High Temperatures

An effective way to break up this boundary layer is to use interrupted (staggered) fins. But care must be taken in their design not to just separate the boundary layer, as thermal choking may then occur further upstream.

The trouble with interrupted fins—and cooling fins in general—is that they increase the resistance to gas flow, thereby increasing friction. This, in turn, increases the pressure drop through the reactor. The relationships involved are:

$$\Delta p = C_2 f v^2 \frac{L}{D} \quad \text{psi} \qquad \text{[Eq. 8-1]}$$

where C_2 is a gas properties coefficient, f is the friction factor, v is velocity, and L and D are length and diameter of the coolant channel.

The importance of pressure drop through the reactor is that aerodynamic energy is lost which otherwise could be imparted to the gas turbine. To overcome this loss, we have to heat the reactor up more. A pressure drop is also experienced at the inlet and exit to each coolant channel in the reactor, at bends and turns in the coolant ducting, and at other constrictions in the primary loop. In all of these pressure drop situations, friction and velocity—particularly velocity because of its v^2 relationship in Eq. 8-1—have a profound effect on the net efficiency of the turbine plant.

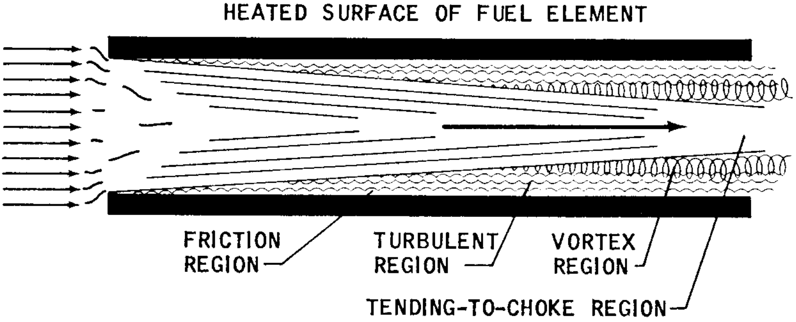

Fig. 8-8 Exaggerated Effect of Boundary Layer Buildup in Gas Reactor

We can reduce pressure drop by reducing velocity. But when we do this, we have to either reduce the reactor power or increase the area of coolant flow through the reactor core. This is apparent in the following relationship where we wish to keep the heat output unchanged:

$$\text{Heat}_{out} = C_3 A_c v \Delta T_c \qquad \text{[Eq. 8-2]}$$

where C_3 is another gas properties coefficient, A_c is the area of coolant flow, v is velocity, and ΔT_c is the temperature difference between exit and inlet reactor gas temperatures. (Compare with Eq. 5-6.)

If we reduce velocity by increasing A_c, we get a larger, less nuclearly efficient reactor. We could reduce velocity by increasing ΔT_c, but then we run up against temperature limitations again.

To minimize losses due to the velocity of coolant flow, the reactor internally has to be aerodynamically contoured with great care. Streamlining becomes a major area of experimental design. Instead of ordinary top and bottom grid places (Sec. 6-5) to hold the fuel and moderator elements in place, we have to use aerodynamic grids. The inlet aero-grid would break up the large single stream of incoming coolant into a multitude of small streams tailored to each cooling channel in the core. The grid must distribute the coolant gas equally to all reactor tubes, while at the same time maintaining a uniformity of velocity and pressure profiles across the reactor as a whole. Only single-pass flow through the core could be used. The exit aero-grid would recombine the separate channel streams into one, thereby re-creating as nearly as possible a homogeneous distribution of temperature, pressure, and velocity.

8-7 Agreement on Helium

There are no compelling thermodynamic reasons for omitting any of the common gases (e.g., hydrogen, helium, CO_2, nitrogen, and air) as a reactor coolant. All have comparable thermal properties, and none is outstanding when compared to water, terphenyl, or sodium. On a strictly volumetric heat capacity basis (ρc_p—recall Sec. 5-6), hydrogen is somewhat better than helium . . . with CO_2 third. Yet, there is general agreement that helium is the best choice for temperatures *above* 1000°F. Many gas cooled reactor concepts attest to this.*

Hydrogen is disadvantageous nuclearly because it captures thermal neutrons to some extent. Its principal disadvantage is metallurgical in nature, well known as "hydrogen embrittlement." It attacks container materials and when under pressure is an explosive hazard. CO_2, normally thought of as chemically inert—and it is at low temperatures—begins to dissociate at temperatures above 1000°F and therefore sows the seed (oxygen) for high temperature corrosion. Its stability under nuclear irradiation for long periods of time is uncertain.

Helium, on the other hand, is the most stable gas available to man. In its pure form, it is both nuclearly and chemically stable . . . at any neutron or temperature level. It does not attack container materials, though it leaks through closure joints and welding seals with annoying ease. Its principal disadvantages are its easy leakage and impurities. It costs about twice as much as CO_2 but this is expected to come down with widespread use.

Commercial helium contains several parts per million of hydrogen, water vapor, air, argon, nitrogen, and CO_2. These ingredients are neutron traps; they breed corrosion and, hence, they are undesired. Consequently, a helium purification system is needed as part of the reactor plant. Make-up

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* Ref: "Closed Gas-Cycle Nuclear Power Plants," Buhler and Gingo, *Advanced Propulsion Systems Symposium*, Los Angeles, Dec., 1957, pp. 117 ff. Also "Small Gas-Cycle Reactor Offers Economic Promise," F. Daniels, *Nucleonics*, March, 1956, pp. 34 ff.

helium can be stored in small, high pressure gas bottles (like CO_2), which certainly is an operating convenience.

8-8 Filters and Heat Exchangers

If all went well, we could pipe the purified helium directly from the reactor to the turbine, thence to the compressor, and back into the reactor again. It would be perfectly safe in the reactor, as it would not become radioactivated. It would be perfectly safe in the turbine, as it would not spawn high temperature corrosion. And any leakage in the turbomachinery and piping—and there would be some—would present no operational hazard. Costwise, excessive helium leakage would be disturbing to ship operators, but otherwise the direct reactor-to-turbine closed loop cycle would be technically feasible.

But, in a practical situation, all won't go well. The most precautious reactor-turbine design and the most exacting pre-startup cleaning procedures will not remove all of the dust, dirt, scale, welding spatter . . . and cigarette butts, inside the newly constructed coolant loop. These particulates of matter are picked up and fluidized in the helium stream . . . and forever remain. They are natural seeding-points for radiocontamination as they pass through the reactor core. To assure that these radiocontaminants do not deposit in the turbine and compressor castings, filters are required.

Even if we were to start with a perfectly clean system, the helium would soon generate its own erosive dust from the materials which contain it. Remember, the helium is hot, dry, and blowing by metal surfaces at up to 250 ft/sec. It will erode the fuel element cladding. Much operating experience is required to see how extensive this erosive action really is. Pending such experience, filters would be a necessary feature on early nuclear gas plants. Fibre glass, paper, activated charcoal, and other commercial filters are available to do the job when the radioactivity level is low.

The radioactivity level would be high should fission residues from the fuel elements escape into the helium stream. Radioactive residues could escape through leaks in the fuel element cladding, by direct diffusion through the hot walls, and by recoil of outer-wall atoms from neutron interaction. These and other radioactivity escape possibilities must be considered as we drive higher and higher in gas reactor temperatures. To isolate the helium-borne radioactive residues from the turbine and its machinery, filters alone will not do.

Initially, therefore, we have no alternative but to install a heat exchanger and separate the closed cycle into two. One side of the heat exchanger would serve the reactor only, and the other side would serve the turbine only. Yes, this would add weight, space, and complexity to our reactor-turbine. There would be a penalty in net thermal efficiency, too. But a two-loop system is the only sound engineering course to pursue until the absolute reliability of marine gas reactors can be demonstrated.

These practicalities would temper our vision of an ultimate nuclear ship plant. We would have to be satisfied with the next-to-ultimate as an intermediate step. Surprisingly, there are advantages in doing so.

8-9 Next-to-Ultimate Plants

Optimization of the direct gas-reactor, gas-turbine marine propulsion plant is a more formidable task than appears at first glance. There are a staggering number of design parameters that must be taken into account.* There are many alternate cycle and powerplant arrangements. Weight and size are very sensitive to small deviations of certain parameters. Efficiencies are likewise sensitive. Differences in reactor size have a profound effect on total shielding weight. Temperature limitations are unknown. These and many other considerations suggest that it is best to separate the reactor and turbine completely: let each develop to its optimum in its own separate way. When this is done, the reactor and turbine may then be brought back together again into a direct, closed cycle.

Actually, there could be two next-to-ultimate ship propulsion plants: one using the steam turbine, the other the gas turbine. The same basic helium-cooled reactor would serve as the heat generator for each turbine type. The coupling between the reactor and turbine would be the heat exchanger. This device would be different for each turbine, of course. In the case of the steam turbine, the heat exchanger would be from helium to water, whereas for the gas turbine, it would probably be helium to air (see Fig. 8-9).

In the helium loop, a blower would replace the compressor as the primary driving force around the loop. The loop would be charged by an auxiliary compressor at startup (not shown), until the operating pressure was attained. Pressurization then would be maintained by a compressed-helium storage with appropriate pressure regulation. Blower speed control would be essential to varying the heat transfer to the heat exchanger. The blower would be totally enclosed, using helium for shaft and bearing seals.

The helium-reactor, steam-turbine cycle would be unlike that of the gas reactor of Sec. 7-9. At that time, we were concerned with reactor exit temperatures of around 1000°F and coolant pressures around 500 psi. We were interested then in producing Marine Standard Steam to compete with the sodium graphite reactor. But in the present case, we are concerned with reactor exit temperatures above 1500°F and pressures approaching 1500 psi. We want to get the size of the reactor down, and its heat performance up. We would exceed Marine Standard Steam at the turbine throttle. We would do this because we would want steam turbines to compete with gas turbines at the higher temperatures. Con-

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* Ref: "The Nuclear Design of Aircraft Reactors," D. S. Selengut, Paper No. 97, Nuclear Engineering and Science Conference, March, 1958. The aircraft reactor is an air-cooled, solid moderated reactor coupled directly to aircraft turbomachinery. Many of the technical principles involved are applicable to marine installations as well.

ceivably, the high temperature helium-reactor, steam-turbine plant would tempt innovations into the science and engineering of nuclear marine propulsion.

The helium reactor to gas turbine system would involve—in all probability—an open cycle air turbine instead of a helium driven one. There are good economic reasons for this. For one, an air compressor would be less than half as large as a helium compressor for comparable pressure ratios across the turbine. This is because the intake would be dense, cool, atmospheric air instead of light, warm, closed cycle helium. The

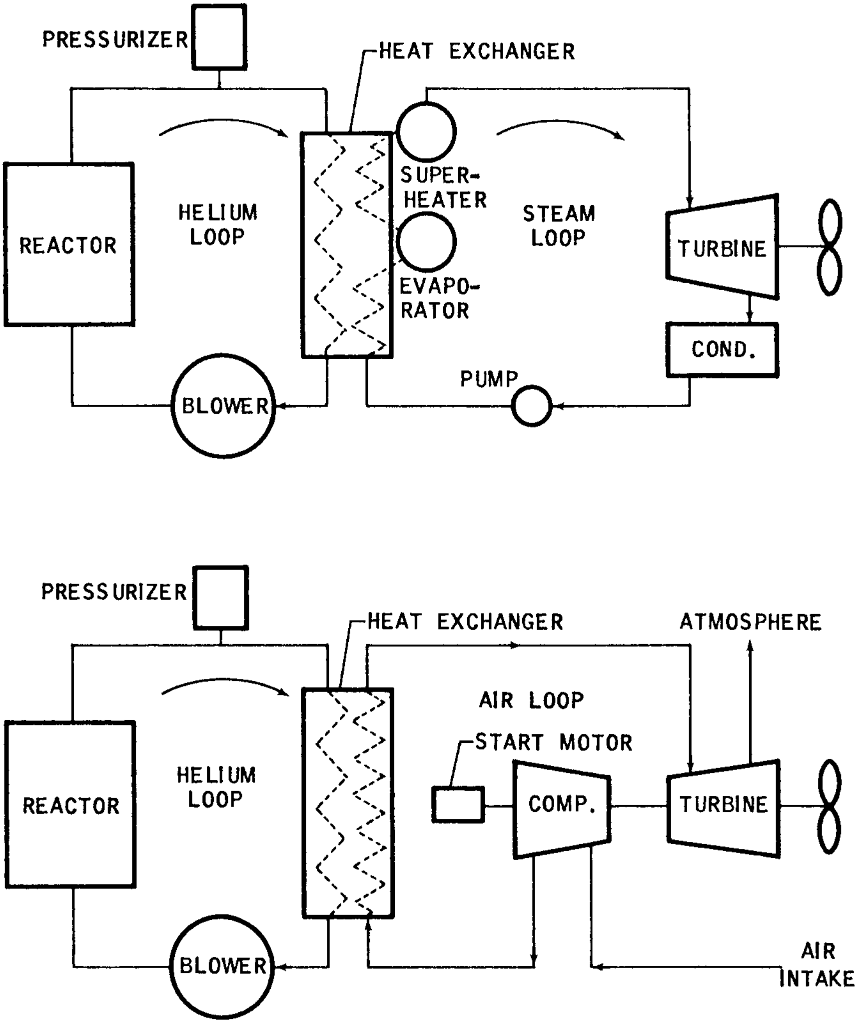

Fig. 8-9 Two Possible Next-to-Ultimate Nuclear Ship Plants

exhaust air, after recuperating as much heat as possible, would be discharged back to the atmosphere. An air intake and dryer would be required, but this could also serve as the turbine silencer.

8-10 Interest in Gas Turbines

Although gas turbines for marine applications were considered in Europe as early as 1910, it was not until 1947 that a gas turbine appeared in a United States vessel. Within ten years, the total installation of gas turbines grew to about 200,000 SHP. These were mostly small harbor and coastal ships of less than 3000 SHP. Nevertheless, there has recently grown a sharp interest in gas turbines for all ship sizes.

One reference points out that since 1952 there have been over 100 technical papers specifically on the subject of marine gas turbines.* This alone is an index of the course of events expected to follow.

This upsurge of maritime interest stems from the success of the aircraft turbine and the realization that it is an inherently high capacity prime mover.† It packs a lot of power into a relatively small space . . . with less weight . . . and less vibration. In some cases, savings of 25% cubic space and 45% deck area are reported.‡ At all ship load conditions (assuming near-constant turbine speed), the gas turbine is more efficient than the steam turbine. It is particularly superior at reduced loads and at overloads. Its near-constant efficiency over a wide range of load variations is especially attractive for merchant ships whose load conditions vary from voyage to voyage, and where sea conditions vary day to day.

The fact that air can be used as the working fluid has a profound effect on fuel economy and operational flexibility. The fact that the working fluid undergoes no phase transformation—as in the case of water to steam—attests to its inherent simplicity . . . and its safety. By varying the system pressure of the working fluid, its mass flow can be varied without changing the pressure ratio across the turbine or altering the turbine inlet temperature.

Once up to speed, the gas turbine has inherent self-stability. Increases in speed cause increases in energy absorbed by the compressor, and this increases the mass flow through the reactor. At a near-constant heat generation, the result is a drop in turbine inlet temperature. Thermal efficiency falls off . . . and thence the speed. This speed stability is one of the more promising operational advantages of gas turbines for merchant ships.

The gas turbine is basically a high temperature device, increasing steadily in efficiency from 900°F to 1800°F—the probable practical limit

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* Ref: "Marine Gas Turbines and Free Piston Gas Turbine Bibliography," J. W. Sawyer, *Journal of American Society of Naval Engineers*, Feb., 1955, p. 159.

† Ref: "The Gas Turbine—The Versatile Power Unit," *Journal of American Society of Naval Engineers*, August, 1958, pp. 490 ff.

‡ "A Marine Gas Turbine Installation," C. H. Johnson, *Transactions, SNAME*, Vol. 54, 1946, pp. 438 ff.

of high-speed rotating materials. Note that this temperature range is significantly above present steam turbines on merchant ships.

8-11 Ocean Gas Turbine Performance

The widespread interest in marine gas turbines for harbor and coastal craft culminated in the world's first transocean gas turbine merchant ship: the *JOHN SERGEANT* (1954).* This was a World War II "Liberty Ship" with a steam reciprocating power plant of 2500 SHP. As a demonstration endeavor, the steam propulsion plant was replaced by an all-gas turbine installation. The reinstallation consisted of two gas turbine units each of 3000 HP, driving separate propeller shafts: a total of 6000 SHP.

Each turbine unit consisted of high- and low-pressure stage turbines, and a 14-stage axial flow compressor. The high-pressure turbine and compressor are common-shaft mounted for a design speed of 6900 rpm. The low pressure turbine is separately mounted, and its 5300 rpm shaft (through reduction gears) drives the propeller at design speed of 110 rpm (see Fig. 8-10).

The gas working cycle is an open cycle atmospheric air intake with a compression ratio of about 5:1. The heat source is a bank of fuel oil combustors around the high-pressure turbine inlet, comparable to aircraft-type turbines. The inlet temperature to the HP turbine is 1450°F, exhausting from the LP turbine at 950°F. Thermal energy from the exhaust air is recuperated via a regenerative heater and waste heat boiler before discharge back to the atmosphere. (1060K)

The sea trials of the *JOHN SERGEANT* attracted world-wide technical attention. More than 600 visitors—U. S. and foreign—were aboard during the three-day trial runs.† All were agreeably surprised at the complete lack of vibration, low noise level, and maneuverability of the ship: its lack of soot, ease of gas turbine control, and excellent overload capacity. There were many enthusiastic expressions of its many advantages. Some claimed, "Only a trip aboard could make anyone change his preconceived ideas." Others exclaimed, "The greatest single advance in merchant ship propulsion since the turn of the century." Few contested that the GTS (for Gas Turbine Ship) *JOHN SERGEANT* was an outstanding technical success!

Much of the success was attributed to the excellent performance of the compressor and the subsequent low pressure drop to the turbine. The rated 6000 SHP powerplant easily delivered 7500 SHP . . . without the two compressors reaching their design speed. The pressure drop in the compressor to turbine piping, via the regenerator, was a mere 2 psi. The pressure at the turbine was 70 psi; mass flow at 95 lb/SHP.

All subsequent voyages of the *JOHN SERGEANT* have confirmed the operating performance noted on the trial trips. The ship is continually

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* Ref: "Gas Turbine Installation in Liberty Ship *John Sergeant*," J. J. McMullen, *Transactions, SNAME,* Vol. 63, 1955, p. 281.

† Ref: "Trials and Maiden Voyage of the Gas Turbine Ship *John Sergeant*," J. J. McMullen, *Transactions, SNAME,* Vol. 65, 1957, pp. 25 ff.

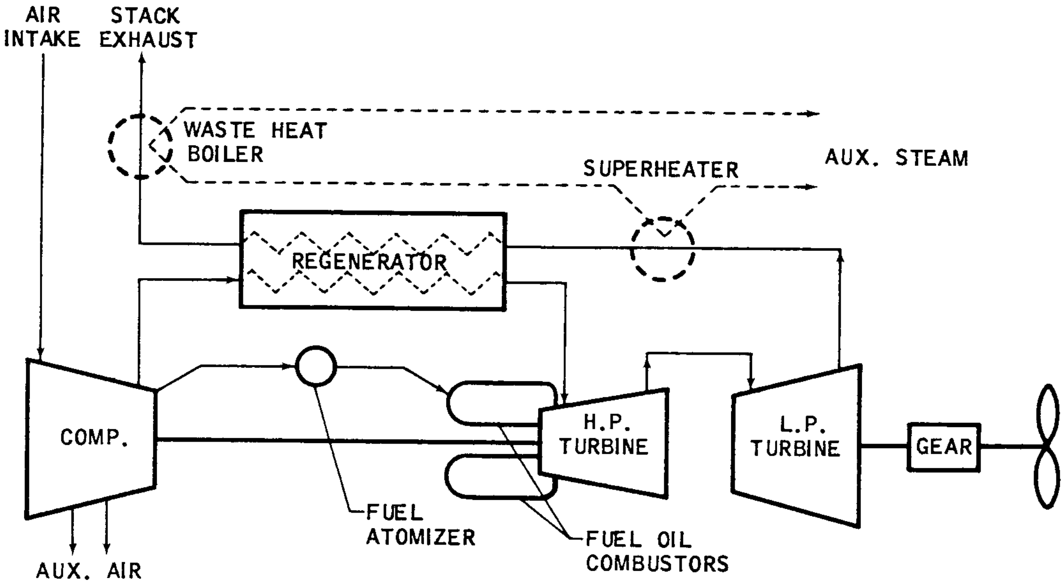

Fig. 8-10 Schematic Arrangement of First Transocean Gas Turbine Merchant Ship

being visited by professional mariners in all ports of call. The interest in and enthusiasm for marine gas turbines appear unabated. This has prompted the original designers to predict that "approximately 25% of all dry cargo ships greater than 7000 SHP, newly constructed in the United States during the next 5 years, will be gas turbine ships."*

8-12 Controllable Pitch Propellers

Much of the success of the *JOHN SERGEANT* is attributed to her controllable pitch propellers. For years, one of the major deterrents to marine application of gas turbines was a satisfactory means of reversal. Ships, obviously, must be capable of reversing their thrust at any time in their course of movement, particularly in harbors and while docking and undocking. The same mandatory need for reversal did not exist in aircraft, which is one of the reasons for early aircraft development of gas turbines.

The reversal problem is not too severe with the steam turbine. A separate astern turbine is used though it usually provides only from one-fifth to one-third the ahead power. With the gas turbine, similar reversal techniques are much more difficult. An astern gas turbine promotes excessive windage losses when idling; there are problems of combating thermal shock and overheating when admitting hot gas (1400°F) to cold turbines. Complicated clutching mechanisms are required, and there is difficulty in attaining reliable stop valves in the switch-over piping. Even so, a gas turbine sister ship of the *JOHN SERGEANT*, the *WILLIAM PATTERSON*, was fitted with two-stage astern turbines and with hydraulically operated gas valves. After about two years of operation, the astern gas turbines were replaced with controllable pitch propellers—similar to those on the *JOHN SERGEANT*.†

Controllable (reversible) pitch propellers are not new to the marine industry. They have found great use on tugboats, minesweepers, fireboats, and icebreakers for a number of years. With craft of this type, low speed, high torque reversals are most frequently needed. The success of these applications points up one of the outstanding advantages of controllable pitch propellers, namely: full ahead power is available for reversal without reversing the propeller shaft. This means, also, the ability to stop quickly in minimum distances. The import of this fact to merchant ship safety is self-evident.

This advantage was also confirmed by the *JOHN SERGEANT*. When compared with a standard Liberty Ship with a fixed-pitch propeller, the *JOHN SERGEANT* was able to "crash astern" . . . and come to a dead stop in less time (see Table 8-2). Her ahead reach distance was one-third less than that of the standard Liberty. This was done without propeller shaft reversal!

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* Ref: "Trials and Maiden Voyage . . .," *op. cit.*

† Ref: "Technical Progress in Marine Engineering During 1957," *Journal of American Society of Naval Engineers*, May, 1958, pp. 245 ff.

As a consequence of the above demonstration, the controllable pitch propeller is a natural companion to the gas turbine. By permitting the propeller shaft to operate mono-directionally at its optimum speed, a wide range of the ship's speed characteristics can be obtained (see Fig. 8-11).

Table 8-2. "Crash Astern" Performance with Controllable Pitch Propeller

	Fixed-Pitch Propeller	Controllable-Pitch Propeller
Name of Ship	Thomas Nelson	John Sergeant
Displacement	9000	8000
Shaft Horsepower	5560	5480
Time to Stop Shaft	35 sec	not required
Time to Reverse Pitch	not required	18 sec
Time to Dead in Water	3 min 1 sec	2 min 34 sec
Total Times	3 min 36 sec	2 min 52 sec
Ahead Reach, Yards	1100	700

Ref: "Trials and Maiden Voyage of the Gas Turbine Ship John Sergeant", J. J. McMullen, Transactions SNAME, Vol. 65, 1957.

For example, at 300 rpm, the ship's speed can be varied from about 16 to 23 knots. This is done by adjusting the propeller pitch. Or, a constant ship's speed can be maintained by varying the pitch to match all conditions of sea, load, and trim. In the field of marine gas turbines, the controllable pitch propeller stands out.

Pitch control is accomplished by means of hydro-mechanical actuation of the propeller blades about an axis perpendicular to the propeller shaft. The propeller shaft is hollow from the hub to a servo-motor in the shaft alley. Concentric tubing mounted in this hollow shaft permits the supply and return of the hydraulic fluid. The rotational force on the blades is provided by rods, links, and ball joints located in the propeller hub. The servo-motor is pneumatically controlled from the main operating console, where automatic pitch adjustment also can be used.

8-13 Timing the Ultimate

One fact concerning the operating success of the *JOHN SERGEANT* has been purposely withheld until this point. Her fuel rate (i.e., pounds of fuel oil consumed per shp-hr: recall Sec. 2-3) is no better than that of modern steam turbine ships. Specifically, her average fuel rate is 0.52 lb/shp/hr.[*] This would imply that gas turbines heated either by fuel oil or diesel fuel (as in free-piston gas generators) are fuel-rate limited. This more than ever confirms the need for some new fuel source. Nuclear fuel?

Possibly these fuel oil heating limitations are behind the intuitive recognition that gas turbines will ultimately combine with gas reactors. This

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[*] Ref: "Trials and Maiden Voyage . . .," *op. cit.*

recognition stems from the inherent nature of the *gas turbine* as a *high capacity prime mover*, and from the inherent nature of the **gas reactor** as a **high capacity prime heater.** Few contest the eventual combination of these two devices on merchant ships. But the matter of timing is uncertain.

The realization of the ultimate depends largely on two factors: one, the development of reliable, long life, high temperature (1800°F) gas reactors; two, the development of reliable, long life, high temperature (1800°F) gas turbines. The central question is: which will get to 1800°F first?

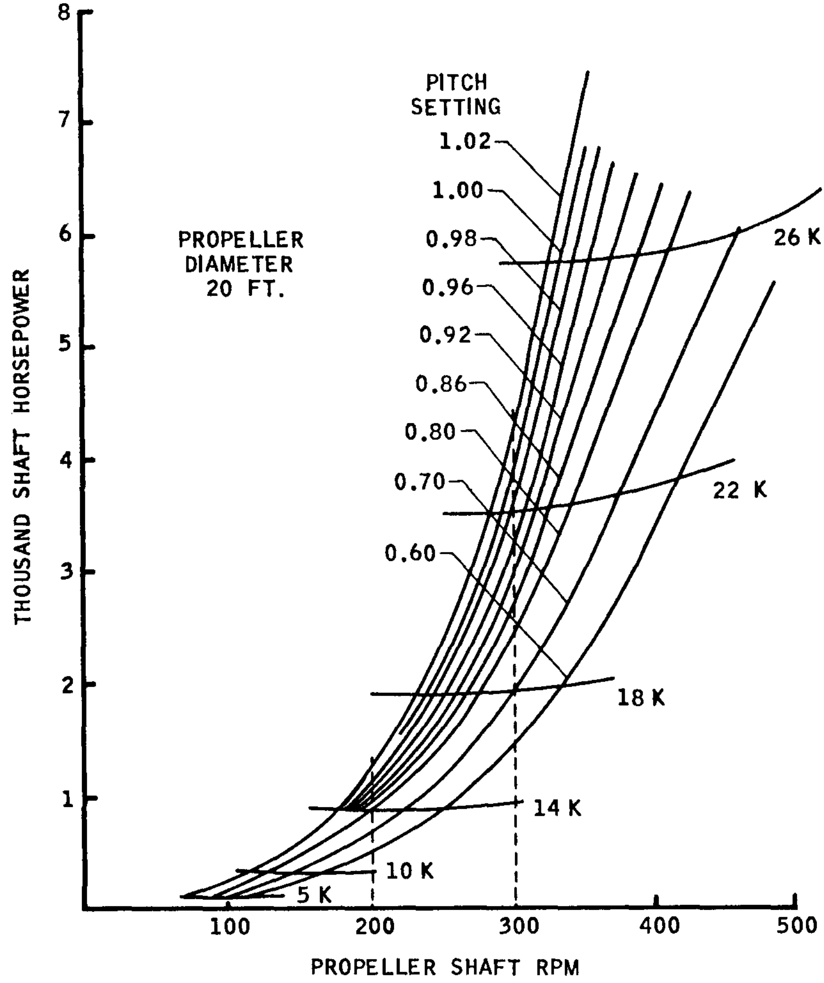

Fig. 8-11 Typical Performance of Controllable Pitch Propeller

(1250K)

Temperatures approaching 1800°F are difficult in gas reactors because: (1) there is likelihood of fission product diffusion directly through the fuel element cladding, (2) there is likelihood of direct bleed-out of the nuclear fuel itself, and (3) the use of traditionally high-temperature materials introduces severe problems of neutron economy. Temperatures approaching 1800°F are difficult in gas turbines because: (1) blade corrosion and distortion are expedited, (2) blade cooling is impractical, and (3) high mechanical stresses at high rotational speeds are involved. The net consequence is that each of these two major devices has a vast field of developmental problems of its own.

Marine gas reactors have not yet been built. So, obviously, a performance demonstration of the reactor by itself is necessary before adapting it to a gas turbine. Furthermore, marine gas turbine units in excess of 10,000 SHP have not yet been built. So, here too, a performance demonstration of the turbine by itself is necessary before adapting it to a gas reactor. Gas turbine units in excess of 10,000 SHP are deemed necessary to avoid the complexity that would be associated with multi-unit installations on nuclear ship sizes of interest (namely: 20,000 SHP and above).

The controllable pitch propeller is admirably adaptable to the speed-load characteristics of gas turbine ships. But propellers capable of controlled pitch on ships of the nuclear-interest size have not yet been developed. For safety reasons this type of propeller is indicated on nuclear ships, regardless of the type of turbine propulsion used. If automatic control of propeller pitch were integrated with automatic control of hull stabilization (i.e., activated fins; Sec. 2-10), any environmental shock to reactors at sea would be minimized.

All in all, the future possibility of the direct reactor-to-turbine gas cycle is highly attractive . . . in the ultimate. Necessarily, many intermediate developments are required, and each takes time. Consequently, no one can predict with certainty the arrival of the ultimate nuclear ship plant. In the meantime, we would do well to develop those reactor types (Ch. 7) nearer at hand.

SUMMARY

We concede that the ultimate nuclear ship propulsion plant is an unknown number of years away. Even so, the potential simplicity of a gas cooled reactor connected directly to a gas actuated turbine is an attractive concept which will gain increasing attention as other nuclear ship developments unfold. Gases, since they do not undergo a phase change (as in the case of water to steam and vice versa) more closely follow the ideal gas laws through every component around the cycle.

Factors opposing the ultimate plant are the long developmental success of the steam turbine, and temperature difficulties in the reactor. For unless we can develop reactors that can produce gas turbine inlet temperatures of at least 1400°F, we cannot compete with modern steam turbines. The attainment even of 1000°F in a gas reactor meets with difficulty because of fuel element materials limitations, the reduced fission probability of the nuclear fuel, the increasing pressure characteristics of the contained fission gases, and the fall-off in effectiveness of control poisons.

Temperature-wise, gas coolants would allow us to go as high as we want. But the low density of gases means a large-sized reactor—compared with liquid cooled reactors—for the same heat output. To reduce the size of a gas reactor, it is necessary to increase the velocity of coolant flow to about 250 ft/sec (approximately 150 knots). This velocity aspect brings aerodynamics into gas reactor design with emphasis on ways to minimize boundary layer heat transfer problems, and ways to uniformize the pressure and velocity profiles through each of the thousands of reactor coolant tubes. If we permit non-uniformities in coolant profiles, risk of tube burnout is great.

Though there are a number of gases that could be used, there is general agreement that helium is the best choice. It is the most stable gas available, as it does not (in pure form) become radioactivated in the reactor and it does not chemically attack turbine and compressor parts. Its disadvantages are easy leakage in turbomachinery and the large number of compression stages required.

Foreseeable chances of being able to connect the reactor directly to the turbine are dimmed by the realization that dust, dirt, and erosive particles (fluidized by the helium) become radioactivated. Even though filters can be used, the possibility of fuel element leaks and the diffusion of fission residues (and the fuel itself) into the helium stream is real. This leaves no alternative but to install a heat exchanger and separate the small closed cycle into two "conventional" reactor loops. This leads us to the next-to-ultimate plant.

Two types of next-to-ultimate plants are possible, one using the steam turbine, the other using the gas turbine. Both turbines would be served by the same type of gas reactor. The use of two such plants would stimulate further advancements in steam technology and would provide time for the development of large (10,000 SHP) gas turbine units. Though there has been a considerable upsurge of interest in marine gas turbines in the past ten years, the largest units actually installed are 3000 SHP (e.g., the *JOHN SERGEANT* and the *WILLIAM PATTERSON*). Larger units than these are required in order to avoid multi-unit complexity on nuclear ships in the beyond-20,000 SHP range.

Of significance regarding the *JOHN SERGEANT* is the fact that her fuel rate is no better than that of modern steam turbine ships. This implies that gas turbines using oil fuels also are fuel-rate limited. Possibly, this is one of the factors behind the intuition that gas turbines will ultimately combine with gas reactors. The matter of timing the ultimate is uncertain. The gas turbine and the gas reactor each has a vast field of high temperature (to 1800°F) developmental problems of its own. So, pending technological break-throughs, we would do well to develop those nearer-at-hand marine reactor types.