The Modular High-Temperature Reactor: Its Time Has Come!

Marjorie Hecht

Linden Blue is vice chairman of General Atomics in San Diego, where he is responsible for the development of the advanced gas-turbine modular helium reactor (GT-MHR). General Atomics, which has a wide range of high-technology projects, has been involved with the development of HTRs for more than 50 years. Mr. Blue was formerly CEO of Beech Aircraft and general manager of Lear Jet, both in Wichita, Kansas. He was interviewed by Marjorie Mazel Hecht on Oct. 27, 2008.

Question: Your outlook has always been visionary: You see the need worldwide for a reliable, safe power source. What do you think will enable us to turn the corner, and begin mass production?

Historically we've gotten our economics in nuclear by making the plants bigger and bigger, and getting "the economies of size scale." But the reality is that everything we have in life that is, let's say, economical, has gotten that way because it's *mass produced.* Everything from coffee cups to cars. There are no exceptions that I can think of right now.

Well, obviously, we're not going to produce nuclear reactors in the numbers that we've produced cars, but perhaps a better analogy would be airplanes, which are produced in serial production, in relatively low numbers. The learning curve get the costs down through serial production. I think it's possible that if you get the right sized gas reactor, you can have these produced in quantities where you get all the benefits of mass production, with favorable learning curves.

Said another way, there are two ways to get economy: One is to make the reactors bigger and bigger, which seems to have reached the point of diminishing return, and the other way is through mass-production.

The latest projection for light water reactors, because of the run-up of commodity prices, has been as high as $6,000 per kilowatt, and if you have a 1,200-megawatt reactor, you're looking at $7 or $8 billion. That's a huge amount, to say nothing of the sometimes disruptive effect of dropping 1,000 or 1,200 megawatts into a given market.

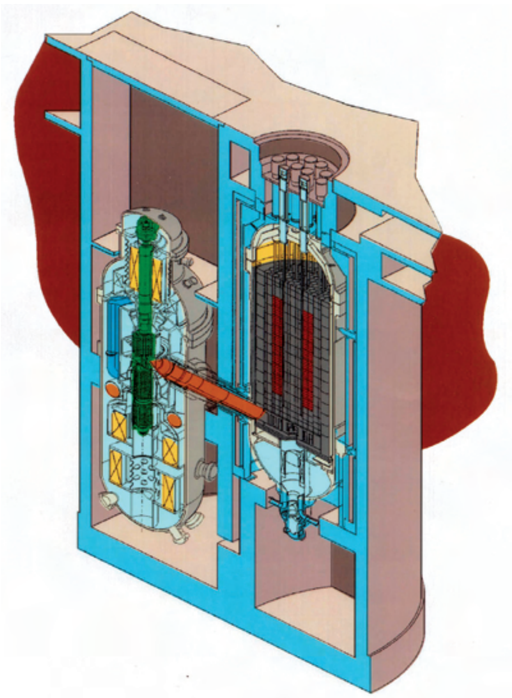
"Technology is a wonderful thing! People invent better things to solve problems. And this is exactly what's happened here. Over this 50-year period, the reactor design has improved dramatically. We've made mistakes, and we've cured them. And now we have something that is so safe, and so economical, and so efficient, and so non-polluting, that its time has come."

Question: You're talking about the capital cost here.

Yes, that's the capital costs, construction. The operating economics are affected by the 50 percent greater efficiency of the gas reactor. Overall, you have an equation that's pretty hard to beat.

Question: And the GT-MHR is designed at a size to be mass produced?

Yes, a good size would range from 100 to 300 megawatts for the HTR, versus 1,200 megawatts for a conventional water reac-



Cutaway view of the GT-MHR, showing the reactor vessel (right) and power conversion vessel. The helium gas directly drives a gas turbine generator, which gives the reactor nearly a 50 percent increase in efficiency.

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Serial production, as with these airplanes during World War II, will enable the fourth-generation nuclear reactors to be economical. Here, an airplane assembly line at the Canadian Car and Foundry Co., in Fort William.

tor. You're duplicating the learning in the production process six times as frequently, and that makes a huge difference. So, the modular approach has always been attractive. Now it's mostly a matter of doing it.

The history of how the light water reactors came about—they came out of submarines. They were the only ones that were available at the time. They've served us well, but the question is, is that what we want to build a lot of for the future? My answer would be no: You want to build the safest possible reactor that you can, and the most economical. I believe that takes you to the modular approach for economy and the inherent safety approach for safety. To do that, you need ceramic fuel and a Brayton cycle. Helium as the heat transfer fluid enables both.

When you are dealing with higher temperatures of a gas reactor and a Brayton cycle instead of a Rankine cycle, you get on the order of 50 percent more thermal efficiency. That is *huge* in something as basic as primary energy. You create heat and turn it into some kind of work. Steam cycles have been doing that very well, ever since Robert Fulton and the steamboat, but there's a better way, if you can use a fluid like helium to directly drive a turbine. So, to go from 33 percent efficiency to 48 percent—nearly a 50 percent increase in efficiency—that's tremendously significant. That lays the foundation for considerably greater economics.

Question: How are we going to gear up to get this done? What manufacturing resources exist already, and what would we need to create?

I think we really have all the resources to do it. Let's just walk through that.

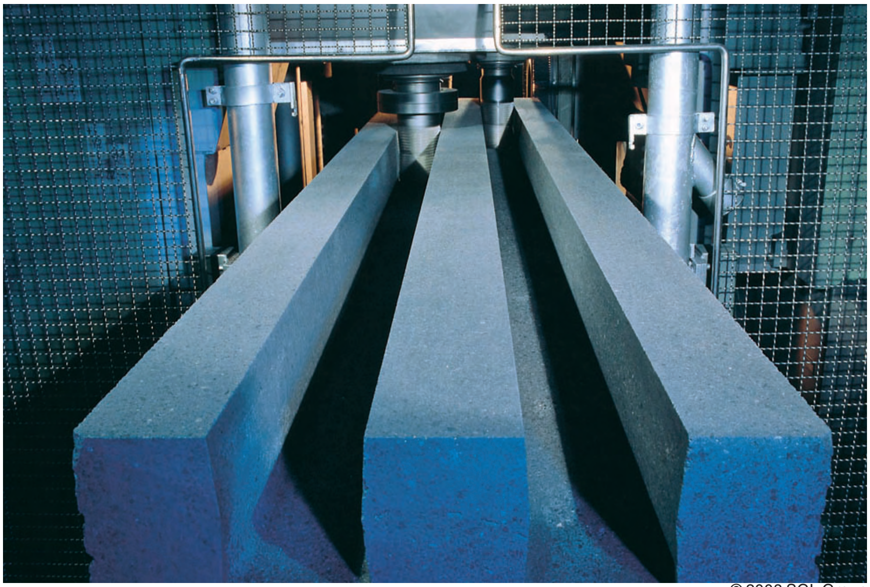
First of all, you've got to have *reactor vessels.* Well, that takes heavy steel. There's heavy steel capability here in the U.S. The steel needs to be rolled, and then some of the fittings need to be machined. There's plenty of machining capability here for that purpose.

Some of the big light water reactors require forgings, and these can only be made in Japan. But I think if we make ours the right size, we'll be able to produce them in a variety of places around the world, rather than using the tremendously expensive forgings.

Question: Right now in Japan, I think if they gear up they can only do nine a year, so that's not exactly mass production.

United Steelworkers

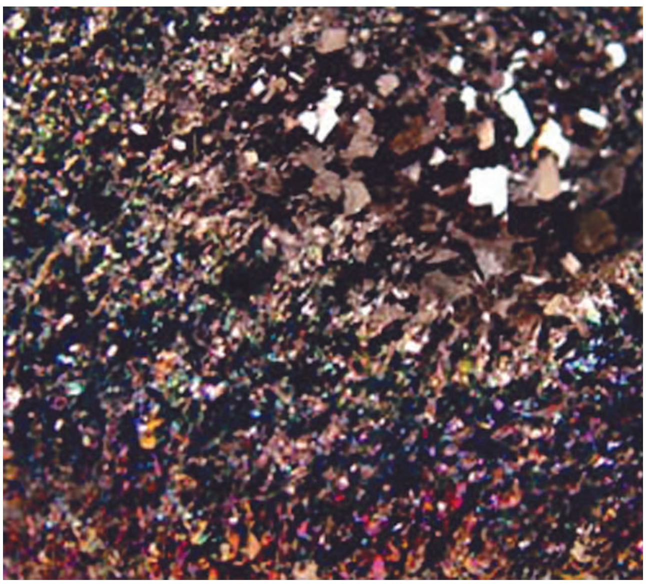
Inside a steel rolling mill, where slabs of steel are transformed into plates, sheets, and strips. Reactor vessels for the modular HTR can make use of heavy rolled steel, instead of the more expensive forgings needed for larger nuclear reactors.



Nuclear-grade graphite is required for the fuel blocks and reflector blocks of the GT-MHR, and the United States has the manufacturing capacity for this. Here, machining of a large cross-section graphite block for use in electrolysis cells.

No, and so you have to look at a way of avoiding those forgings, and I think machined steel plate is the way to do that. Keep in mind that the characteristics of the forgings or steel plates should be different between a water reactor and a gas reactor: A water reactor cannot sustain a leak, because if you lose water as a coolant, you can have a meltdown. But in the gas reactor you cannot have a meltdown, because of its inherent safety.

So I think there's a production capability for the vessels, with a combination of rolled steel and steel plates that are machined.



A close-up of silicon carbide, used in coating the TRISO (tristructural-isotropic) fuel particles for the HTR.

Then you go to the *graphite reflectors.* There's plenty of capacity in this country to produce nuclear-grade graphite. It's very pure and it can't burn. The industry has plenty of capability for turning that carbon into something useful, namely *reflector blocks* for the reactor, and also the *fuel blocks.* So, that's a matter of mobilizing the resources that are already out there to produce carbon logs. They have to be machined, and there is plenty of machining capacity for that.

Then you get to the *fuel.* There are all kinds of places that you can make fuel. The tiny ceramic fuel particles have to be produced in great quantity because they are about the size of a grain of sand. But the processes for doing that have been around for many years. We produced fuel at our site in San Diego many years ago in huge quantities. And between the nuclear fuel manufacturers around and the national laboratories, there are enough places where you could produce the fuel. Obviously, the fuel needs to be tested, and the quality needs to be controlled rigorously, but we have almost 50 years of experience now with ceramic-coated TRISO fuel particles, and that's a darn good base from which to operate.

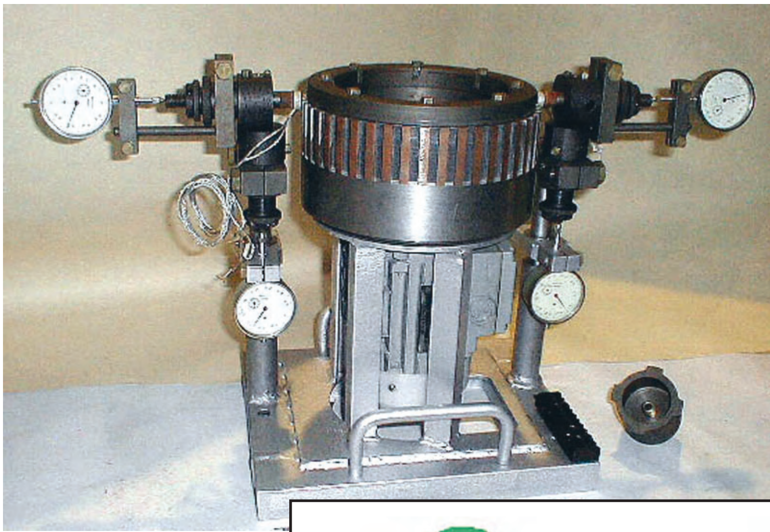
Then you go to things like *control rods,* which are very straightforward. The gas reactor can shut itself down automatically even without the control rods, because of the negative temperature coefficient, which means that if the reactor heats up over a certain point, it will shut itself down. The control rods are just a simple mechanical device.

And then you get to the *power conversion module,* the turbine. You can think of it as a jet engine, which instead of having a big fan on the front, it has a generator. That turbine operates at lower temperatures, lower speeds, and lower stresses, and far, far fewer cycles (the things that sometimes wear out engines) than jet engines do. And also they are not subject to weight sensitivities as jet engines in airplanes are.

So it's a relatively unchallenging use of turbine technologies to produce turbines for high-temperature reactors. The engineering codes for designing the turbines are well established, as are production techniques.

The exercise then is to build a turbine that takes a hot gas, which turns the turbine, and that is attached to the generator. On the other end of the jet engine is the compressors. These compress the helium gas, and then send it back on through the reactor for another load of heat energy—in a continuous cycle.

When you ask the turbine manufacturers if there's high risk in that part of the power conversion module, they say, "No, there's very low risk." The turbine guys say that there may be risk in the reactor design, but not in the power conversion module." By



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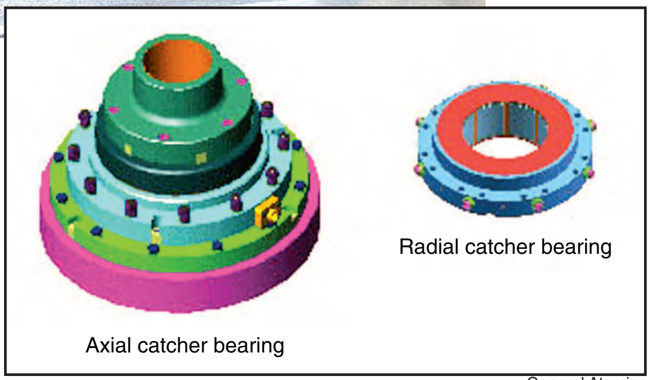
Electromagnetic bearings on a test rig. Because there is no friction, there is almost no wear on these bearings. Inset is a drawing of the catcher bearing used with the electromagnetic bearing in the unlikely case of an electricity outage.



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contrast, our reactor guys, who have been working with the reactors for almost 50 years, say, "Well, no, the reactor isn't risky at all, after all the work we've done over these 50 years, but we don't know about the power conversion module."

Obviously, you have to form a team that has all the necessary disciplines to deal not only with the reactor, but with the power conversion module.

And when you get into the capability to build the turbine, there is Rolls Royce, General Electric, and other turbine manufacturers. There's plenty of capability out there to do the rotating machinery.

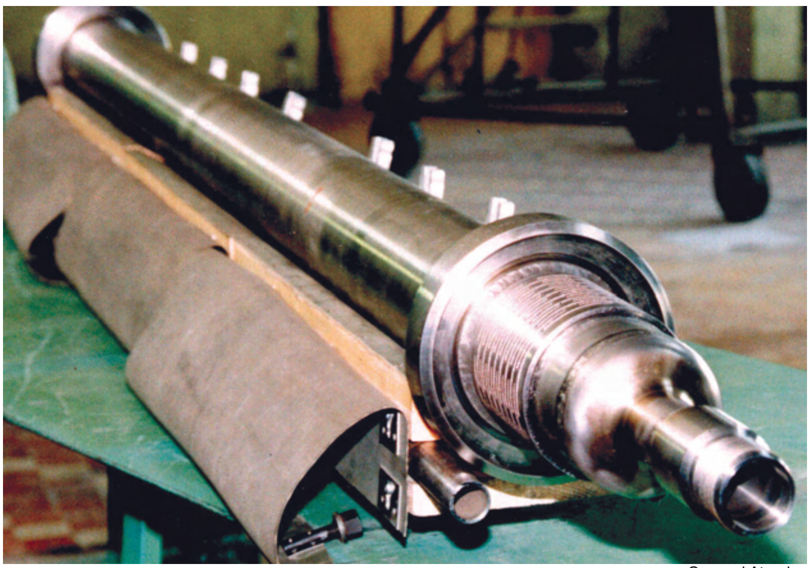
A critical element in the power conversion module is the *bearings* for the turbine. Magnetic bearings are a state-of-the-art bearing system, which was not available 20 years ago, but are in common use today, particularly in gas-pumping booster stations. Magnetic bearings are a far better solution than the oil-lubricated bearings that we used in Peach Bottom 1 [the high-temperature reactor in Pennsylvania in the 1960s], which worked just fine, and better than the water-lubricated bearings that we used in the circulation pump in Fort St. Vrain [the Colorado HTR which operated 1976-1989], which worked very poorly.

The Achilles' heel at Fort St. Vrain was the water-lubricated circulation bearings, and we simply don't have those problems with the magnetic bearings. Magnetic bearings are a very elegant technical solution for bearings, just like the turbine itself. Magnetic bearings have almost no wear, because there's no friction.

The art in using magnetic bearings is having a *catcher system* in case the electricity goes off, for any reason. Of course, that's extremely remote, because you have back-up batteries, and a back-up source of electricity. But even in the case where there was a total loss of electricity, the catcher bearing solution is something that's very susceptible to good design.

The *generator* is very straightforward. There are all kinds of generators everywhere in the world, so that's not a problem.

The *recuperators* in the system are just heat exchangers, and the science of heat exchangers has progressed mightily in the last 20-30 years, and so the *plate fin recuperators* are very efficient and relatively inexpensive. They are not susceptible to the problems of the leakage in heat exchangers, because you are just leaking helium to helium, and if you have a small leak, it doesn't go outside of the system; it remains inside the pressure vessel. It only shows up in a small loss of efficiency.



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A recuperator, the type of heat exchanger used in the GT-MHR, is highly efficient, compact, and relatively inexpensive.

So you take all these technical aspects, which some people might think of as challenges, and you examine them item by item, and you see that the industrial infrastructure is there, the technology is there, and it's just a matter of matching the industrial infrastructure and the technology to the money to get a prototype built.

And once a prototype is built, and it has proven its reliability, then people will look back and say, "Gee, this is obviously a much better technical solution; why didn't we do this years ago?"

Question: It sounds like the manufacturing capability is there, at least in concept, and some of it is operating already in the U.S. and elsewhere. But we're missing that crucial element of *political will* here, and we need that to get this done.

That's true. But here the gas reactors have real advantages. First of all, I think it's much easier politically to deal with modules of 100 megawatts, rather than reactors of 1,200 megawatts.

Number two: it is the safety characteristics that any community can get their arms around and understand. A high-school physics class can do the calculations, and they can see that you simply can't get to temperatures that can fail the fuel, so you can't have a meltdown and you don't need an evacuation area, as some reactors do. So, if there's nothing to evacuate, you don't need an evacuation zone, and they say, "That's the kind of reactor we would like to see. And because it assures low-cost electricity to our communities and factories, and a good industrial capability, we look at all the alternatives, and see that this is a better alternative than coal or oil, or even than other nuclear."

American people are smart, and if all the facts are laid out to them, and they can see that this really is a different kind of physics that governs these reactors, then they say, "Yes, this is better than the alternatives."

We all know that we need energy. Energy is what advances civilization and living standards, and this looks like the best source of energy there is. Even horses cause a certain amount of pollution.

Question: Quite a lot, if that's all you have for transportation. . . . I think other countries, especially in the developing sector, are particularly interested in this reactor, because it can accommodate to a smaller power grid, and be added onto as the grid increases.

That's very important, and obviously that is a much better solution.

Also, because of the modularity, maintenance is easier. All reactors require some maintenance. Obviously if you have a 1,200-megawatt reactor, and you shut it down for maintenance, you've got to replace it with 1,200 megawatts from something else. In the case of a modular reactor, any place that you have a bunch of them, you can just shut them down for maintenance one by one, and the amount of power that you're losing is so small, that you don't have to have a source of back-up power. That is a significant factor any place you put them, but particularly in small countries where they don't have a grid where they can bring other power in.

It's a far better way to handle the electricity load of a smaller country. It's far better because you're not dealing with a safety equation which absolutely demands that everything be perfect all the time, and so you can see this kind of technology being employed in Third World countries where you probably wouldn't want to have a large light water reactor.

Question: Well, a large reactor would overwhelm the grid of most of those countries. . . . You mentioned at the HTR press conference in Washington that you thought we could be producing 60,000 of these reactors, and I wasn't shocked by that number, because we've estimated that the world will need 6,000 reactors of 1,000-megawatt equivalent by the year 2050, just to keep up with the growth in electricity demand. So, how do we get this going?

We simply have to build a demonstration reactor. And then once it is demonstrated, and once people understand that it's real, and they see the economics of it, and see the safety of it, then there will be just overwhelming demand for it. That's the kind of challenge or problem that every manufacturer loves to see. It's a lot easier to produce things in quantity, than it is by single units.

So, getting the money matched with the technical capability and getting the first one built is what it's all about.

Question: There is a demonstration reactor being built, in South Africa, of the PBMR pebble bed variety, so it would make sense if here, under the NGNP, the Next Generation Nuclear Plant, we go with the GT-MHR type of high-temperature reactor. But, NGNP is a very "slow boat" at the moment.

I agree. NGNP would be a very good thing to do. I think that this technology is ripe for the private sector to take it up and do it. . . .

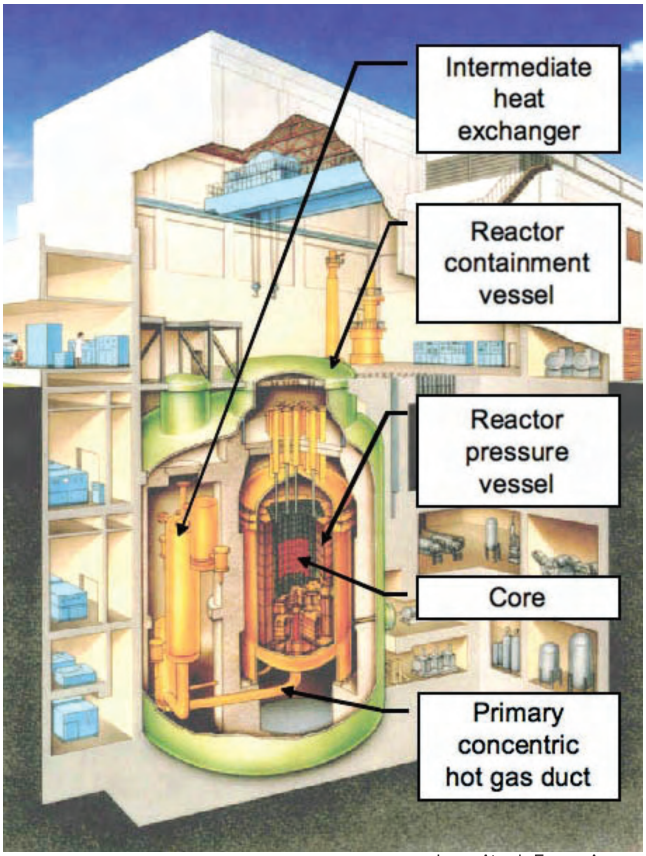
Question: What about Russia? You have an engineering program going with the Russians on the GT-MHR. Can they put any funding into it, in terms of building a prototype there?

The Russians have been collaborating with us for quite some time, in work on a plutonium disposition program [burning up weapons plutonium], which everybody wants to see happen. And the Russians do a superb job of designing and engineering and the physics. They have a good background in this technology. So I think collaboration with the Russians on this could be very real, and has good potential.

The demand is great enough, so that there should be a lot of participants in this kind of program.

Question: The Russians seem to be moving faster in terms of putting new reactors into motion. Of course, they are building industrial-size conventional reactors and fast reactors.

That is true, and exactly what their rate of speed will be as



Japan Atomic Energy Agency

Schematic of the HTTR, Japan's 30-megawatt high-temperature demonstration reactor, which has a prismatic block core.

Japan Atomic Energy Agency

Sintering fuel particles for Japan's HTTR at the Nuclear Fuel Industries, Ltd.

they deal with the lower price of oil, I don't know. The Russians have their own economic problems right now. We have found the Russians to be very good partners in the plutonium disposition program, and that could very easily be converted to a development of a civilian power reactor.

Question: What's the estimated cost of the first reactor, the demonstration reactor, and what would the cost be when you're in mass production?

I believe that the first module could be built for between $600 million and $1 billion. That's my estimate. There are some estimates that are higher, but I think that when you apply manufacturing disciplines to it, and keep things simple, that would probably be a realistic number.

When you get into mass production and come down the learning curve, I think you're looking at less than $2,000 per kilowatt, or about $200 million for a 100-megawatt reactor. Right at the moment, that's actually a lot better than the big light water reactors. So, at that kind of a rate, you really have something that is very economical.

The other thing that the world is going to see is more electric vehicles, and this kind of reactor would be an ideal way of producing electricity to power electric vehicles. Essentially, you could fill your electric tank at home at night for the equivalent of 75 cents per gallon; that's really attractive. Many people who are now paying $3 to $4 per gallon would be overjoyed to be able to charge their cars at night for 75 cents per gallon of gas equivalent.

Question: It's also very convenient. But you have to have that electric power grid.

Yes, and you have to have that off-peak power—that's between 11 PM at night and, say, 5 AM. With nuclear plants, you don't want to shut them down. It makes sense to sell off-peak power at a lower rate, particularly to charge electric cars.

Question: I think the problem we face now in this time of financial collapse is that we need a Franklin Roosevelt approach. . . . And a critical part of this is building nuclear plants. You really don't have a future without nuclear.

That's right: Modern industrial societies need power, lots of it. Solar will come along; wind can provide a little bit. But the heavy lifting can only be done by hydrocarbons or nuclear.

Question: And we want to save the hydrocarbons for other uses, not just burning them up. Nuclear is an optimistic way to look at how we can build ourselves out of this collapse.

Yes. It's basic production, not paper streams of profit. It's adding basic energy for production. Building such plants would put a lot of people to work. It would obviously do good things for the construction industry. It would have a huge effect throughout the economy to have a major surge in building these plants, and it would save the $7 billion a day that has been going from the industrial world to the oil producers. That was the figure at the time that oil was at $120 a barrel, so it's less than that now. But even so, there's a huge transfer of wealth to the oil-producing countries. HTRs would dramatically change that.

I think I told you my theory for what the potential of this is. Right now we get 20 percent of our electricity, but only 8 percent of our *total* energy from nuclear. If we go to the French example of producing 80 percent of power with nuclear, that would raise us from 8 to 32 percent of our total energy, just by itself. That would create a huge difference in our oil consumption and natural gas imports.

Then, if you assume that we could provide half of the transportation fuel by using electric vehicles, and then half of the process heat from this kind of nuclear—and you know because of the higher temperatures, we can do most process heat applications that the lower-temperature nuclear reactors can't do. So between the French example on electricity, and half of the transportation and half the process heat, you're up to the potential electricity from nuclear to 62 percent. That would almost eliminate our balance of payments problem. To say nothing of getting the price of oil and gas down to realistic levels. It just has a huge effect. The environmental advantages would be another big bonus.

General Atomics

The dedication of the Peach Bottom HTGR Atomic Power Station in 1967. From left, Lee Everett and R.G. Rincliffe, Philadelphia Electric Co.; Atomic Energy Commission Chairman Glenn Seaborg; and John Kemper, Philadelphia Electric Co.

Question: I think there are also the educational and cultural effects of going nuclear, because when you have a society moving forward like that, it gives kids a future. Now what do they have—training to run a windmill? We're going backwards.

It could give a lift everywhere. Right now we're mortgaging our future, buying all that oil, and the HTR is a real alternative.

Question: We could be producing hydrogen too, as a fuel.

Yes, that comes next, and that has significant potential. I think in the short term, the electricity for vehicular transportation makes sense. You already have the electrical grid for distribution.

People could see that instead of sending all that money to oil-producing countries, we could keep that money inside this country. Nuclear has no pollution, as with burning hydrocarbons. That's a better way of doing things. So what's the negative here? The answer is *inertia*! We've got to get it done!

Question: I have an historical question now. When did General Atomics get involved with the high temperature reactor?

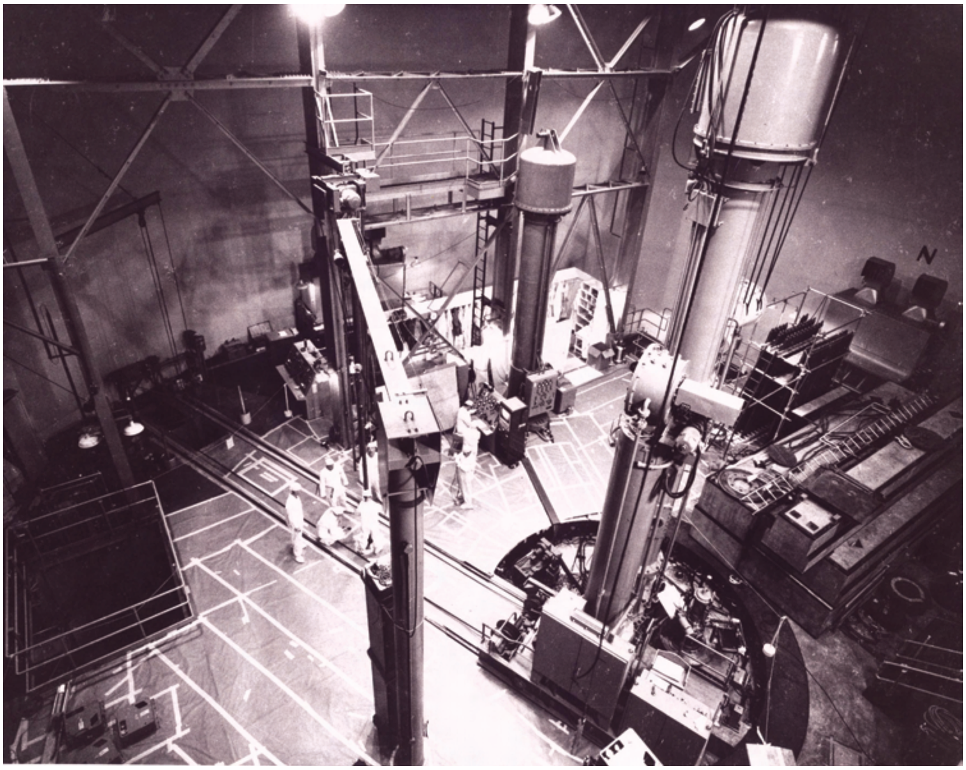
It was about 50 years ago. First of all, General Atomics was founded for the peaceful use of nuclear energy. It was back in the Eisenhower Atoms for Peace era, in the middle 1950s. And you had a lot of very smart people, who asked, "What is the best way to do this?" And they said, well, in submarines you obviously need very very high power densities, greater power output per reactor vessel size, because space is at such premium. But for terrestrial applications, the primary criterion should be the ultimate safety. And how do you produce the ultimate safety? You make *ceramic fuel*, not metallic fuel, and you use helium coolant instead of water, because helium is a noble gas and doesn't corrode.

Of course, back in those days we were still using a Rankine cycle, and it wasn't until the late '80s or maybe early '90s that we decided the technologies were mature enough to do a Brayton cycle. But since that period we've felt that the direct conversion Brayton cycle was the thing to do.

So it's been in that 50-year period that we've been evolving the HTR, and everything has been improved, from the fuel, to the jet engine-like turbines.

We have also had a major setback with the Fort St. Vrain capacity factor. It was never a safely issue; it was a hydromechanical problem, not a nuclear problem. We just screwed up in the design of those lubricator bearings. The water could get into the reactor, and so they would have to shut the reactor down to drain it out. So magnetic bearings are a huge advance.

Technology is a wonderful thing! People invent better things to solve problems. And this is exactly what's happened here. Over this 50-year period, the reactor design has improved dramatically. We've made mistakes, and we've cured them. And now we have something that is so safe, and so economical, and



The General Atomics Reactor operating floor during fuel loading at the prototype Peach Bottom HTGR, 1966. Peach Bottom, operated by the Philadelphia Electric Co. at Peach Bottom, Pennsylvania, successfully supplied power to the grid from 1967 to 1974.

so efficient, and so non-polluting, that its time has come.

Question: Yes, it's overdue. in fact!

Well, you recognize that, and what you're doing is drawing attention to the problem, and you're saying, "Hey, there is an alternative, there is a solution." All too frequently people say, "There's no way to deal with this." Well, there *is* a way to deal with it.

Question: The PBMR people proposed for Africa having regional centers to train engineers and technicians and perhaps a continent-wide regulatory agency. Have you any thoughts on that?

That could be a good solution for Africa. I think that the U.S. is the gold-standard for nuclear licensing, and I think that there's plenty of residual capability in our universities to properly train people, so I don't look at that as a major problem. One of the reasons, again, is that this is such a simple system. You want to have experienced people running them, but if you have people with less experience, they still can't mess them up—in the way human beings messed up at Three Mile Island and Chernobyl. It's just inherently not possible for human beings to cause meltdowns in these modular reactors. So obviously, you do need to train a lot of people, but the U.S. has a great labor force to work with.

And then you need a lot of computer-savvy people running them, and that's sort of everybody in the current generation. Because increasingly Moore's Law is going to govern nuclear control, just like it does everything else, where you have the vastly greater capability to control machines electronically. You also have much better systems for safety.

Question: What's Moore's Law?

Gordon Moore, the visionary head of Intel, many years ago said that computing capability would double every 18 months. Now he said that 20 or 30 years ago. Well, it has worked like clockwork. When you have that kind of a compound improving effect, you have a dramatically increasing capability. That's what's happened in computers, and that's why the world is increasingly driven by computers. And controlling nuclear reactors is just an absolutely ideal application for automated electronic controls.

Question: But you still need that human element.

You still will have that human element. You enable the human beings to do a much better job. It's like flying an airplane, which I know something about. Right now, because of the electronics that Moore's law allows, it's almost impossible for a pilot to lose what we call situational awareness, where they become confused and they don't know exactly what's going on, or where they are. These advanced electronic systems make everything dramatically easier and therefore much safer. And that's one of the reasons you're seeing such an improvement in aircraft operations, and the same thing can be done with reactors.

Question: I wish that there were a similar "law" about mass production of nuclear reactors. . . .

Well, you don't have Moore's law in all areas of production, but you do have the benefit of it. Since there's a lot of electronics in any sophisticated power plant, you get a lot of benefits from the miniaturization, the redundancy, all of the advantages of modern computing, so that's a big reason why it makes sense to have *modular* reactors, because you can have a standard set of electrical controls, and the price of those controls further reduces the price of reactor modules and their operation.