The Egghead and Science

Lecture by Thomas Pigford
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59 minutes, 58 seconds

Speaker: Thomas Pigford

Transcribed by: Sherry Yin

Time Transcription

00:00 Marian Longstreth: It's a great pleasure to welcome all of the students who come to the Meet the Scientist Lecture series. I can see that spring fever is flourishing somewhere because there are not so many as usually come. These lectures are co-sponsored by the Theatre and Arts Foundation of San Diego County, General Atomic, Convair, Convair Astronautics, and the Scripps Institution of Oceanography. Today, we are honored in having the assistant director of the John J. Hopkins Laboratory for Pure and Applied Science as our speaker. He is also chairman of the Department of Engineering. He is a modern-day Prometheus, robbing the sun of its secrets to give men the hottest fuels he has had yet to burn. He obtained his doctorate in science at the Massachusetts Institute of Technology where he became assistant professor of chemical engineering and coauthored with Dr. Manson Benedict, a book, *Chemical Nuclear Engineering.* He has been a consultant to the Atomic Energy Commission on the Savannah River Project and also on their Nuclear Aircraft Propulsion Program. He will speak to us now on the future of nuclear energy. I take great pleasure in presenting to you Dr. Thomas Pigford, Dr. Pigford.

1:41 [Audience clapping]

02:00 Dr. Pigford: Ladies and gentlemen, it's a real pleasure to have the opportunity of meeting with you today and I had seriously debated which of several topics I might speak on but as it usually turns out when one gets to this stage, preparing a presentation is not an easy job. I once talked to a group in Boston on the Egghead and Science and I thought this might be an interesting one for you. We've been so deeply involved here in San Diego in the development of some very new, new problems and equipment on atomic energy right here in San Diego itself and I thought you might like a bit of the local flavor. And as a matter of fact, I've been so deeply engrossed in that myself. It's a lot easier for me to talk to you about this one. Now, I hope you will find this of some interest. Now what I want to do today is give you a bit of science and engineering. And I don't know how to define these or break them apart, so let's say it's all technical work. And in this one has basic concepts of reactions, ways of utilizing materials to carry out these reactions, and apply them in a practical way, and finally, frequently unfortunately, considerations of costs. Because to an engineer or to an applied scientist, the value of this product to the public, to you or to me, is determined as to whether it can be used economically and usefully. Now, in talking about nuclear energy, I'm really talking about a subject with much broader and deeper implications because it gets at the heart of what the philosophers, I gather, consider the route to the development of standards of living, the development and utilization of energy.

04:00 Dr. Pigford: Now, I believe one of my associates has talked with you recently about ways of converting energy to work. That itself is a very broad subject relating to the very heart of science. How does one go from something hot to something moving?

Now, I'm not going to cover that but what I'm going to try to go into is how do you get something hot, how much do we need in terms of total energy, and what are the ways of getting it? And in this, I hope to show that nuclear energy is really important to us even though there are some real, real serious problems connected with the question of when it will actually be economical. If you'll bear with me a moment, I just want to introduce some terms for us so that we can all be talking the same language. And I'd like to show you a slide which is sort of like a chemical reaction, which indicates some of the processes we're dealing with here. May I have the first slide? Now we will need the lights off on this one I believe, to make it visible.

05:18 Dr. Pigford: What this is is a diagram just showing what happens when, when nuclear fuels undergo fission. Now, fission is, is a word that's been with us now since about 1939. It still seems sort of exotic. About five years before the rockets and missiles became so popular, it was one of the most popular terms in the comic books and so forth, but basically, it's nothing exotic. It's, it's like the explosion of TNT where one takes a large, complicated chemical molecule there and if you jar it and apply a little bit of excitation to it, it blows apart and releases energy. Fission is the very same process except for this when one deals with obtaining energy from TNT or other high explosives, we're dealing with chemical reactions and as you know these are reactions which, which reactions between atoms and basically these rearrangement of the electronic structures, these planetary electrons around atoms. In the nuclear fuel field, we're not dealing with atoms. We're dealing with the central part of atoms, namely the nucleus, which is a very, very tiny microscopic, submicroscopic part and those are the things that react to the nuclear fuel.

06:47 Dr. Pigford: Well, here's what happens. Now that big model, orange-looking thing up there is considered to be a nucleus of uranium, now, especially uranium-235. 235 as a designation on uranium. There are several kinds of uranium, a chemical element, and there are different kinds they call isotopes, like heavy water and light water. Heavy water, heavy hydrogen has an isotope of hydrogen. Now, the 235 designation is a way of calling out the isotope. It happens to be roughly equal to the weight of it and that little thing on the left is a neutron, one of the particles that comes out of a nucleus. A nucleus is made of, as you probably know, of, built up of two different sorts of particles, little tiny uncharged ones, neutrons, very hard dense ones. They are many millions of times more dense than lead even. And then another particle almost the same size but which is charged - protons.

07:48 Dr. Pigford: Protons and neutrons make up the nucleus and it was found, in a rather startling discovery, that when a neutron would hit this special uranium-235, it would blow it apart and release a great amount of energy. Now, the energy is, is it appears in this case mainly by the high speed of these two fragments left over when the thing blows apart and these fragments happen to be two new chemical elements now. They are moving at many millions of miles a second and if slowed down, they would indeed have temperatures of many millions of degrees. That's, that's the way the

heat, most of the heat comes out. Also, coming out of that are some electromagnetic radiations, which are basically the same as light but very, very short wavelength. In fact, these happen to be among the most penetrating radiations that have ever been observed, called gamma rays. Just a special kind of electromagnetic radiation called gamma rays because of the extremely short wavelength and they carry very high energies. And finally, the important thing is that besides the radioactive fission fragments, these are radioactive because they themselves are quite excited and will tend to boil off charged particles like electrons, in some cases more gamma rays and thereby generate radioactivity.

09:21 Dr. Pigford: Besides those, one then has some extra neutrons coming off. See on the average you have around two and a half of those neutrons, which then go along and hit more uranium nuclei to make them split apart. And so besides those, let me trace the path of some of these fission fragments, which are these high-speed heavy materials left over from the splitting up. These then, as a I say, undergo radioactive decay, on the average, they generate quite a few electrons, which are moving at extremely high speeds, much higher than the speed of electrons in vacuum tubes for example, or even electron microscopes, very penetrating radiations and very lethal radiations as a matter of fact. And then finally, after emitting many of those in a few, few more gamma rays, the electromagnetic radiations, they decay to materials that no longer emit radioactivity. Now, this is a very powerful source of radioactivity. In fact, the gamma rays themselves are so penetrating that they are much, much more penetrating than the x-ray one uses in a doctor's office. It requires many, many feet of lead, in fact, to protect one from the radiations surrounding a nuclear reactor. Practically, this usually is a rather expensive approach, and so instead of that we will use about 10 feet of very carefully poured concrete to protect us. Now, this is simply by way of introduction to give you the terminology. Now, may I have the lights, please? I want to tell you a little more of the special things about this.

11:10 Dr. Pigford: I've about come to believe that the field of nuclear energy is the field of the misplaced decimal point. We are dealing with things millions of times larger or millions of times smaller than our normal experience would have us, have familiarity with. For example, the, the amount of energy released in nuclear reactions. Well by comparison, if one takes a pound of uranium and lets it undergo completely, complete nuclear combustion and I use nuclear combustion in a rather broad sense, I mean complete nuclear fission, that will liberate 3 million times as much energy as a pound of very good grade coal. Or another way of putting it, a pound of nuclear, a pound of uranium undergoing this nuclear combustion is the same amount of heat as, as 1,500 tons of coal or 330,000 gallons of gasoline. Now this itself obviously has several implications. The first is that very compact energy source that one talks about for a moment, a large power plant, which is the, for example, the type San Diego Gas and Electric Company uses here.

12:29 Dr. Pigford: Well, their plants, they have several in the network and this is the source of electrical energy that we find at our homes and the electrical energy going to by-in-large to industry. Now, these plants are, are quite large. Just to give you a feeling of the unit of size, one talks about plants of about 100,000 kilowatts. In the San Diego Gas and Electric system, there are many larger than that and a few smaller. Now, this will define as a central station power plant, the source of energy for industry and the main source of energy for our homes, electrical energy. Now, such a plant as this, if it burns coal that requires several hundred tons of coal per day to keep it running and obviously there's a big logistics problem to keep a stockpile of coal coming in, to keep the railroad cars coming in, to avoid the strikes, and, and the cost of transporting the coal is quite significant. In this particular area in San Diego, we are too far from many coal fields and we have to burn oil, which is considerably more expensive. And because of this cost of transporting fuels, one finds that there is a wide variation in the cost of power throughout this country and a much wider one throughout the world.

14:03 Dr. Pigford: For example, French, France, and Belgium, I think generate electrical power for around twice or more the cost than costs in this country. And yet in this country, the factors are 50 percent or so of variation in cost. Now, what is the import of this? Well, as I mentioned before the, the utilization, availability of energy is the key to our industrial economy and our standard of living. One can look over the world populations and see those places that have large energy resources like coal, hydroelectric, wood and know how to use them. These are the places that have advanced well in the world; those that don't have them have a different area of economy, either they haven't learned how to use them or haven't learned how to get them from other people or else they pay a very dear price for them and as a result, they're, they don't have the conveniences that we have in this country. The cost of energy then is a very - and availability - a very important key to our economy.

15:07 Dr. Pigford: Now, you can certainly recognize then that those countries that have to import for thousands of miles, large tonnage quantities of coal, have a serious burden on industrial advancement. Whereas if we had a nuclear power plant, I'll say this size and such power plants are actually now in operation, one would find that in the, now I'm presenting the most idealized case, the required daily makeup of uranium to that plant is not several hundred times but one-quarter of a pound. To be somewhat idealistic again, the plant superintendent could carry that uranium to work in his briefcase or his vest pocket. Now actually, I don't think he would do that. He could as a matter of fact. It's fairly easy to carry fresh uranium around. It's not at all dangerous, but instead, I think what he would do is just order a new shipment of fuel once every two or three years, not have to worry about it in between. And a more important implication is that the cost of transporting this small amount of fuel is fairly nominal, very small fraction of the total and because of that when we see the real broad application of nuclear energy, we will see that there's an entirely new distribution of the cost of energy throughout the world, no longer will an industrial

economy be tied to locality, localized fuel reserves. People will now be able to look, locate large industry where the product demands it to be located rather than where the fuel resource demands to be located.

16:42 Dr. Pigford: Think of the implication here for example on India, a very, very undeveloped country and they have practically no coal or oil. No coal at all, very large reserves of iron but it takes coal to, to process the iron. No energy source, they have enormous quantities of thorium and uranium but they learned how to use that, to think what a different country India will be. And Brazil, again one of the countries in the world that has the largest reserves of thorium, another possible fuel like uranium. Australia is another one. And as a matter of fact, Africa is one of the greatest ones in the world in this category. Think of an industrialized Belgian Congo and this is what we may think of very seriously in the future. As a matter of fact, we are presently building a nuclear reactor over there, for them, which is for the purpose of their beginning to learn how to use the enormous quantities of uranium they have. Now, another implication occurs of the high energy content is the fact you can do special things by not having to continuously make up your fuel.

17:52 Dr. Pigford: This is one reason why a nuclear-propelled submarine or airplane, why these are so important and attractive on a military basis, can cruise for years without having to be refueled. And the *Nautilus* has indeed cruised 65,000 miles before it had to have a refueling of its reactor. A nuclear-propelled airplane could ideally perhaps fly around the world several times or simply fly for a long, long time and think what a viable reconnaissance this would be. This unfortunately turns out to be a much more difficult problem than a nuclear submarine and this is one reason why we don't have a nuclear airplane in the air today. Basically, airplanes just aren't designed to carry around enormous quantities of lead or concrete, which is required to shield the crew. In fact, one of my associates who I worked with on the nuclear airplane project finally concluded that if we never developed the operating nuclear engine, at least we could drop the shield on the enemy and do just as much damage. That’s just about the sort of the problem we have here. The submarine, on the other hand, can carry a lot more weight and because of that, it was a very successful development. We have many, many, many nuclear submarines now going into operation.

19:10 Dr. Pigford: Let me show you a bit what the, what the technical features of a reactor are now. And to carry out such a development, to, to go from the basic physics here to a operating practical machine requires some very, very careful analysis, materials work, experimental work in chemistry, metallurgy, solid state physics, engineering. It's a problem that, that seems more than any other I've ever known of to bring together the large number of disciplines of science and technology. Here’s what one of them looks like and I'll show you some of the problems that we have. If I may have the next slide here. I'm going to approach this gradually in degrees so that we can go from the reaction to the techniques and finally see what an operating machine looks

like. Well, a nuclear reactor of course has no resemblance to a conventional furnace where one burns coal or gas. In fact, it looks more like a, a Swiss watch which has been scaled up to many feet in size. It consists of what we call fuel elements, which are long usually metallic rods of uranium, which are then clad or coated with special very, very high, highly corrosion-resistant metals such as stainless steel or zirconium, a metal which had only been used in tiny quantities until nuclear energy came along.

21:00 Dr. Pigford: And such fuel elements are very carefully made. The uranium itself cost anywhere from 30 dollars a pound to 8,000 dollars a pound. The kind used in the submarine *Nautilus* cost 8,000 a dollars pound. The zirconium itself cost 30 dollars a pound. Obviously, when one gets through fabricating this material, you have, you have pieces, fuel elements which are extremely expensive, very precisely made and this schematically shows such fuel elements. This one, as a matter of fact, happens to be a tube. You're looking at the end of it right here and there is the uranium unfortunately shown in the light color with zirconium clad around the outside and inside. The cladding is simply to keep the, the radioactivity inside the uranium, I mean the materials that actually emit activity so they won't get spread over the entire plan, to keep the coolant from corroding away the uranium and then the coolant, in this case, it happens to be a liquid metal. In fact, in many projects, we've worked on liquid iron as a coolant. Think of the problem of pumping liquid iron around to cool a, a furnace. Well, that’s exactly the sort of thing we're dealing with here. This one happens to be a much simpler problem, this is liquid sodium and it flows up along the outside and the inside of that fuel element and gets hot. Basically, the fuel element looks just like an electrical heater. It’s a piece of metal that sits there glowing red-hot, white-hot in this case, and the energy is generated right within that metal and just transferred by conduction to the outside. So the sodium flows along and picks up the heat and carries it away outside the reactor. Now, we know that the nuclear reactors are really a development from the atomic bomb itself, they are controlled atomic fission bombs. How do we control them?

23:08 Dr. Pigford: Well, we’ve found that one way of making them more controllable is to slow down the, the neutrons which are generated and these are the things that are the chain carriers that propagate the nuclear reaction. If one slows them down, they move much more slowly and the reactor’s more easily controllable. And one slows them down by letting, see what happens is those neutrons which are, jump out of the uranium and they just fly through a solid just like it were a gas. This is basically because they are uncharged particles you see. They jump out of the fuel element and we let them hit the material which is fairly lightweight. In fact, low atomic weight like hydrogen or lithium or beryllium or graphite carbon for example. Well, carbon is a good one. They hit carbon and they recoil off a carbon many, many thousands of times and they speed up those carbon atoms - they get it hot - but finally, those neutrons slow down to a fairly respectable speed of only a few thousand miles a

second. And by that time then, things are going slowly enough that we can control the reactor a lot better.

24:24 Dr. Pigford: Now, I've introduced this point of control only to make my explanation simpler. The main reason one uses a slower-downer like graphite and this one, this is called a moderator. You see it moderates the neutron energies. The reason we use that is not mainly for control but because it makes the uranium react better. When the neutron is slow, it can wander around inside that piece of uranium and it has a greater chance of hitting it. It's just amazing that the neutron can walk around inside of a solid for such a long time and not hit anything. But it has to hit that little tiny nucleus and there's so, so much space between the nuclei in the, in the material relative to the size of the neutron itself. Probability is not great of a collision so we moderate the neutrons so they can hit the uranium nuclei very easily and then blow it apart. Now, if I may have the, the next slide. I want to carry this to a more practical picture of a reactor.

25:35 Dr. Pigford: Now, as you probably recall from the previous slide. We then had many, many in fact hundreds of such fuel elements surrounded by graphite stacked together. Here is a, the way that they would appear finally in a practical reactor. One has a large cylindrical vessel, which in this case may be 8 or 10 feet in diameter, and here schematically are those fuel elements with the graphite, stacked together. Now, why do we stack them together? Well, there are two reasons and let me have the light for a moment so I can explain this with some simple models here. The reasons we stack them together is - the first reason and this is an engineering reason, the most practical one, the most demanding one. You can only get a certain amount of heat out of a given piece of material, like a given rod. Like you know on your stoves, you have to have quite a bit of coil of Calrod heaters on your electric stove to get enough heat up into your, into your saucepan otherwise you'd use a little tiny heater. Problem of enough surface for heat transfer just to get the heat out to the coolant. Likewise, we have to have enough fuel elements so that we can get a large amount of heat out of it because we want to heat up a lot of material and finally transfer it out for useful purposes. Another reason, and this is I think a more subtle one, which also has some implications beyond the reactor itself, is what makes the reaction propagate? Well, I said, it's the neutron flying up from uranium and hits another one. The neutron you see is the chain carrier, it's a chain, a link in the chain of one reaction propagating another and so forth. If we couldn't do that, it would be like trying to operate a fire, a boiler by just tossing matches in one at a time.

27:41 Dr. Pigford: You need something that will be self-sustaining. Now, this is analogous for example, if you tried to burn a fire in your fireplace and try to build it with just one log even if you have a lot of kindling. In general, this is very difficult. In fact, I've never been able to do this and I think the reason scientifically is that this log is surrounded by these cold outer walls of the fireplace and it radiates heat. It loses heat more rapidly than it can generate it and the fire won't continue. Heat is the chain carrier in

conventional combustion. It's one of the chain carriers. It also happened to be very active molecular species called free radicals which are also the chain carriers. You gotta have enough logs, usually about three so that the thing is, the logs can see each other and re-radiate that heat and not lose it all out to the surroundings. There's a critical mass for a fireplace, in short. Actually, there's a critical mass in burning gas, now this one's a little harder to see because you know that pilot flame on your stove is a very tiny thing and it burns quite nicely. But I once did some interesting research on just what is the minimum size of, of a bubble of gas that can be ignited. If it gets too small, you see when you try to get it ignited, it loses its heat too fast to the surroundings and loses a chain carrier and the burning just won't propagate. The problem is when you get it smaller, well, think of this log in the fireplace, that log has too much surface area to lose its heat from. Whereas, when surrounded by another log, the heat comes back to it. You've got to have a small surface area and yet a lot of material burning. The greater the surface the more rapid the loss of the heat.

29:34 Dr. Pigford: There's a minimum amount of material then below which the surface-to-volume ratio gets so large, the loss rate relative to the production rate of energy just kills it. That's the minimum size or a critical mass found throughout nature and we have such a thing in the nuclear field. The trouble though is that neutrons as opposed to, to molecules, diffuse so easily through materials that it's hard to keep them from escaping. One needs to put a great deal of material together like a thousand logs, and fuel elements look like logs in some cases, in order to minimize the loss relative to the production and then the corresponding amount of uranium there is a critical mass. Now, this places an unfortunate limitation on, on nuclear energy. Now, when we first realized how much energy there was from each pound of uranium, why we computed a little tiny chunk of uranium about that big, that's enough energy potentially available into it that it could heat our home for the rest of our lives.

30:45 Dr. Pigford: And that's quite true, it could. But the trouble is unless you put it together not with a few more chalks of uranium but many, many pounds of it, it just won't liberate any heat at all. And as a result, there's a minimum cost of a, of a practical nuclear reactor. And that cost is so large and it's a fact of nature, a fact of life that I don't think you'll ever see a nuclear furnace or heater in your home. You can't afford it. Nor will you see one burning running an automobile, you can't afford it. The only places you'll see nuclear reactors applied then are places where one, cost makes no difference or I shouldn't put it so bluntly, this cost is not the primary criteria such as military applications or in second case where you can afford to make your plants so large or you want to make it so large that you can afford to spend a lot of money for it. For example, the cost of a plant like this to San Diego Gas & Electric Company, conventional plant, is about 20 million dollars.

31:45 Dr. Pigford: Well, once you're talking about 20 million dollars then the investment you put in the uranium is not so great and you can afford to do this sort of thing. But if in

our home, you are talking about a 200 dollars furnace, well the uranium itself for that would cost I expect around 25,000 dollars. That's a minimum amount you could use and so I think the idea of seeing little tiny nuclear power plants throughout the community, homes, automobiles, commercial airplanes even I think, is fiction. There's nothing at all to it. It is a material that has to be used in large quantities to make it economical. Now, let me go to a, the next stage on a reactor showing you what a final design looks like. This happens to be one that our crew in General Atomic has recently designed and we are building such a plant right now. This is a, see it looks like a quite a complex machine and I'm not going to attempt to define it in detail but basically here is that lattice with the reactor core which contains these rods of fuel elements. And to control it, we insert in it some of these rods of special material which simply absorb the neutrons. They absorb the chain carriers and they tend to put out the fire. They shut the reactor down - that's that technique of control. These are the control rods then and they are driven by remote, remotely operated devices at the top. This is a vessel which is made of steel. This one happens to be six inches thick, ten feet in diameter. So you see in the nuclear field, we are dealing with very heavy equipment as well as very precise equipment, the nuclear fuels.

33:55 Dr. Pigford: Now, this basically is what it looks like, this then is the furnace of a nuclear power plant. Let me then show you by the next slide how one utilizes this nuclear furnace. Here schematically is that reactor, I expect Mr. Ferguson may have shown you the same sort of thing. This particular one happens to be a gas-cooled reactor. We are using helium to cool it. Why? Mr. Ferguson probably pointed out the advantages of going to very, very high temperatures so that you can increase the efficiency of converting heat to work. The higher the temperature the more efficient is your cycle. Well, going to, to high temperatures on a coolant requires a very noncorrosive gas. The trouble is that besides dealing with very expensive materials in the nuclear reactor, we're dealing with materials that corrode quite easily. All the bad parts of nature seem to be with us right here in terms of the materials for nuclear reactors, extremely difficult. Therefore, we must seek out a non-corrosive coolant.

34:54 Dr. Pigford: Helium, which as you know is a, is an inert gas, a noble gas, all of its electronics shells are filled. It can't share any electrons with other chemicals. It can't undergo chemical reactions. It's completely inert chemically. It cannot corrode things and so it makes an ideal coolant for a high-temperature reactor. It then flows through the reactor, comes out quite hot, 1,300 degrees Fahrenheit. That, that's almost as hot as a flame, you see, and then flows through a heater and it's pumped back to the reactor. And in that heater, we generate steam and the steam then expands through a turbine, which drives a generator. In this case, is driving a propeller there because we're working right now on a, a reactor to propel a merchant vessel. And then the steam condenses and is pumped back to the boiler. This is the power cycle you see and in the nuclear fuel one just doesn't, doesn't deal just with a reactor but rather with a whole plant because the problems propagate all the way through and backwards.

36:08 Dr. Pigford: Now, the next slide gives you a final picture, away from the schematic sort of thing, as to what a plant looks like. Now, this happens to be the first industrial or the first large-scale industrial nuclear plant in this country. It was built by the government as a, to obtain experience. It's far from economical. It is getting us good experience on how to develop practical ways of utilizing nuclear fuels. It was under the head of Admiral Rickover who was the man who developed the nuclear submarine. Now to show you how the plant has built up, this tiny thing here happens to be the reactor. That one incidentally is a water-cooled reactor. To get water at high enough temperature to get to the conversion of heat to work requires high pressures to keep it from boiling. That's the sort of thing that's used to propel the submarine *Nautilus*, a water-cooled reactor. We call them pressurized water reactors. In fact, the vessel, the big can that this one is, is in, is made of steel, nine feet in diameter, eight-inch thick steel walls. Imagine welding a piece of steel with walls eight inches thick. A major, major problem of blacksmithing.

37:32 Dr. Pigford: Now, this reactor, and power plant in this case is encased in a large steel building. Why do we go to a steel building? It's a rather expensive thing. The reason is this - a reactor has in it a terrific amount of radioactivity. In fact, it has the equivalent of tons of radium. Now we know that a gram even of radium is a large quantity for a hospital, quite lethal. Tons of radium. Imagine the magnitude of the, of the radioactivity that could be emitted if we had an accident. Now, in fact, we don't think we'll have an accident. We haven't had any accidents except some minor ones. In some cases where we tried to have them to see how bad they could be. But until we've had years and decades of experience on these, one has to be extremely cautious to be sure that all possible radioactive materials are contained right inside the plant. And that is one thing that adds a good deal to the, to the cost of the nuclear reactor. Now if I may skip the next slide, or no, let's have the next slide for just a moment, please. I want to show you all the other things that one must worry about and put into operation to have a nuclear power industry running.

38:59 Dr. Pigford: The reactor plant is only part of it, it happens to be the, the heart of the, the process because it's what generates the energy. But this is a lot more complicated than, than just mining coal and sometimes washing it or pulverizing it and feeding it into a power plant. In this case, we're dealing with many, many different exotic materials that are quite expensive, hard to find, hard to purify. Well, this gives you an idea, or a few of them, we mine uranium. A whole new industry has developed on this. The uranium is purified, it goes into a fuel element factory where one makes the fuel elements. Now the trouble is that only a small part of the uranium we get out of the ground contains this kind that fissions, that blows apart, the U-235. In fact, only one part in 140 is that kind. And most reactors require that this be pulled out and separated so that you can use it more efficiently and so what one does is instead of sending that uranium directly to the reactor, you send it to what is called an isotope separation plant. You're separating the uranium isotopes and this is done by a, in a very large industry.

40:21 Dr. Pigford: These are the largest plants in the chemical industry in the world as a matter of fact, located in Oak Ridge, Kentucky, and Ohio. And in this case, one has little tiny membranes where the uranium isotopes which are now made gaseous, by combining them with fluorine, which forms a gaseous compound fortunately. These gaseous isotopes then diffuse through this barrier. We know a lighter material tends to move around more rapidly than a heavier material, has higher translational energy and so because of that the lighter material uranium-235 goes through faster and one after many, many thousands of repetitive processes like that, finally gets out almost pure U-235. By that time, it appears to cost something like 8,000 dollars a pound. That then is put back into the reactor, that's the way the submarine *Nautilus* is fueled. Occasionally one must pull the fuel elements out - and by now they are extremely radioactive - put them behind and in shielded railroad cars and transport them to some factory where one tries to recover the remaining uranium.

41:32 Dr. Pigford: In the conventional power fuel, may I have the lights, please? The, if one utilizes 90 or so percent of your coal or gas, you are doing reasonably well. People like to have over 95 percent of your fuel actually burned. The nuclear fuel if you can actually can burn 1 percent or more than that, you are doing extremely well. There is no nuclear plant operating which has really proved itself yet, that has done that well, just 1 percent. And so because of that, the fuel that is left over, if it’s operating a few years, has a lot of viable uranium. You can’t afford to throw it away, it must be reprocessed. Then you're dealing with handling tons of radium light material. It’s on an enormous plant which is made strictly of concrete walls, eight feet thick. Robots, mechanical robots operate the plant. Such plants are in operation at Hanford, Washington, Savannah, Augusta, Georgia, and in Idaho.

42:43 Dr. Pigford: Now, I want to skip to a little non-scientific question here for a moment. Why should we fool around with nuclear energy? I pointed out that it is extremely difficult as special applications, special features because of the high heating value. But excluding the military for a moment, the final proof of the pudding is the cost. Well, what is the cost? Any technical man has to worry about this because he's got to make things that operate well and don't cost too much. Number one assesses the economics of a thing like this, you’ve got to figure out two things. What does it cost to operate the plant? What does it cost to build it? Both of these are important and when you get an electric bill at home or your parents do, the charges are based upon adding up the operating costs as well as what they call amortizing the capital cost, the building costs over a period of something like 20 years. And so every month, you pay a little bit back to them for what it cost them to build that plant. So you got to hold both of these things down, the capital cost and the operating costs and the cost of building it.

43:57 Dr. Pigford: Say for example, this one costs 20 million dollars then the cost of this can be expressed by dividing this number by that, which comes out to be around 200 dollars per kilowatt - which is the unit cost like the dollars per pound of metal. In fact,

I would like to point out, I think that San Diego Gas & Electric bills them a little cheaper than that, I've only rounded off my numbers here. Let's see what the nuclear plants cost. Next slide shows that. Now here is a sort of a compilation of cost. Well here on the left-hand scale is the dollars per kilowatt. It's a function of the generating capability, how many kilowatts, in this case, megawatts, are turned on. A megawatt is 1,000 kilowatts you see. And so here on our scale is 100,000 kilowatts and we have actually around 150 dollars per kilowatt as the representative cost of conventional plants and the cost per unit goes down the larger it is. Simply, you get steel more cheaply the more you buy. The dollar per pound goes down the more you buy.

45:17 Dr. Pigford: Now, let's see what the experience is on nuclear plants. Well, here happened to be a set of data, they are very scattered. This is the sort of data we deal with all through the nuclear field, unfortunately, both cost data and scientific data. And the circles show the estimate, the prediction of the plant cost, and then the little black circle on top shows what it actually costs. This is to point out how difficult it is to estimate the cost in this field. Now for example, here's one that unfortunately I worked on once which is a plant that we estimated to cost about 300 dollars per kilowatt, clearly not economical but the first plant we felt that it should be built because the cost would go down in the later ones. Well, when it was finally built, I must admit that it was never built, they found that finally, it wasn't worth building. They came close to spending 2,000 dollars per kilowatt. Well, this was a little embarrassing, we were off by a factor of 7. In fact, Admiral Rickover, who is the man that developed the atomic submarine has - may I have the lights please - has the theory that the accuracy of your cost estimate in this field is inversely proportional to the square of the distance the way you are from building the plant. So if we don't have to build a plant for 10 years, we estimated it won't cost very much at all. The closer we get to it, the more expensive it is and this unfortunately is something we are stuck within the field.

46:54 Dr. Pigford: Now, this isn't based on, it isn't, the reason for this is not only because we are a little naive and can't estimate the cost very well. It's also because we're dealing with brand new materials, welders haven't worked with before, metallurgists don't really know quite what's the best way of putting them together, engineers are having to invent new things as they go along. And so the trouble is we don't know the cost of these plants until we build them. This is a rather expensive experimental program to build, one after another plant, each costing perhaps 60 or 80 million dollars to learn what the cost of nuclear energy is and that's just where we stand today in the nuclear field. Well, why is it worthwhile? Let me skip the next slide and go to the proof of the pudding here. The final slide is what I hope to do to show you that what I'm working on really is worthwhile in spite of all what I said as to how much it cost.

47:55 Dr. Pigford: Now, this happens to be a compilation of the world requirement for energy sources, so this is the key to our economy, our future life, as a matter of fact. Now, a gentleman named Putnam is given the job a few years ago by the US government of summarizing how much energy the whole world has consumed and so his summary was an extremely interesting one. He started from the year zero and worked up to the year 1850 and admittedly the data were a bit difficult to get but he did his best there and he has presented that the total consumption was between 6 and 9 trillion million BTUs [British thermal unit]. The better way to say, 6 to 9 with 18 zeros at the end of it and so rather than to keep talking about those 18 zeros all the time, I'll just say 6 to 9 Q units. And you see I'm talking about the misplaced decimal point again in the nuclear field, or the energy field. So these are important really for comparative purposes right now and for the next 50 years, four units.

49:23 Dr. Pigford: During the latter part of this century 10 units, more than you see, are the equivalent of the consumed about all the world's history up to now. Shows how rapidly we are consuming energy, we've a terrible appetite for energy. This is partly because of the expanding population, partly because you and I are daily using more energy, not necessarily for heating our homes or more automobiles but better products because, because products themselves require energy. And 2000 to 2050, 70 units. In this country, we are doubling our consumption rate every seven or eight years, and in other countries more rapidly. Now, how much energy sources do we have to supply that?

50:07 Dr. Pigford: Well, here are the compilations briefly. Each one of these is an interesting case but I won't have time to go into it. Coal is the greatest of the conventional fuels, 21 units available. So you see that can certainly get us through this century. Oil and gas, this includes incidentally undiscovered oil and gas, that itself is sort of interesting as to how the geologists can predict how much they haven't discovered yet but they really can and it has five units. Oil, shale not very much. Solar energy, a terrific amount every year, which is in the troposphere, not very much, so much reaching the Earth and the feasible amount to be recovered during the next 50 years, 5 units. Wood, not much. Falling water, not very much at all. This is interesting because we're looking looking upon Grand Coulee and Boulder Dam, as really being enormous energy sources. The trouble is, compared with the requirements, there just is not much left. Tides, wind, natural steam, thee are very insignificant. Nuclear, uranium, and thorium, 570 units, about 20 times as much energy available there as in the total of all of the above more conventional energy resources which we will call fossil fuels as well as the input from the sun.

51:26 Dr. Pigford: There's another energy source here. May I have the lights please on this? It's the fusion. Now the fission, as I said, is blowing apart of heavy materials like the atomic bomb and we are actually using fission, as I say, in many power plants. Fusion is the opposite of that. It's like the hydrogen bomb where you fuse nuclei together. Now, this is sort of like burning carbon in air. You take some light atoms

and fuse them together to form some heavy molecules. Here one can for example take deuterium, a heavy hydrogen that professor Urey discovered, and fuse together deuterium - generates a terrific amount of energy - and there is so much energy potentially available there. For example, if one takes the known amount of water throughout the world, that does not have much deuterium in it, only has one part of the deuterium in 7000 parts of hydrogen. But, we can extract that heavy water for something like 30 dollars a pound and at that cost it's, is just insignificant. It's very, very cheap to us at that cost because it generates so much heat. And therefore from extracting all the deuterium, or heavy water, from the oceans of the world, we have enough energy to last us for a million years at the predicted rate of consumption and I don't think we need to worry about it much more than that.

52:53 Dr. Pigford: Then why don't give up the fission reactors and work on fusion? The trouble is they're too far away and the basic feasibility is too questionable. Professor Teller, I think, to one of these groups has stated that probably not before the year 2000 will we see a practical controllable fusion reaction. And it's not clear then whether we will learn how to get energy out of it in an usable way. We see the great amount of energy available in uranium and thorium which works like uranium and we must develop this. There's no doubt about it, it must be developed because we must have another energy source. The only question is when and the when deals with the cost. If it still continues to cost so much, we won't see it in the picture until maybe many, many years from now, then the simple cost of living will skyrocket. I believe though that we will see the cost coming down very rapidly. We see them coming down rapidly now and within seven to eight years or ten years perhaps, I think you will see energy developed economically from nuclear fuels. And this will be done in the large power plants of the sort that the utility companies have. Thank you very much.

54:06 [Audience clapping]

54:13 Marian Longstreth: Thank you so very much! Dr. Pigford. Now, some of you must have questions that you would like to ask. Do I see a hand? Over there.

54:27 Speaker 1: Yes, you said on the chart there, solar unit, solar power is 5 units. That just seems so small to me for all the sunlight.

54:42 Dr. Pigford: Well right on that point. Actually one previous amount of energy which is in the troposphere. I cannot remember the numbers, one can figure out about kilowatt a square meter, equivalent [unclear] from the sun and this turns out to be many many units per year and so if one accumulated those over the 50 years, it would be a large quantity. In fact, it would outweigh uranium and thorium, not fusion but no doubt more efficient. The trouble is that to my estimate here, which is really another man's estimate, is that estimate of the amount we might see utilized during the next 50 years and it is an optimistic estimate. The efficiency, cost, and feasibility of utilizing large amounts of energy from the sun is a difficult one. I must point out

that people of opposite points of views appeared on the panel a few weeks ago, a gentleman who is here with us right now. I don't believe in it. The techniques are [unclear]. One which I worked on at one time was trying to use the sun's energy to very rapidly develop plants, algae.

56:05 Dr. Pigford: And this algae, which has very high energy content could be burned, but this has all fallen by the wayside. People don't like to eat algae. And secondly, it turns out, cows don't make enough energy that way to get enough from burning it. It's just too expensive, much, much too expensive, more expensive than nuclear energy. The other technique is solar collectors, but unfortunately to compete - see I'm talking about those energy applications which generate enormous watts of energy. To do that by solar there is no plant, or plant concept that I know of which is considered, you know feasible or economic. There are indeed some very well and small applications like metallurgical furnaces. In fact, in India, they had a big campaign to give housewives solar stoves. And these are quite simple. [unclear] and put outside and the sun comes down every day and cook their meat or their bean sprouts in that and they cook it. But, problem was, just like anything else people in India weren't used to this. So they put a nice bowl inside and used it to hold cow dung and burnt it to to generate heat. So it became the furnace and they did not use it for cooking at all. Well, this is a rambling answer to your question. One doesn't know, potentially there's as much energy from the Sun as there is from [unclear]. Yes sir.

57:52 Speaker 2: Is it feasible to have atomic energy on a train?

57:56 Dr. Pigford: Well, this is a question. It has been looked at, there have been some designs, and I must answer your question in the matter of opinion. Of course, [unclear]. I believe it's technically feasible, we can do it today. I do not believe it's economically feasible in terms of the trains and the method of operating the trains that we talked about today. To the travelers, the economics are interesting only from this enormous amount of power happening. The submarine wouldn't be economical. The cost of a nuclear plant for a submarine is much, much greater than the cost for conventional plant, not enough power happening there and yet there is much more power in the submarine than there is in the train. So you are talking about a little tiny power plant which already costs a lot anyway because it is a nuclear plant. And then secondly, we have some special problems in the train shielding, you can't make it too fat or it won't get through, through the trestles there, but those can be solved. It's mainly one of economics on the train, and I do not believe we will see it used. There have been some discussions of large overland trains where they pull enormous cars with big fat [unclear] wheels through the Arctic, maybe so, but I'm a little skeptical. I would like to believe these things because this is my field and I'd like to sell it as much as possible, but frankly, I think that that's fiction.

59:34 Marian Longstreth: Are there any more questions? If not, thank you so much, Dr. Pigford. I can see that we are in for another kind of world revolution, can't you?

59:51 [Audience clapping]