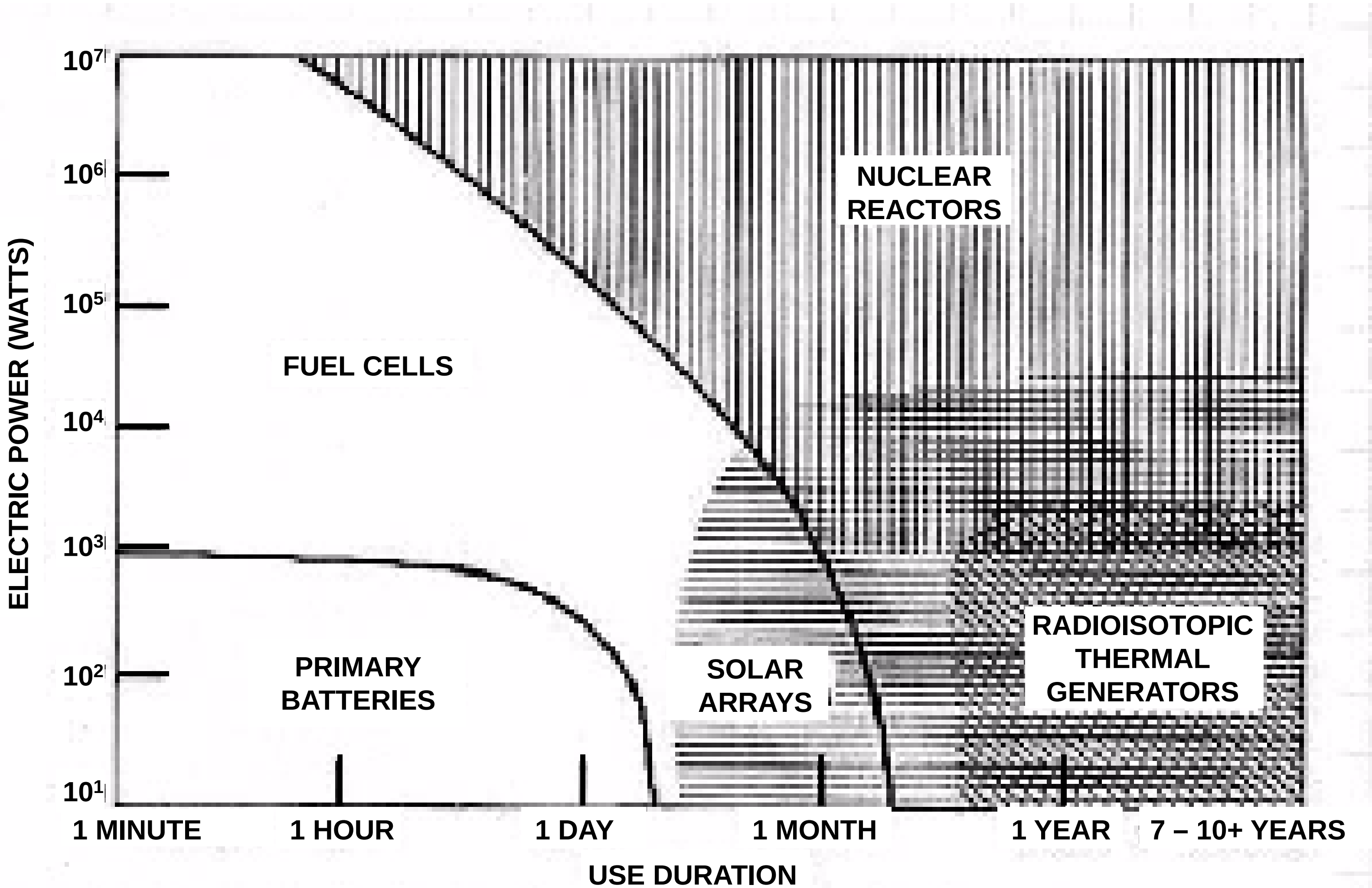
Power Generation Specific Energy Trade Space



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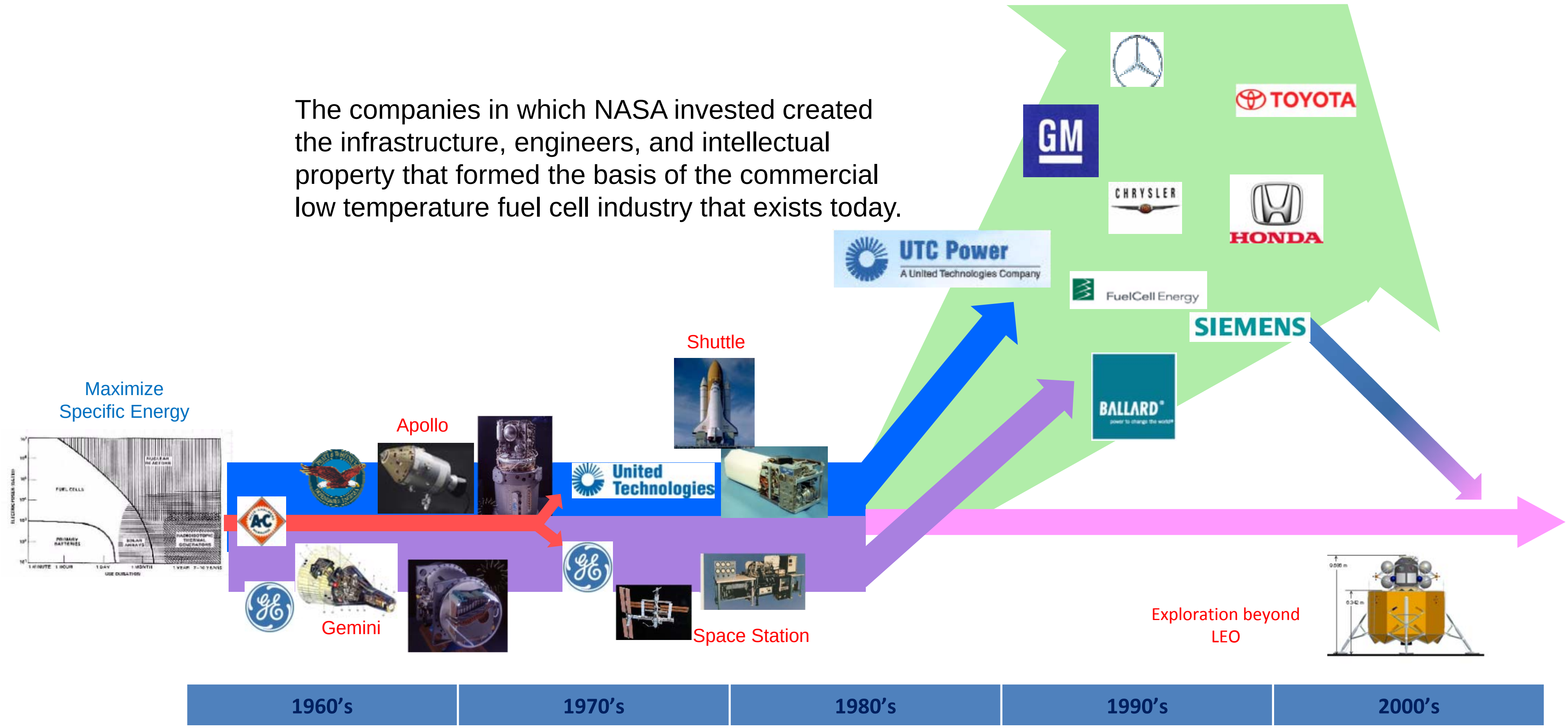
Modern Fuel Cell Technology is a Spinoff of NASA's Human Spaceflight Program

The companies in which NASA invested created the infrastructure, engineers, and intellectual property that formed the basis of the commercial low temperature fuel cell industry that exists today.



Investment from NASA's Human Spaceflight Program in the 1960's – 1980's brought fuel cells from the laboratory to their first practical application

NASA continues to drive innovations in spacecraft low temperature fuel cell technology development while leveraging commercial advances.

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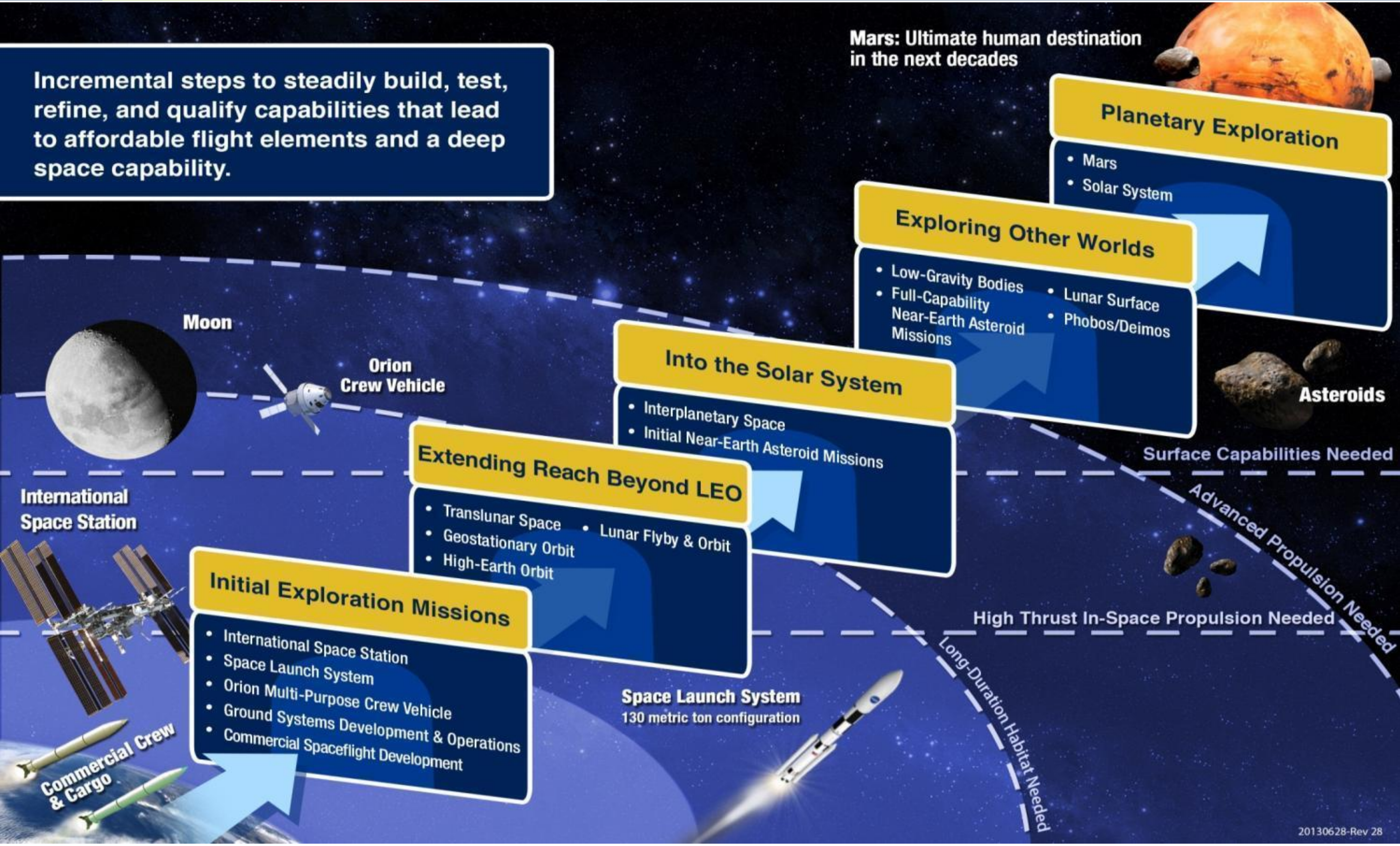
Technology Roadmaps Will Look Forward to Needed Capabilities Using NASA's Capability Driven Framework



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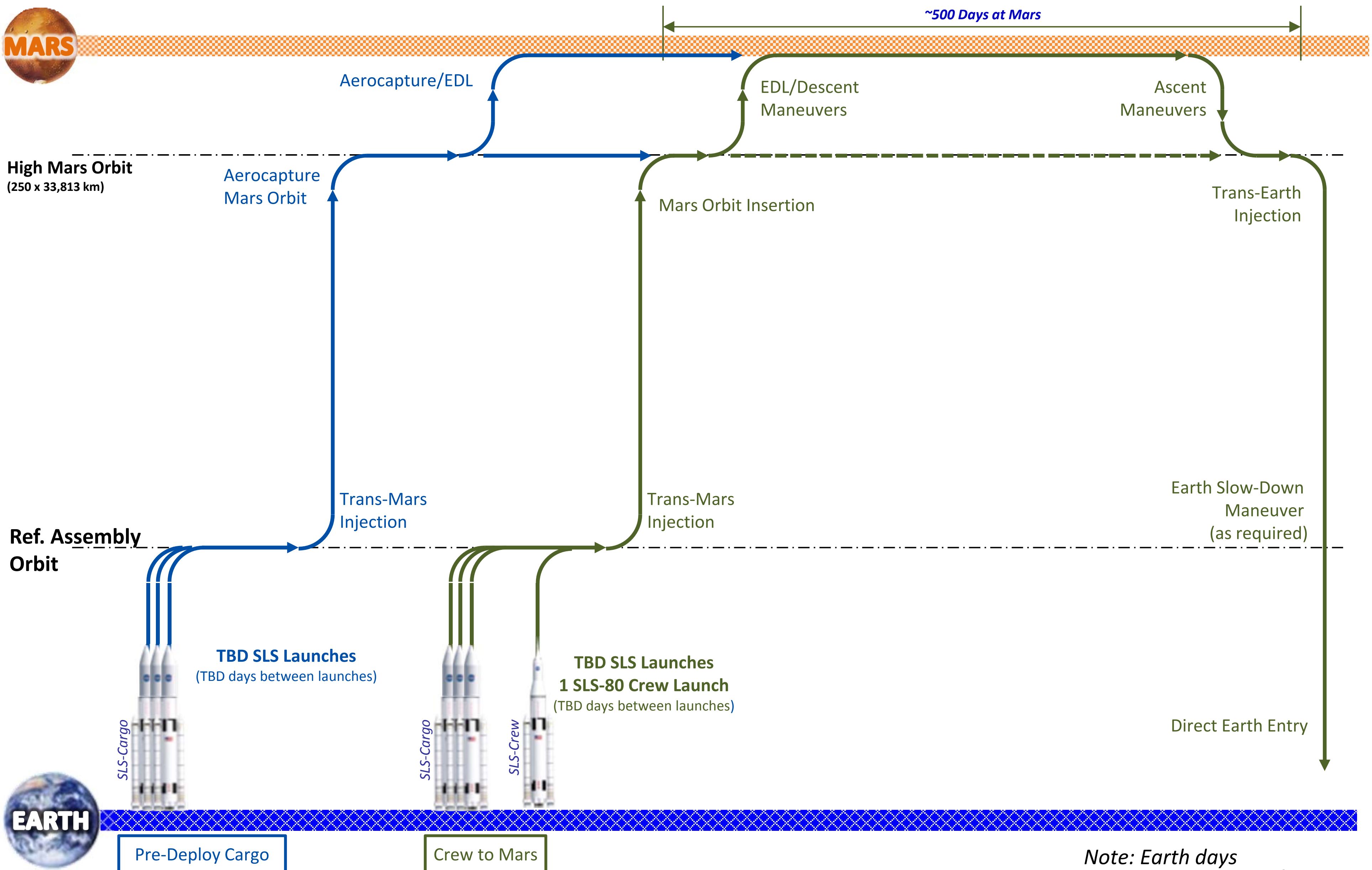
DRM-9: Mission Architecture – Crewed Mars Surface Mission

- Notional Long Surface Stay Mars Operations



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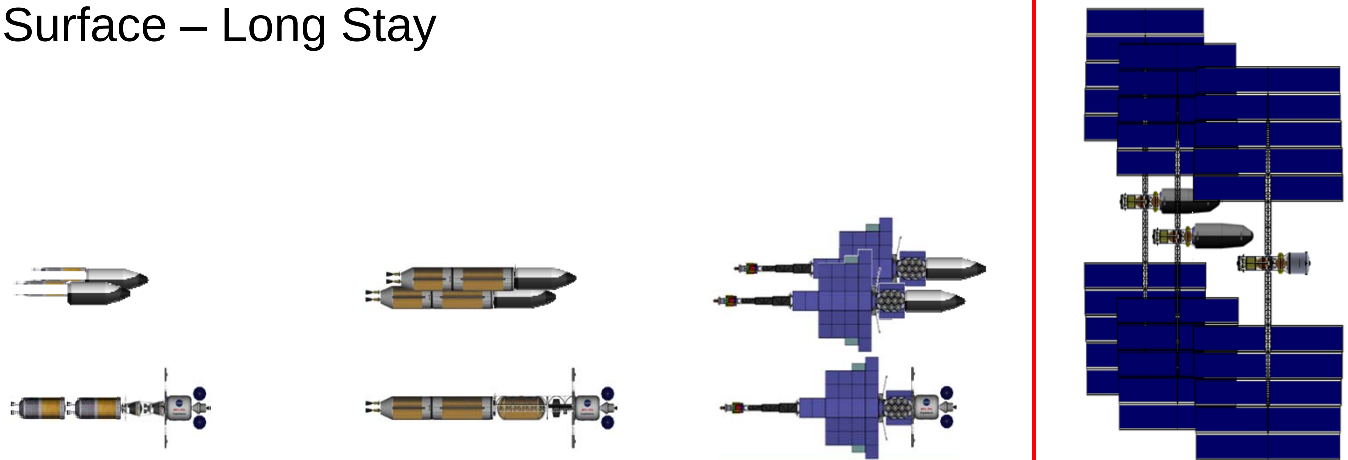
Power to Mars

DRM 9: Mars Surface – Long Stay

Cargo Missions ǂ

Crew Mission



	Chemical	Nuclear Thermal	Nuclear Electric	Solar
Electric Propulsion Power	**n/a**	**n/a**	**2.5 MW_e piloted**	**BOL 1 MW_e piloted**
Total Launch Mass (mt)	~1,250	~890	~770	~780
# Heavy Lift Launches	~12	~9	~7	~7
SLS delivery to LEO (mt)	105 & 130	105	105 & 130	105 & 130**
Trip Duration (Days to Mars, Days on Mars, Days return)	180 / 500 / 200 880 days total trip	174 / 539 / 201 914 days total trip	309 / 400 / 224 980 days total trip	439 / 300 / 326 1065 days total trip

Chain Reaction

1939	1940	1941	1942	1943	1944	1945

Chain Reaction

1939	1940	1941	1942	1943	1944	1945







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Chain Reaction

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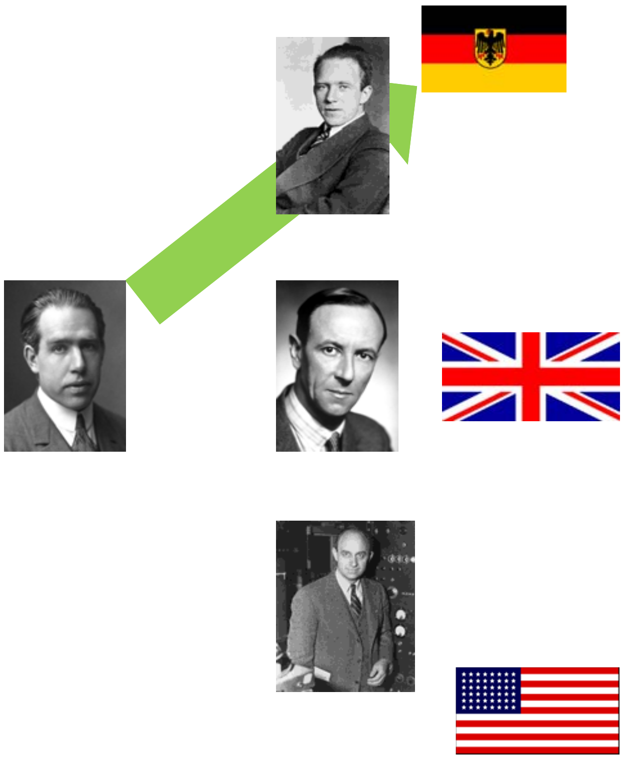

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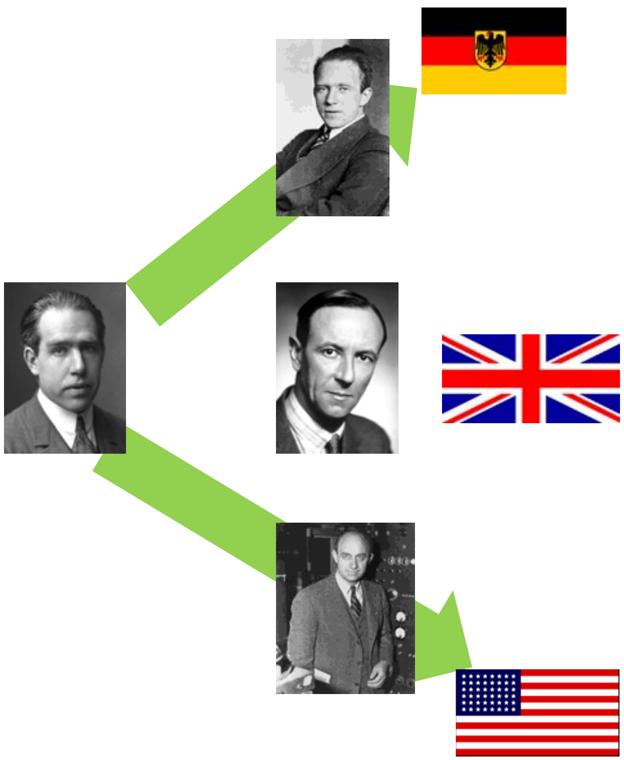

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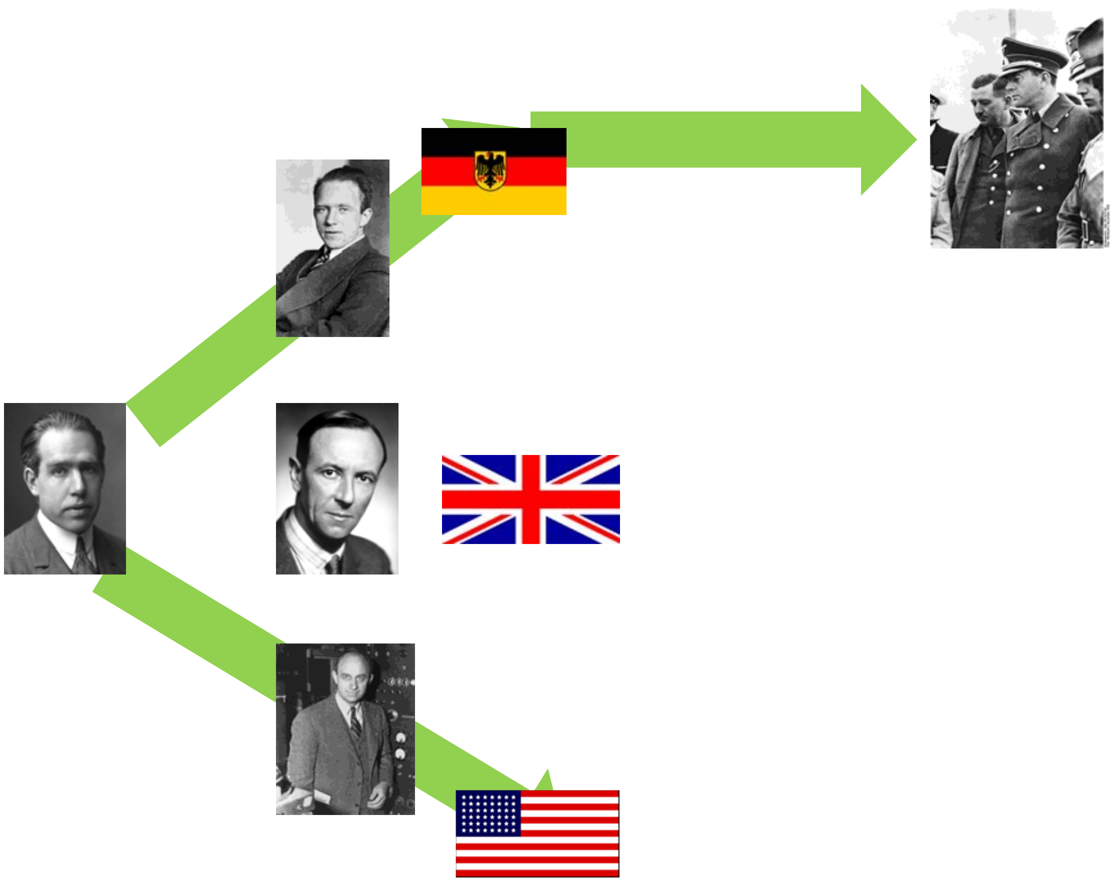

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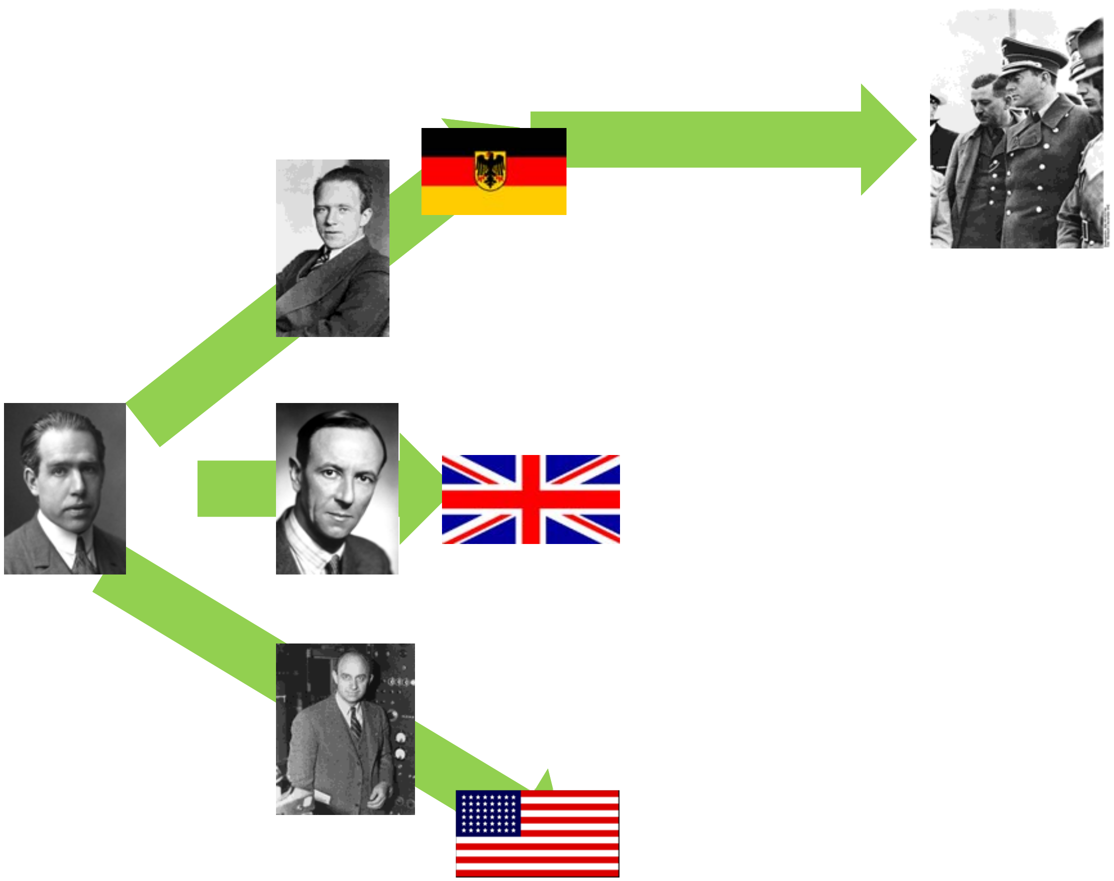

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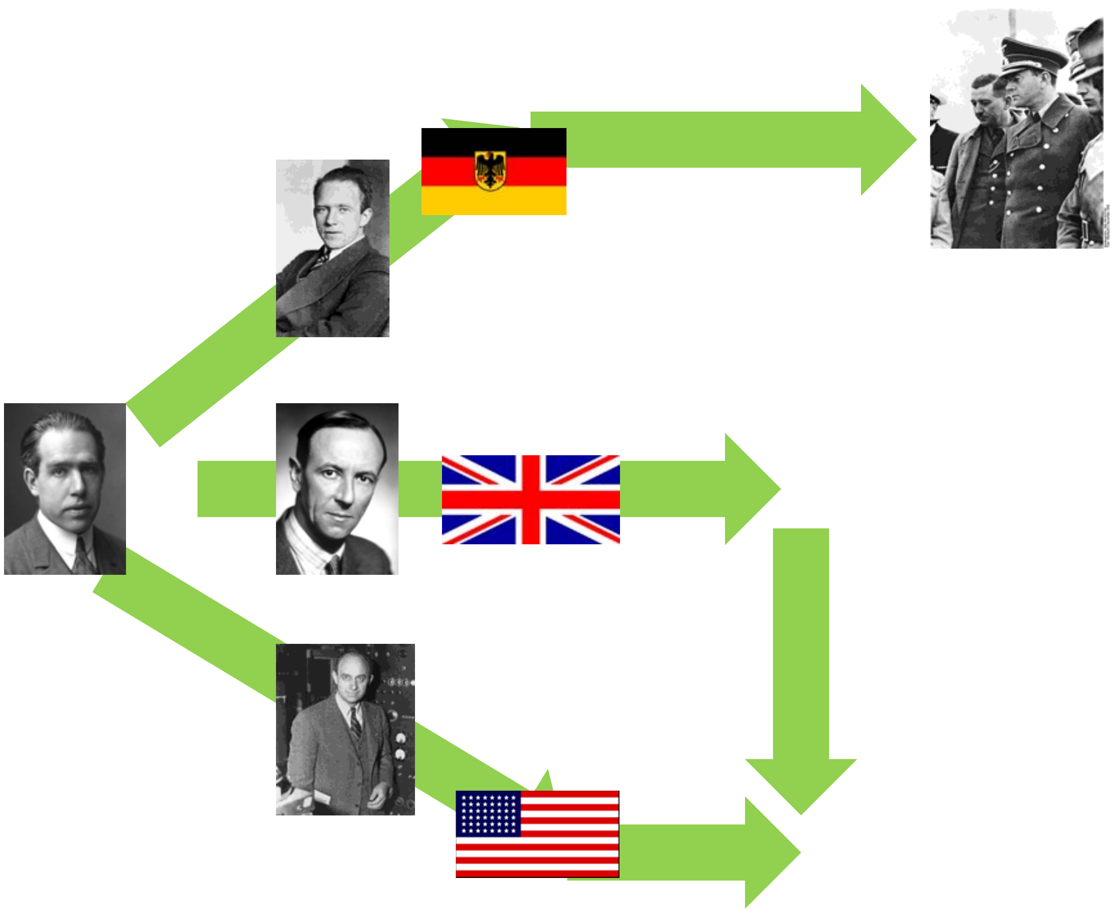

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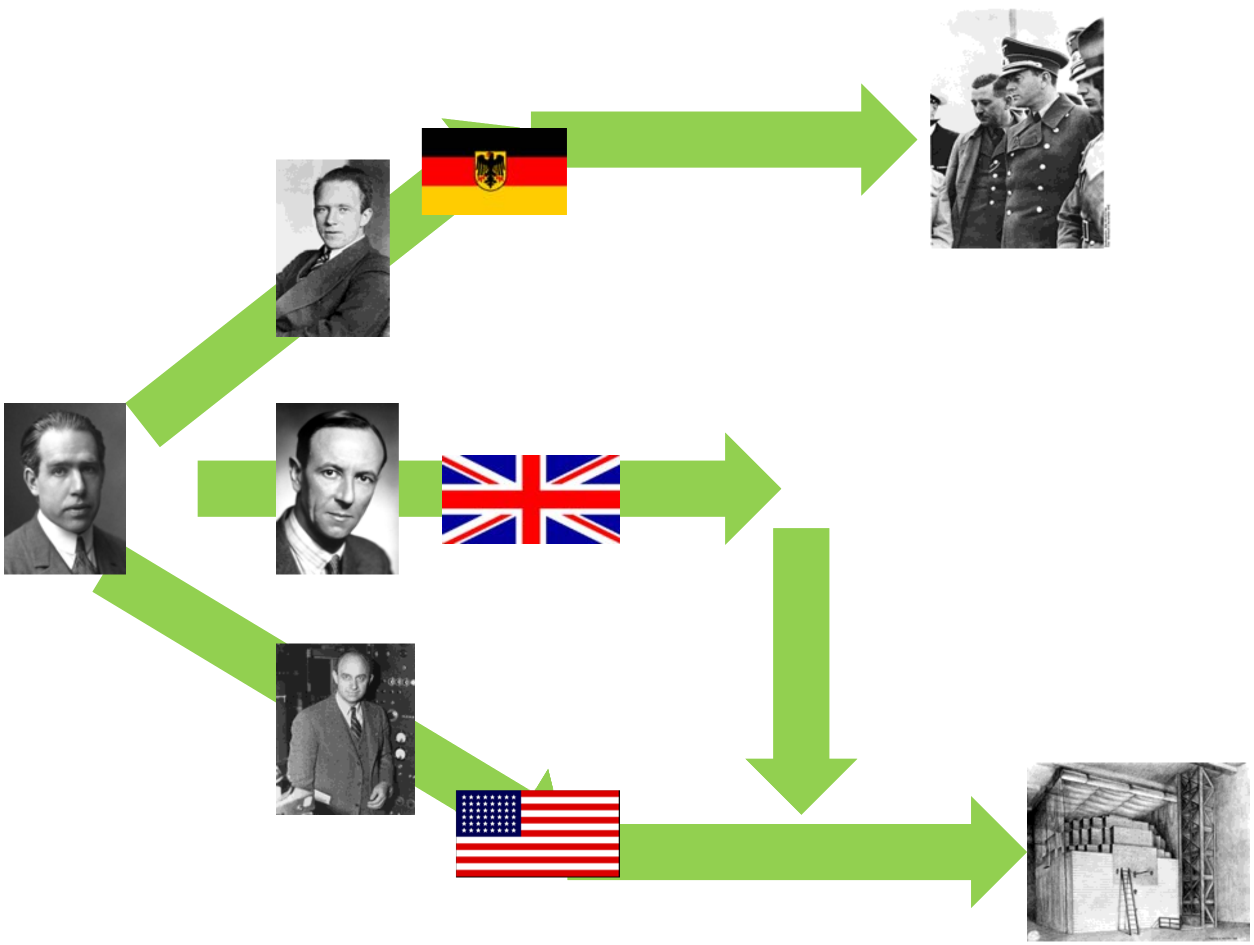

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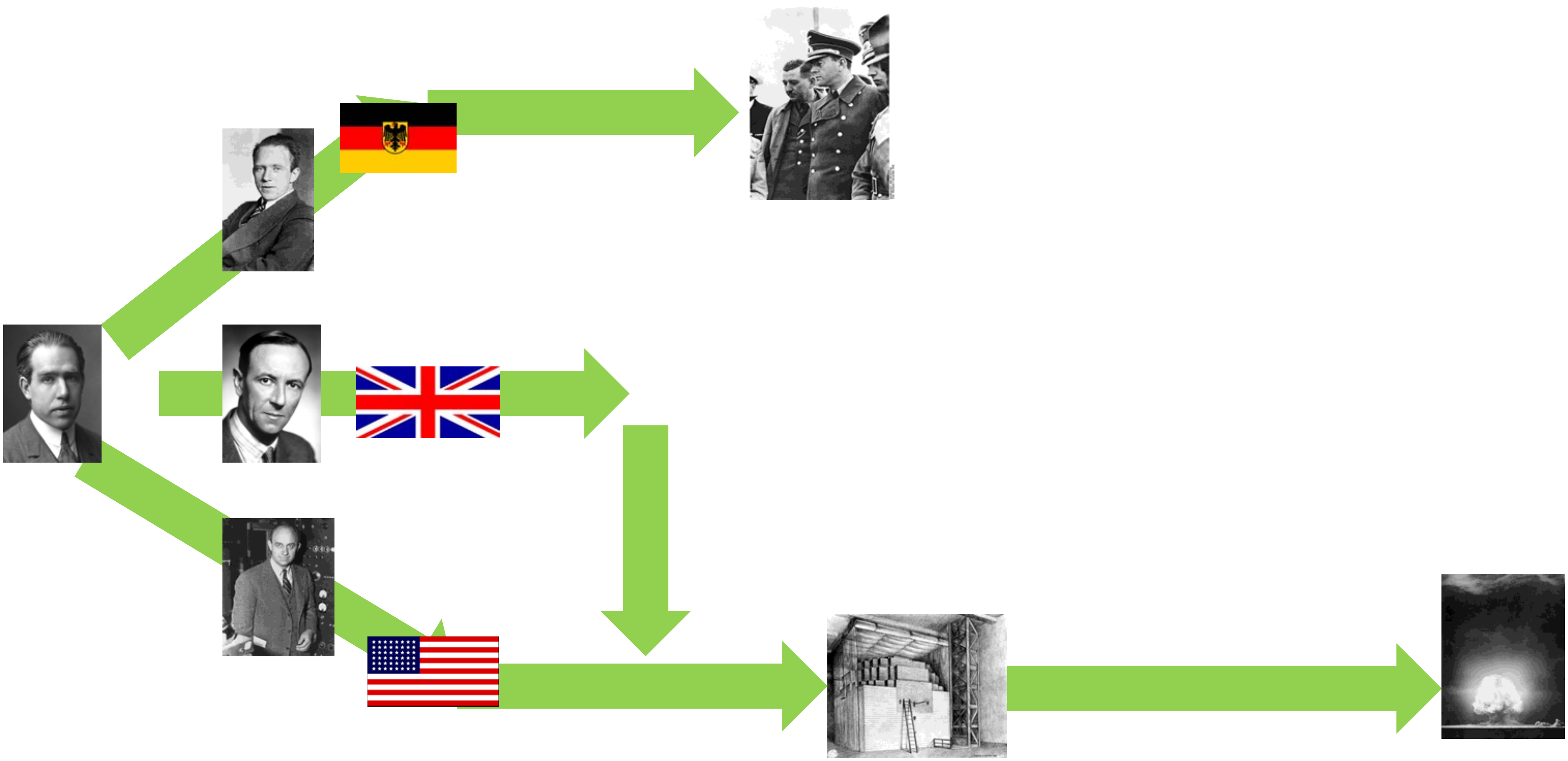

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One of the most gratifying aspects of serving as an engineer or scientist at NASA is the accolade received from the general public for our leadership in developing technology that has moved our nation forward. I often myself receive the benefit of such praises from the parents of my children's schoolmates, from people seated next to me on an airline flight. The gentleman who invited me to speak here today told me: NASA is where we are all going!

I sometimes have to sheepishly redirect credit for many energy innovations to where it is due: For example, the development of modern photovoltaics was pulled by the Defense Department. But where has NASA advanced energy technology? The best example is the low-temperature, hydrogen oxygen fuel cell.

The basic chemistry of this was worked out in the 19th century, and some experimental devices were demonstrated in the early 20th, but the fuel cell remained a solution in search of a problem until the advent of the Apollo moon program in the 1960's. NASA's engineers had to find a means of powering human spacecraft independent of the Sun and at the lowest mass possible. [Specific Energy Locus chart] This chart, from that era and based on fundamental physics, displays the locus of maximum specific energy solutions for a given power demand and mission duration. From this, engineers decided that a fuel cell had to be engineered for the Apollo spacecraft. Thus, the Moon shot program produced a problem for which the fuel cell was the solution, and the Space Shuttle continued to do so. NASA's investment thus brought the fuel cell from a technology demonstration to practical use. It formed engineering teams that would become the basis for those that grew in response to the "Hydrogen Economy" initiative in the 2000's. In fact, all of the commercial fuel cell teams today, including those in the automobile companies, can trace their corporate, intellectual property, and even personnel heritage back to the firms built in response to NASA's need in the 1960's and 70's.[green arrow chart]

So, what is NASA doing now for energy technology? While NASA has many unmanned missions in the works, from another Curiosity-type rover for Mars to a robotic mission to Europa, NASA's primary driver for power and energy technology is our long term goal of the human exploration of Mars. The agency is now in the process of building a set of development roadmaps for each of the technologies needed to support NASA's mission, [technology strategy chart] and I have the honor of leading the team building the roadmap for power and energy. Of course, the energy roadmap the most important one! But seriously, the primary technology challenge of a human mission to Mars, the technology which has the most leverage on our mission capability, is energy for in-space electric propulsion. Human Mars mission architectures [DRM 9.0 chart] involve sending ahead cargo for a surface base on slow, unpiloted flights. The crew is then sent on a high power sprint of about six months duration when Earth and Mars are aligned closely. Time is of the essence for this segment of the mission, as crew exposure to deep space radiation must be minimized. The crew then remains at the Mars base for some 600 days until the planets align again for another high power sprint home. The key figure of merit for this propulsion system is "specific mass", so many kg per kW. The lower the specific mass, the shorter the transit time to Mars (with everything else held constant). NASA's latest trade studies [graphic on Mars in-space trades] for propulsion point to a solar power system for the electric thrusters. For this option, the 1 MW arrays would require radiation hardened, inverted metamorphic photovoltaic with 33% efficiency at beginning of life to yield a specific mass of under 30 kg/kW. Note that the nuclear fission option studied (with a specific mass less than 20 kg/kW) offers notably shorter transit times to Mars. Design studies for this option point to a solid core, fast spectrum, nuclear fission reactor, operating at 1500 Kelvin (almost twice the operating temperature of a typical civil power reactor) and a heat rejection radiator area of 4200 square meters! The specific mass of 20 kg per kW is a fraction of the specific mass of a submarine nuclear plant. While the nuclear option offers less exposure of the crew to deep space radiation, it would be massively more expensive to develop. In either case, the total mission requires up to seven launches of some 130 mT each (twice the mass a Space Shuttle Launch would put into low earth orbit and most of which are required just to get the propellant into Earth orbit). While some of the technologies involved in these systems, such as the large the solar arrays, will require expensive development work, none require a disruptive breakthrough in physics or engineering. In NASA's planning, these technology development efforts are spread along an incremental development path that, accounting for projected budgets, offers a Human Mars landing just over 20 years from now, in 2035.

Humans to Mars is a very long and very expensive mission. The funding-constrained technology development path is long. Those heavy 130 mT launches may cost over billion dollars each! So…what does it take to make that mission faster, cheaper, and sooner? Now, there are breakthrough energy technologies that, theoretically, get that specific mass down to 2 or even 1 kg per kW. Such a system could, with only three heavy launches, get a crew to Mars, have them spend a month on the surface, and get them back inside a calendar year. Not only that, these technologies could theoretically be developed from subscale physics proof to operating systems at much less cost than that required to certify a fission reactor. However, these technologies have barely made it out of the peer-reviewed literature, much less out of the laboratory, and NASA's technology investment plan does not pull on them. Why?

We have the space program the taxpayers tell us to have…..and they tell us through the mechanisms of our representative democracy, with all the "sausage making" that involves. Our job at NASA is to give the taxpayers the best possible program for the money they want to spend and to manage that money in the way they tell us to. In this environment, when proposing plans for the future to the White House and Congress, NASA is motivated (as any large corporation would be toward their shareholders) to avoid betting the future on getting a disruptive breakthrough. Once program managers have a real budget and schedule, the last thing they want is to have to invent something. So…how do we make an energy breakthrough happen? When speaking of energy policy and climate change, elected officials are fond of declaring: We need a Manhattan Project to solve these problems. Let's take a look at that:

[Manhattan Project timeline chart] Let's go back to 1939. In January of that year, nuclear fission in natural uranium was observed in laboratories in Copenhagen, Washington DC, and Berlin. In April, Nobel Laureate Niels Bohr presented a paper at the annual meeting of the American Physical Society, announcing that a slow neutron fission chain reaction in uranium's rare isotope U-235 could release energy at such a rate to enable a power plant, and maybe even an explosion. However, he was uncertain of how to ever concentrate that isotope. Paying attention to that conference were Rudolf Peierls in the UK, Enrico Fermi in the United States, in Werner Heisenberg of Germany. They (and their associates) all saw the implications. In September, Nazi Germany invaded Poland, kicking off the greatest tragedy of the 20th century, and Heisenberg and his associates met with Germany's War Ministry to discuss military applications of nuclear fission. The next month, Franklin Roosevelt read a letter from Albert Einstein that warned that a tremendously powerful bomb might be created from fission and that Heisenberg was probably working on it. Roosevelt responded…. by forming a study committee, which reported in November that slow neutron fission in natural uranium could make a power source and that, while a bomb was possible with slow neutron fission in uranium enriched in U-235, the enrichment was a doubtful proposition. In December, Heisenberg told his government essentially the same thing. Both teams of physicists recommended pursuing development of a reactor as an energy source and then moving incrementally toward a weapon. In both countries, scientists were telling decision makers what they could do and why that was good. In both countries, government officials responded with limited interest. There was a war on (or there was about to be). They needed weapons more urgently than an energy source. As late as June 1942 in Germany, Albert Speer asked Werner Heisenberg what it would take to make a bomb. Heisenberg really didn't understand the question and proposed continued incremental development of a reactor. In the U.S., nuclear efforts went nowhere for two solid years after that famous letter from Einstein to Roosevelt.

It was in the UK that physicists looked at fission with a different perspective. They were being bombed. Peierls and his associates were first to ask the question: If one could concentrate U235, how much would it take to sustain a chain reaction with fast neutrons, thereby making a very powerful bomb. It turned out to be just a couple of kilograms. In July of 1941, they told the UK government this: "We need a weapon, a bomb, and here is what it takes to get it; here is where we might be wrong and here are the massive costs…..and, by the way, if we have figured this out, so has our erstwhile colleague Werner." These physicists did not just say what they could do and why that was good. They recognized what was needed and explained what it would take to get it. The UK government was nearly bankrupt. They could not swallow this, so they sent their team to the U.S. That goaded the U.S. government to, in November 1941, commit $2 million ($30 million today) to obtain experimental proof of a fission chain reaction, to see if the physicists were right. A year later, the Chicago Pile proved they were. Within weeks, ground was broken at Hanford and Oak Ridge, and two and half years (and $2 billion 1940 dollars) later came the Trinity test. Nuclear fission had gone from a physics paper to a weapon in six years, with civil nuclear power as a spinoff. It is important to note from this that, from the get-go, physicists presented to the government that making a bomb would require what was essentially "unobtainium," plutonium and enriched uranium. Some 95% of the billions spent after the Chicago Pile went into obtaining that "unobtainium." Hold that thought.

So…what is in the physics literature today that might prove as disruptive as nuclear fission. There are a few concepts. There is buzz about Low Energy Nuclear Reactions or "LENR", a further development of the 1990's "cold fusion" concept, whose premature advertisement brought discredit on otherwise solid scientists. The idea is that, by exposing a metal surface with certain characteristics to deuterium gas at the right conditions, a LENR cell can produce heat using essentially no fuel and producing essentially no radiation. Physicists disagree on what nuclear reactions may be going on, and independently-verified experimental data is next to non-existent. So, I'll talk about another of these advanced concepts, for which the physics are better understood: this is the harnessing of the aneutronic nuclear fusion reaction between Hydrogen and Boron-11. The basic physics are well understood and are considered much more difficult than even those of Deuterium-Tritium fusion in the Tokamak. The engineering challenges of plasma confinement have yet to be met. Getting to a “Chicago pile moment” for any given confinement concept would cost $10s of millions. However, if the physics projections are proven correct, no “unobtanium” would be required, and the development costs to spaceflight from the “Chicago Pile moment” forward would be no more than those required for a multi-MW photovoltaic array. This technology could give NASA the low specific mass energy source needed to make human Mars exploration look like sending a crew down to the South Pole for the austral winter. Now, as a “spinoff,” it would also enable a civil power plant that would emit no carbon, produce no radioactive waste, require a per MW capital investment on the same order as that for a gas turbine plant, and consume only tiny amounts of an abundant fuel. To say that this would be disruptive to civil power generation would be an understatement. In fact, any commercial firm that succeeds with this technology would not have time to support NASA’s pidd’ly little Mars mission.

Whoever tries to get hydrogen-boron-11 fusion to its “Chicago Pile moment” has to be willing to gamble at least tens of millions against long odds. The physics are tough. However, if the taxpayer wants NASA to send humans to explore Mars and beyond and do it in our lifetimes, this is what it takes. If investors want their entrepreneurs to be, in the energy industry, the ultimate disruptors, rather than the disruptees, this is what it takes.

Thank you for your kind attention.