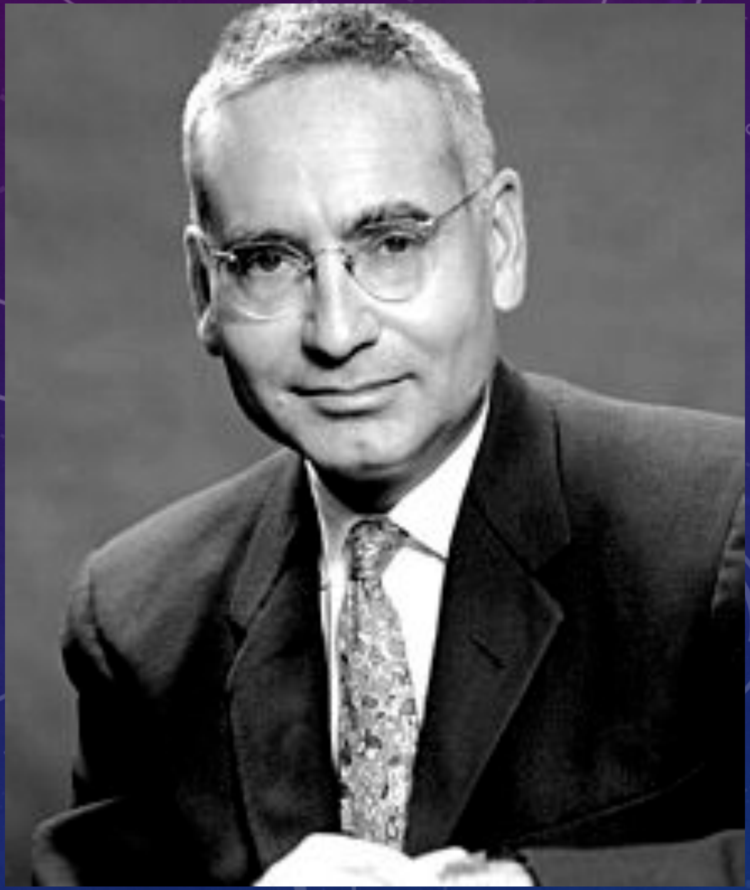
THE FIRST NUCLEAR ERA (BY ALVIN WEINBERG, OAK RIDGE)



SUB-TITLED:

THE LIFE AND TIMES OF A TECHNOLOGICAL FIXER

REVIEWED BY

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ALVIN WEINBERG: LIVED 1915 – 2005
: EARLY DAYS (1939 -1943)

- Alvin's PhD (University of Chicago) used diffusion theory to understand neurophysiology, but with WWII starting, he was asked to apply his diffusion skills to see if beryllium would be a good moderator for a chain reactor. (Then his boss, Carl Eckart, suddenly took off for California!)
- Eugene Wigner arrived in early 1942, and informed Alvin that the real purpose of the project was to create plutonium (^{239}Pu) for use in an atomic bomb, as well as to study the nature of the chain reaction.
- Both men worked out a theory of how the chain reaction can be achieved, and the best ways to study and analyze it.

FERMI'S PIONEERS: - PHOTO OF EUGENE WIGNER

- Eugene Wigner, Nobel laureate ('63) for atomic nuclear theory; lived 1902 – 95 →

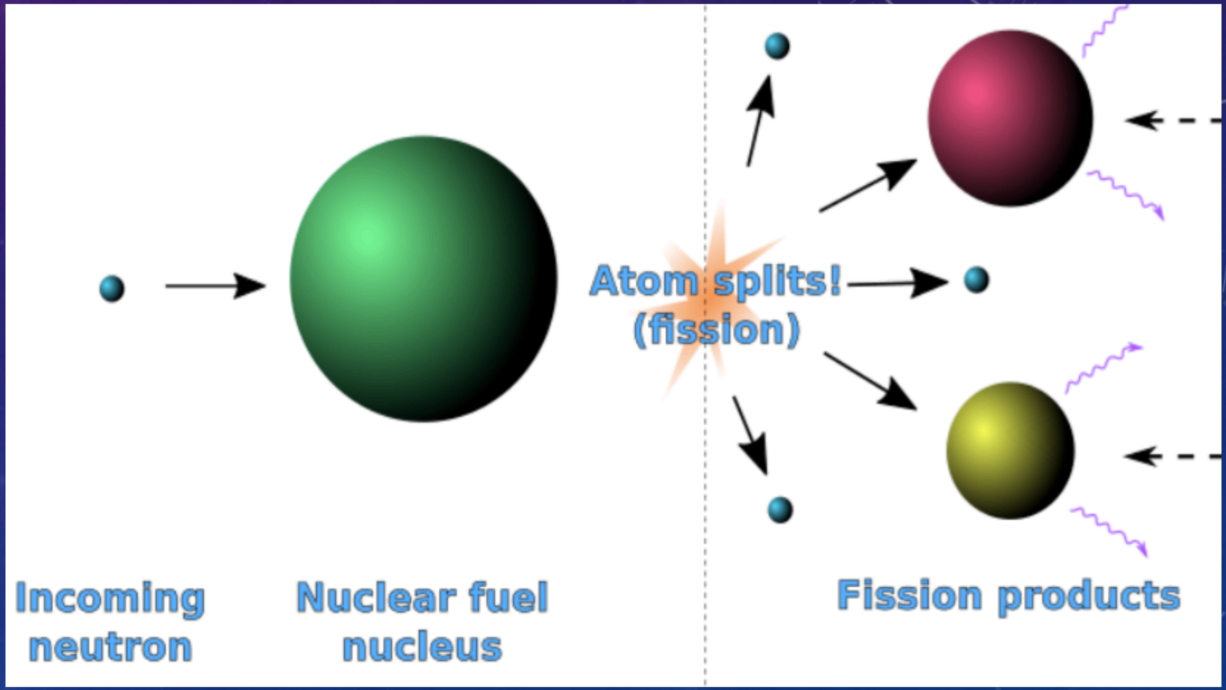
- Arthur Compton, Nobel laureate ('27) for Compton effect.
- Leo Szilard, conceived the nuclear chain reaction ('33).
- Walter Zinn, calculated pile size for reactors.
- Bob Christy, helped Weinberg with uranium lattice design.
- Gale Young, a close collaborator with Wigner.
- (Edward Teller & Robert Oppenheimer visited occasionally.)

HOW CAN WE MAKE A NUCLEAR CHAIN REACTION?

- BACKGROUND:
- Of the 2 isotopes, ^{238}U and ^{235}U, only ^{235}U fissions with slow neutrons; both fission with fast neutrons. Immediately after the first fission in a block of solid uranium, neutrons are slowed by collisions with ^{238}U, and are removed from the "chain" as each ^{238}U is converted into plutonium (^{239}Pu). Thus, to maintain a chain reaction, one must first:
- 1) ***Slow the neutrons*** of fission to "thermal" energy levels with a "moderator", so the neutrons can fission the remaining ^{235}U with high probability.
- 2) ***Disperse the uranium atoms*** within the moderator such that the neutrons are slowed immediately. (Imagine U nuclei as raisins in a big cake of graphite moderator.)
- 3) ***Make the pile*** (of dispersed uranium lumps) ***large enough*** so the neutrons escaping from the surface of the pile are just balanced by the neutrons produced by the fissioning ^{235}U nuclei inside the pile. When the two are in balance, the pile is "***critical".***

ANALYSIS OF A FISSION CHAIN REACTION

- If we make the pile larger than ideal for criticality, then the reactor is said to be super-critical, and the chain reaction “runs away”.
- If the pile is smaller, subcritical, the chain reaction dwindles and dies.
- The multiplication constant, K, = 1 for perfect chain reaction, although to obtain a working pile of practical size, k must be >1 by 3 - 4%.



COMING BACK FROM THEORY TO SOME HISTORY:

- Back in 1941 this was well understood by Fermi and Wigner, but not by Weinberg, who, even when he understood it, doubted it was feasible to achieve (rather like exceeding the speed of light).
- Fermi was only able to obtain a *k* value of 0.87 in Oct. 1941, so he improved his "pile" (Stagg squash court) by conducting 31 experiments in 1942-43. After much refinement of the pile lattice, and removal of boron traces from the graphite, the chain reaction was first demonstrated on Dec. 2, 1942.
- (Since the squash court was small, only 50 people could be invited; since Weinberg ranked at 54th , he was regretfully not among them.)

THE W (WATER) REACTORS TO MAKE PLUTONIUM (Pu)

- Designs were begun in April 1942 (8 months before $k = 1$) for making Pu (for bombs), cooling material was discussed at length, and Wigner finally chose water. Plans were submitted in Jan. 1943; the 500 MW reactor was built in Hanford WA (by Dupont) to produce 500 gm/day.
- In retrospect, Weinberg likened Wigner's creation of a complex reactor to Mozart's composing a piano concerto; Wigner may have taken 4 months > Mozart's few days, but the complexity was enormous. He viewed every day's delay for making the bomb as a gift to the Nazis.

CONCEPT OF THE BREEDER REACTOR

- On April 26, 1944 Fermi and Leo Szilard outlined ideas for fast reactors, and next day Szilard came up with the name “breeders”, which produced more Plutonium than they consumed.
- Back then they believed that breeders were essential for future energy, given their assumption that U reserves (from the Belgian Congo) were only a few thousand tons.

PRESSURIZED WATER REACTORS BEGAN IN 1944.

WIGNER & WEINBERG →

- Experiments with **<u>non</u>**-enriched U in light water revealed that *k* didn't quite reach 1, even in its best lattice configuration. Weinberg reasoned that they could make more Pu (for bombs) by using <u>low-enriched</u> uranium (LEU), moderated and cooled with ***<u>pressurized</u>*** light water. These two improvements became the standard for building future light water reactors (LWRs).

POLITICS OF THE BOMB : LEO SZILARD'S CAMPAIGN

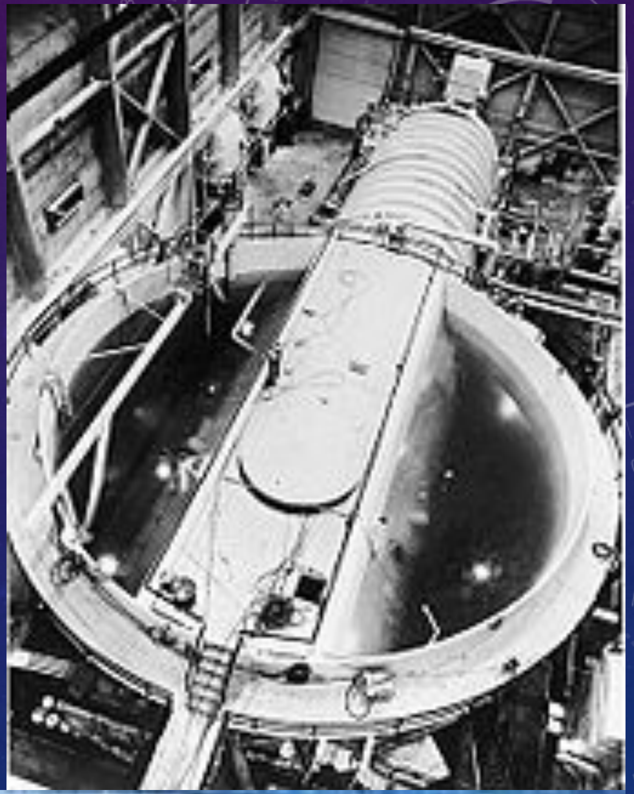
- In early 1940 Leo proposed that all papers on fission be withheld from publication.
- By early 1945 we heard of great progress in Los Alamos on bomb design. Leo was convinced that bombing civilians would place a moral onus on us, not unlike that borne by the Germans, who had used poison gas in WWI.
- He therefore led attempts by scientists to mobilize against its use.* Arthur Compton countered this with specific choices and advice.
- ____
- *See: *A Peril and a Hope: The Scientific Movement in America, 1945-7*, by Alice Smith

THE MOVE TO OAK RIDGE – MAY 1945

- Clinton, part of Arthur Compton's Metallurgical Lab, was a sibling of his other branch, Argonne Lab. Run by Dupont and the Corps of Engineers, its atmos-phere was very different from that of a university.
- This X-10 research reactor was built in 9 months, going critical on Nov. 4, 1943, and eventully developing 1 MW. Six other, very different research reactors were built here over the next few decades.

RICKOVER AND THE NAUTILUS

- Captain Hyman Rickover first came to ORNL after WWII to attend Weinberg's course on reactor theory. Years later, when "Rick" and his naval team returned to decide on a coolant for his nuclear submarine reactor, they had to be persuaded to accept the ideas of compactness and simplicity (boiling water) over efficiency (hot sodium).
- Photos show the Nautilus reactor (above) and the submarine during sea trials. →



ALVIN DIRECTS THE OAK RIDGE NATIONAL LAB (ORNL) 1948 - 1974

- Alvin Weinberg accepted the position after many others had walked away. This was for many reasons, partly because he loved the region, but mostly because he was able to appreciate the unique scientific contributions by the ORNL to the utilization of neutrons from high-power research reactors.
- In the early days they explored all sorts of power reactors, comparing the advantages and disadvantages of each type. Alvin calculated that there were ~ 1,000 possible ways of combining various fuels, coolants and moderators. But once pressurized water gained a foothold, other possibilities were preempted as being too expensive.

NUCLEAR ENERGY FOR PROPULSION OF AIRCRAFT - NEPA

- The goal (demand) of the military was to fly on nuclear power for days (or weeks) without ever touching the ground. (ICBMs were only a dream back then.)
- This was wishful thinking, for nuclear reactors are utterly unsuitable for this. The smallest reactor would weigh 50 tons, and shielding the crew would have added another 100 tons.

AQUEOUS HOMOGENEOUS REACTORS – 4 ADVANTAGES

- 1. Solid fuel elements are eliminated, reducing complexity and complications.
- 2. Gaseous fission product (^{135}Xe), a fission “poison”, can be removed easily.
- 3. Solid fission products can be removed continuously without shutdown.
- 4 Control rods are not needed, reducing complexity and possible catastrophe.

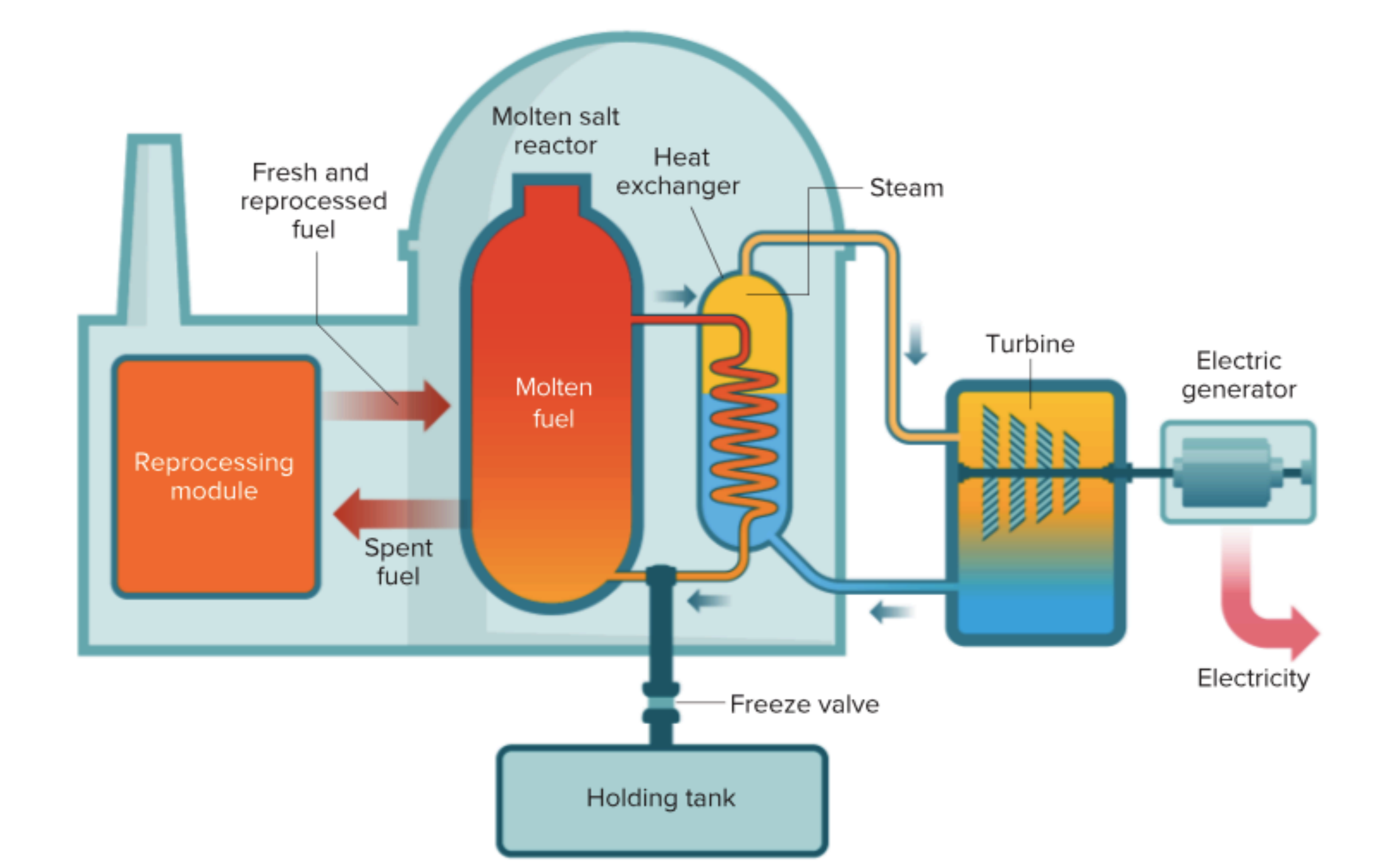
AHRs: - 2 DISADVANTAGES…!

- 1. The entire circulating system (pumps, heat exchangers) becomes radioactive, so manual repairs would be hazardous to personnel.
- 2. Control of fuel inventory would be difficult, especially if fuel precipitated; if it segregated in one spot, it might over-heat there.

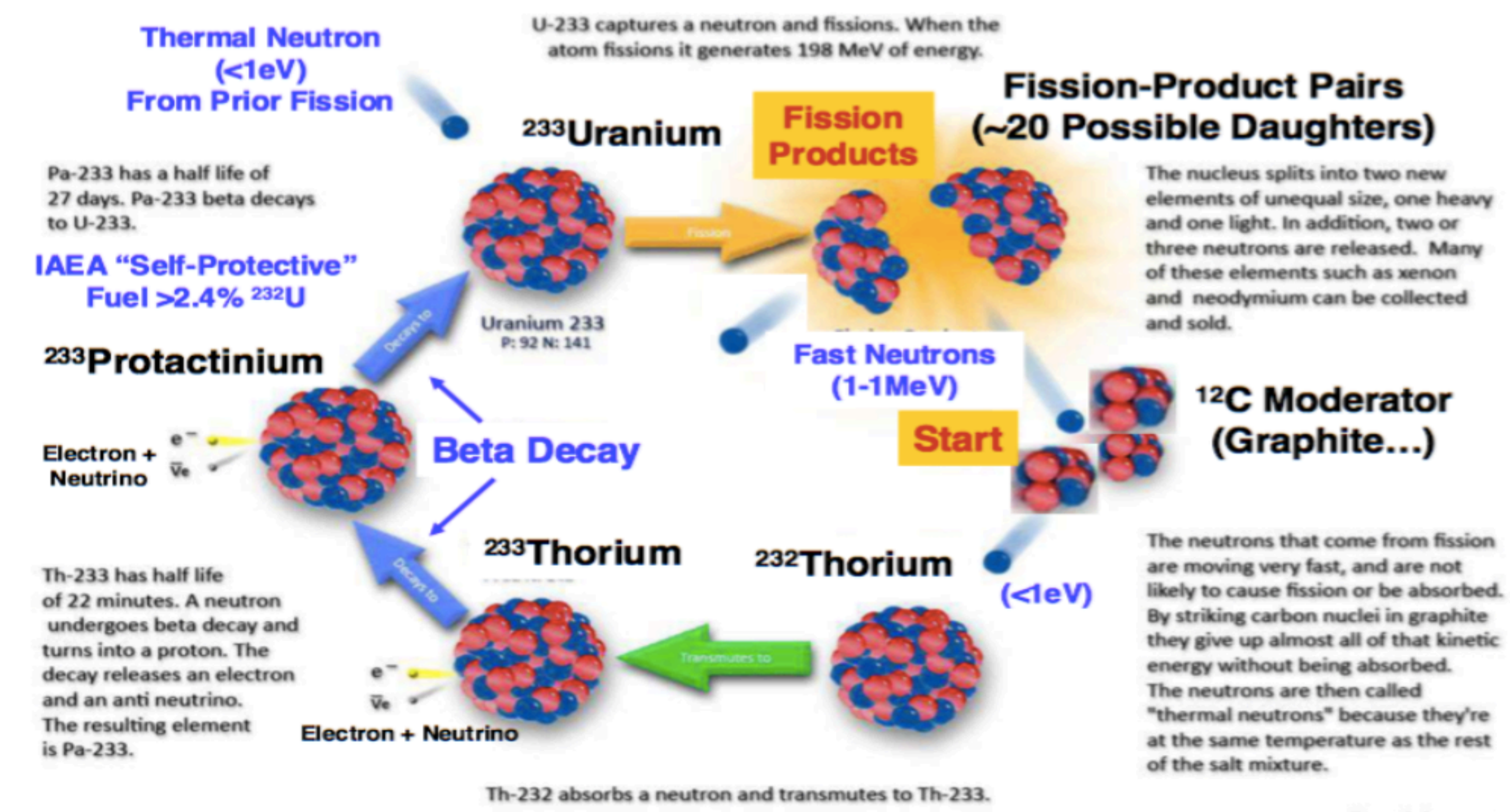
MOLTEN SALTS HAVE 3 BIG ADVANTAGES OVER OTHER HOMOGENEOUS AQUEOUS SYSTEMS

- 1. The thermodynamic stability of fluoride salts of U & Th allows them to be inherently compatible with stainless steel pipes, without using metal oxides for pipe protection.
- 2. These salts boil at such high temps (1700 ºC), they can operate at normal pressures, in sharp contrast with water (which needs 67 X atmospheric).
- 3. Thorium as well as uranium dissolves in molten fluorides, which enhances versatility. Note Alvin → at the controls.

MOLTEN SALT REACTORS ARE ***SAFE***.



Thorium Breeding Cycle



THE THORIUM THERMAL BREEDER WAS LEFT TO DIE

- Alvin became obsessed with the idea that humankind's whole future depended on the breeder. He published extensively (1958 – 59) and travelled around the world, giving optimistic lectures. A 1962 AEC report featured the thermal breeder, but in spite of all that, crucial support for its further development was never provided. WHY?
- 1. The fast breeder arrived first, and was given preliminary support.
- 2. The molten-salt technology is entirely different from other reactors. Milton Shaw (director of reactor development at AEC) thought so.

IS NUCLEAR POWER ECONOMICALLY FEASIBLE?

- As LWRs increased in number and size, → GE and others (Westinghouse) offered them at prices lower than coal plant prices.
- Later, however, they found that the economic scaling law of *bigger-is-cheaper* did not apply, especially as extra safety features were added, so construction costs mounted.

YEAR	PLACE	POWER (MW)
1957	Shippingport	60
1960	Yankee	175
1961	Dresden	210
1964	Oyster Creek	515
1965	Brown's Ferry	1,000

NUMBER OF LIGHT WATER REACTORS (LWRs) INCREASED

- As LWRs were built rapidly in USA → where fossil fuels are plentiful. They were accepted even more in Europe, where fossil fuels are less frequent.
- By 1972 over 400 large nuclear reactors were either operating, in construction or on order around the world.

YEAR	LWRs in USA
1967	47
1968	60
1973	125

NUCLEAR REALITY: THE FAUSTIAN BARGAIN

- Nuclear reality became far less utopian as the 1960's → 1970. As warned by Fermi back in 1944:
- 1) Nuclear reactors create radioactivity on an enormous scale. If a reactor failed catastrophically, radioactivity would be spread widely.
- 2) Breeders produce materials that can be weaponized. If fissile material were diverted clandestinely, the world might be threatened by nuclear malevolence.
- Alvin's most influential critics were Ralph Nader and later, Henry Kendall of the Union of Concerned Scientists (UCS).

THE WEAPONS CONNECTION

- In a 1985 book, written with M. Alonzo, Alvin explains that a country bent on the clandestine production of nuclear bombs would NOT choose Fermi's route of extracting plutonium from a power reactor. (Iraq, Israel, Pakistan and South Africa obtained their bomb materials long before they had power reactors.)
- While this does not prove that a country with a flourishing nuclear power industry couldn't decide to use that technology to weaponize, it begs the question: **Is this worry necessary, or was it just manufactured?**

WASTE DISPOSAL

- Wastes pose a much smaller hazard than reactors do. Solidified wastes, after cooling outside for decades, produce relatively little energy. If water reached waste packages, radioactivity could be leached and dispersed to a large population, but only slowly. If a transport accident occurred, larger does of radiation could reach a small population, but the risk of large doses of radiation to large numbers of people is precluded by thermodynamics.
- Meanwhile, Australian researchers have invented ***Synroc***, a synthetic ceramic that is resistant to attack by groundwater, and Sweden is using copper canisters to encapsulate waste in stable strata.

Could We Have Done Better?
Alvin Suggested These 4 Ideas for the Future.

- 1. Put all reactors on relatively few sites (~100 in USA). We have 80 acceptable sites now, so we need only 20 more.
- 2. Increase security at all these sites to avoid diversion or terrorism.
- 3. Professionalize all nuclear operators, similar to airline pilots.
- 4. Reorganize the utility industry by separating nuclear <u>generation</u> of electricity from its <u>distribution</u>. The former should be in the hands of a very single, powerful entity, possibly the government.

KEY "STRENGTHS" PERTAINING TO THORIUM

- 1. The capacity for more complete fission (higher burnups); hence, less "waste".
- 2. Higher melting temperatures and improved thermal characteristics.
- 3. Less production of Pu and minor actinides, allowing Thoriun to be a robust fertile matrix for consuming surplus Pu from used fuel inventories.
- 4. The capacity to reach higher conversion (breeding) ratios in thermal and epithermal neutron spectra.
- 5. Can be a fuel additive to uranium oxide, improving operation and safety.
- 6. These synergies combine to allow more efficient use of fuels more safely, and this is all independent of using the molten salt technology.

ALVIN WEINBERG'S LASTING WORDS OF WISDOM

"During my life, I have witnessed extraordinary feats of human ingenuity. I believe that this struggling ingenuity will be equal to the task of creating the Second Nuclear Era. My only regret is that I will not be here to witness its success." - 1994

HERE ARE MY WORDS OF WISDOM:

TAKE CARE OF THE ELDERLY AS WELL AS OUR BABIES!