Alvin Weinberg considerations on nuclear energy and the reactor MARS

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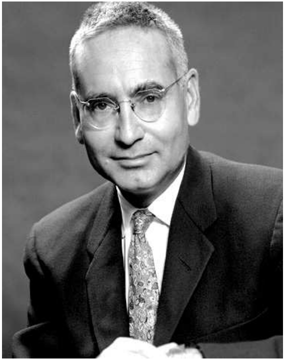
Summary of the presentation

- A. Weinberg (1997): the First Nuclear Era has ended, a Second Nuclear Era will have to deal with the public's fear of radioactivity from nuclear reactors and its fear of hydrogen bombs
- key point: publicly acceptable reactors must have features that, in the public's mind, represent a transparent, easily understood improvement over existing reactors
- idea of "super-safe" reactors, centered on the notion of inherent safety: safety depends upon passive systems which operate according to laws of nature
- the SMR reactor MARS proposed by Sapienza University of Rome is a cheap, simple, extremely safe PWR plant incorporating all main well-proven features of a "traditional" PWR plant [1]
- MARS constitutes a revolutionary change in the nuclear industry that can accomplish the objectives of the Second Nuclear Era

[1] "600 MWth MARS Nuclear Power Plant", Vv.Aa., Department of Nuclear Energy and Energy Conversion, Sapienza University of Rome (1997)

Alvin M. Weinberg

Alvin Martin Weinberg (April 20, 1915 - October 18, 2006) was an American pioneer of nuclear energy who was the Director of Research at Oak Ridge National Laboratory during and after the Manhattan Project



- Under his direction the Laboratory worked on the Aircraft Nuclear Propulsion program, and pioneered many innovative reactor designs, including the pressurized water reactors and boiling water reactors, which have since become the dominant reactor types in commercial nuclear power plants
- In 1960, Weinberg was appointed to the President's Science Advisory Committee in the Eisenhower administration and later served on it in the Kennedy administration.

Weinberg's considerations on Nuclear Energy, April 1997

Weinberg's foreword to the book: "600 MWth MARS Nuclear Power Plant", Vv.Aa., Department of Nuclear Energy and Energy Conversion, Sapienza University of Rome (1997)

*That the **First Nuclear Era** has ended in much of Europe and America is no longer arguable. In Italy, for example, all operating reactors have been shut down (but Italy imports substantial amounts of nuclear generated electricity from France). In America, no civilian plant has been ordered for twenty years, and development of the fast breeder, which many saw as a key to the long-term future of nuclear fission, has been stopped. This tragic state of affairs was anticipated by Enrico Fermi in 1944. Speaking extemporaneously at a meeting of the "New Piles Committee" at the University of Chicago's "Metallurgical Laboratory" (code name for the wartime plutonium project), Fermi pointed out "The public may not accept an energy source that is encumbered by vast amounts of radioactivity, and that produces a nuclear explosive, which might fall into hostile hands".*

Weinberg's considerations on Nuclear Energy, April 1997

Yet the case for continuing, even expanding nuclear energy remains strong. The world's almost 6×10^9 *people now use 13 Terawatts-year of energy each year. Of this 76% comes from fossil fuel, 18% from renewable resources and 6% from 433 nuclear reactors. By the year 2100, the world's population may double - where will humankind get the energy needed to support, say, 11 billion people? Most experts regard renewables as unable to met the need by themselves though all agree that research on renewables and conservation ought to continue. As for fossil fuels, these will eventually run out; moreover, the observed increase in CO2 from 285 parts per million (ppm) to about 370 ppm - cannot be regarded with equanimity - even if CO2 is not as strongly implicated in global warming as current global circulation models predict. As Roger Revelle once pointed out, the doubling of CO2 in the atmosphere constitutes a geo-physical experiment on a massive scale, and the consequences, both direct (on the biota) and indirect (on the climate) are poorly understood.*

Weinberg's considerations on Nuclear Energy, April 1997

This humankind must preserve the nuclear option. It must create a **Second Nuclear Era***, an era in which the public's confidence in nuclear energy has been restored. If Fermi's skepticism is correct, and I believe he was right, than a Second Nuclear Era will have to allay the public's fear of radioactivity from nuclear reactors, and its fear of hydrogen bombs. Of these twin fears, I judge the latter, requiring changes in the very structure of international relations to be the more difficult. On the other hand, the fear of radioactivity does admit technical fixes, quite independent of institutional changes. Of the two aspects of possible radioactive pollution caused by reactors - waste disposal and reactor accident, I regard the latter as the more central, even though squabbles over radioactive wastes appear daily in the press.*

Weinberg's considerations on Nuclear Energy, April 1997

If the criteria for secure disposal of radioactivity is that no member of the public is likely to receive a yearly dose greater than 30 mrem (the standard deviation of the natural background in Italy), then the criteria has already been exceeded by all of the proposed methods of disposing of radioactive wastes. In other words, despite the fear engendered by the words "radioactive wastes", I do not believe this fear is rational. Properly sequestered radioactive wastes pose no hazard to the general public.

Weinberg's considerations on Nuclear Energy, April 1997

I cannot say the same for reactors. As the two reactor accident, Three Mile Island (TMI) and Chernobyl demonstrate, a malfunctioning reactor can pose serious threat - even though TMI caused no discernible biological harm. The public's reaction to TMI and Chernobyl was immediate and drastic. This reaction led designers to ask "Can reactors be designed for which the probability of melt-down is zero?" And if such reactors were the technical basis for a Second Nuclear Era, would this not eliminate one of the public's concerns about reactors? When these ideas where first discussed by David Lilienthal in 1980, the reactor community could not answer this question. But once the question was raised, ideas for "super-safe" reactors emerged. Central to the discussion was the notion of inherent safety - i.e., a reactor whose safety was ensured not by engineered, active systems, but by inherent passive systems that depend on well-recognized natural laws.

Weinberg's considerations on the reactor MARS, April 1997

One result of these preliminary investigations was to sharpen the definition of "zero" probability. Ordinary pre-TMI Light Water Reactors had core-melt probabilities, as determined by Probabilistic Safety Analysis, of $10^{-4}/RY$. In Sizewell-B, A PWR built in England, the core-melt probability was reduced to $\sim 10^{-6}/RY$. Yet the issue cannot be decided by PSA - the public does not distinguish between a core-melt every 10,000 years/reactor, and one ten times less frequent. It has seemed to me that publicly acceptable reactors must have features that, in the public's mind, represent a transparent, easily understood improvement over existing reactors. Several reactors that embody inherently safe features have been proposed. These include the Westinghouse APWR, and the General Electric ABWR - these are in the class of incrementally improved LWR's. In the case of inherently safe reactors there is the small gas-cooled HTGR of General Atomic and the PIUS reactor of ABB. Of these I would consider only PIUS to be truly inherently safe.

Weinberg's considerations on the reactor MARS, April 1997

Prof. Maurizio Cumo and his colleagues have proposed another approach to inherent safety in the MARS (Multipurpose Advanced "inherently" Safe Reactor). The distinguishing feature of MARS is its pressurized envelope, containing water at low enthalpy but high pressure. This ingenious feature makes MARS invulnerable to pipe rupture and other Loss of Coolant Accidents - but more important, it makes such accidents "impossible" by a device that is transparent. To take care of other accidents, Prof. Cumo and his colleagues have resorted to engineered active features - such as an automatic secondary safety system, and a valve operated residual heat removal system. The calculated probability of core-melt in MARS is $10^{-7}/RY$ *- three orders of magnitude lower than the* $10^{-4}/RY$ *characteristic of most of the world's light water reactors. But more than this, the core melt scenario does not lead to breach of containment, and therefore MARS can be located in populated areas.*

Weinberg's considerations on the reactor MARS, April 1997

A probability of $10^{-7}/RY$ is the same as the probability that a city-destroying bolide will strike New York City. In effect, "zero probability" is being defined as equal to the probability of a natural occurring mega-disaster. This definition of zero is in a sense consistent with Prof. Cumo's suggestion to define "zero exposure" in terms of the standard deviation of the natural background. MARS is an original idea that deserves full investigation. I hope that, in publishing their ideas, Prof. Cumo and his colleagues will generate the support that obviously will be needed to bring MARS into being. Future generations, dependent as they will be on nuclear energy, will be grateful to the inventors of MARS for offering this original approach to inherently safe reactors.

MARS (Multipurpose Advanced Reactor, inherently Safe), developed at Sapienza Dept. of Energy Engineering, is a cheap, simple, extremely safe, single loop PWR plant incorporating all main well-proven features of a “traditional” PWR plant

Reactor type	PWR
Nominal power	600 MWth
Coolant core inlet temperature	214°
Coolant core outlet temperature	254°
Nominal pressure	75 bar
Fuel elements number	89
Fuel element grid	17 x 17
Fuel rods per fuel element	264
Fuel rod external diameter	0.95 cm
Fuel rod active length	260 cm
Fuel rod cladding thickness	0.63 mm
Fuel rod pitch	1.26 cm
Control rod guide tube	1.224 cm
Control rod diameter	0.978 cm

MARS: basic policy

Basic policy adopted in the reactor design of MARS

As suggested by Alvin Weinberg: any new technology in the energy sector, to be accepted and widely used, should respect nature and its balance ⇒ the radiological impact on the surrounding population of a nuclear plant during its production life should be "at most" comparable to the one corresponding to the standard deviation of the natural radioactive background, and the worst conceivable accident has a chance no greater than that of being hit by a meteorite that falls on Earth.

MARS: safety characteristics

MARS focuses on intrinsic safety or totally passive requirements, meant as security based on unavoidable laws of nature and not on security systems which, to intervene, need sensors and motors powered by electricity (i.e. active systems) and/or intervention of careful operators

The calculated probability of core-melt is MARS is $10^{-7}/RY$ *- three orders of magnitude lower than the* $10^{-4}/RY$ *characteristic of most of the world's light water reactors*

MARS: factory construction

A major characteristic of a SMR like MARS is that allows for a transition from long and complex buildings on the site to factory construction, with assembly and controls of movable parts of plant in equipped environments and in a short time

This transition could represent a revolutionary change in the nuclear industry

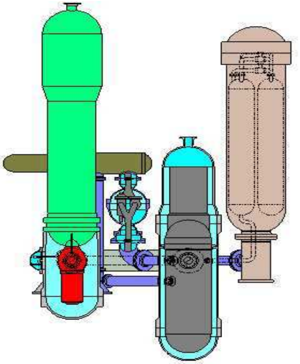
MARS: other advantageous characteristics

- methods and manufacturing technologies are well-known and well tested $\Rightarrow$ no risk of failures and economic uncertainties about its implementation
- removal and replacement of all components of the reactor is foreseen $\Rightarrow$ reactor is constructible in workshops, quickly and with low costs, and its life is extending as pleased with the simple substitution of pieces that have completed their technical life
- decomposability into pieces of flanged and bolted metal permits a quick and total final dismantling $\Rightarrow$ at end-of-life on the site remains just the concrete containment building, non-radioactive
- decommissioning costs would be very low, by repeating the same operations in reverse order of assembly
- aggregating more small power modules overtime, with limited costs, allows a gradual increase of power of electric stations
- possibility of cogeneration of electricity and heat (for example, to desalinate sea water)

MARS: economics

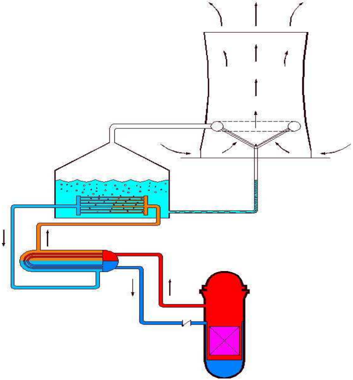
- reduced costs achieved through a great simplicity of the design, with elimination of redundant "active" safety systems
- reduced costs stemming from extension of useful life of the system, guaranteed by easy replacement of worn or obsolete components
  - extension of life is an essential device for nuclear installations which have, in the cost of electricity, a predominant component of system cost compared to the cost of the fuel

MARS: primary loop scheme



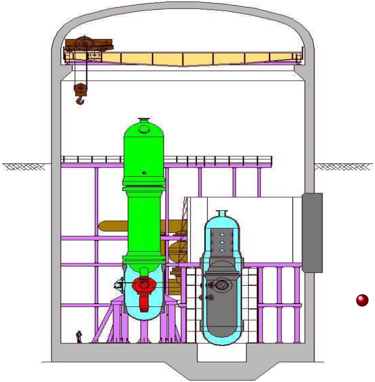
- The primary loop consists of a single vertical steam generator with U-tubes, and canned rotor pump directly attached to the generator output nozzle
- A steam bubble pressurizer controls the primary loop pressure
- On/off valves are installed on the primary loop to isolate the steam generator and the primary pump in the event of an accident of generator tube rupture

MARS: Safety Core Cooling System



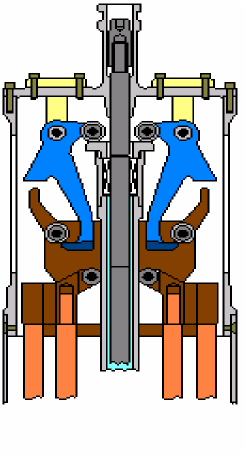
- Connected to the reactor vessel there is a Safety Core Cooling System (SCCS)
- The SCCS system is designed to transfer the residual heat from radioactive decay, after the reactor scram, to air outside, without intervention of any "active" (powered) system, but for simple natural convection in columns, initiated by different water temperatures, and related densities

MARS: pressurized containment



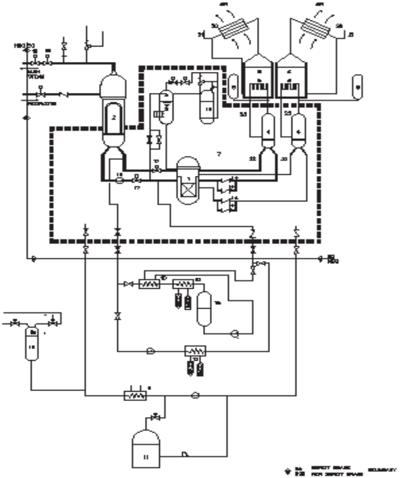
- The entire primary loop and the SCCS system are placed inside a pressurized containment at the same primary loop pressure, with water at 70° C
  - elimination of the primary stress on the walls of the primary loop, with an intrinsic defense against the Loss Of Coolant Accident (LOCA) and withdrawing of the most effective control rod
- The SCCS system had two sets of components, each one able to remove 100% of the residual radioactive decay heat
- The activation of the SCCS is automatic, without need of operators intervention or of control and safety systems

MARS: Emergency control rods



- To implement the reactor scram, in addition to the traditional system of control rods, there is an original system, passive type, which is triggered when the primary coolant temperature reaches a set value
  - two concentric tubes of different coefficient of thermal expansion, fixed to a unique basis, which as a result of differential expansion causes the drop by gravity of a second group of control rods

MARS: overall reactor scheme



Legend

1. reactor
2. steam generator
3. pressurizer
4. heat-exchanger (reactor coolant/ intermediate coolant)
5. heat-exchanger (intermediate coolant/ final heat sink coolant)
6. water reservoir
7. pressurized containment for primary loop protection (CPP)
8. intermediate loop pressurizer
9. heat-exchanger (primary containment water cooling system)
10. chemical and volumetric control system heat-exchangers
11. water storage tank
12. residual heat removal system heat-exchanger
13. pressurizer relief tank
14. safety core cooling system check valve
15. primary containment pressure control system pressurizer
16. main coolant pump
17. primary loop on/off valve
18. VCS tank
19. steam line on/off valve
20. ultimate heat sink condenser
21. communication path with the atmosphere
22. safety core cooling system primary loop
23. safety core cooling system intermediate loop