MARCHETTI-3

Energy Islands in the Final Configuration of the H_2 Economy

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The technique to analyze the structure of energy markets I inaugurated in 1974 showed an unsuspected stability in its long-term evolution and consequently permitted to forecast configurations far ahead in time.

The classical experiment to forecast "only" 50 years ahead, even with wars and depressions incorporated, is shown in Figure 1. The market shares of oil and coal predicted with the data available in 1920 were only a few percent off mark in 1970.

The 1974 type of analysis does not give the possibility to forecast when a new primary energy is going to be introduced. Consequently, the forecasts work only inside the time constants of the substitutions, about 100 years, or 50 to be prudent.

However, in 1980, in a study of innovation, I found that a new primary energy source is introduced, about every 55 years, at the beginning of an innovation wave (Figure 2). These waves can be forecast through their internal regularities.

Actually the present wave of innovations is still going on an we can assess its complete structure only after its end (some visible innovations may bankrupt and not enter the final count).

So up to now the curve reported is still a forecast. But nuclear energy start in the 1970s sits precisely on its tail as it should.

Using the sequence of new primary energies as predicted through the innovation frame, we can then prolong the primary energy plot by a couple of hundred years (Figure 3).

Candidates for the following starts are not lacking. We have fusion slowly poking ahead for 2025. And some subtle manipulation of the core of "elementary" particles may produce more. Solar I keep in the waiting list. It is too diluted to fit the historical evolution of constraints.

One thing is clear, however, natural gas will be the last of the fossil fuels.

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And substitution with nuclear stuff (or solar) must be complete because the increase in total energy consumption would vanify in due time any partial substitution.

We can then split world energy history in three segments: renewable (wood and hay), fossil (coal, oil, and gas) and nuclear (of various denominations). Their substitution is reported in Figure 4.

Nuclear machines are not much for the moment, and extraordinarily expensive for small applications (like plutonium electric generators). Consequently an energy carrier, like electricity, is inevitable and actual. the strongest second candidate energy vector is hydrogen.

Once we decide on hydrogen, the structure of the network is basically defined by hydrogen transportability and the spatial density of consumption.

Today an electrical power station can "see" about 100 km around (the mean distance of electricity transport) with the density of consumption of industrialized countries.

Because of superior transportability, a gas system with pipelines can see 1,000 km around or a territory 100 times larger. This means generating units 100 times more powerful, for similar spatial density of consumption.

This is an important edge for hydrogen. Small can be beautiful, but big is cheap after the technology has had time to settle. When nuclear plants were designed in relative freedom, the scale factor of cost was about $\sqrt{V}$.

This means that the *specific cost* of a nuclear reactor 100 times larger is about ten time smaller. A big bonus in a nuclear system where most costs are capital costs. This is only a potential to be developed in time, obviously not a prototype cost, but it may produce a continuous edge for H_2 versus electricity when the alternative is possible. H_2 may finally be 10 times cheaper at consumer level than electricity.

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The territory seen by an oil source is the world, due to the very high transportability provided by oil tankers. But H_2 can be liquefied and may enjoy a similar situation also if with the added cost of liquefaction.

These considerations led me in 1970 to conceive displacing the H_2 generating capacity into far away islands with very large reactors, grouping them for logistic purposes.

Displace production has many extra costs, like hydrogen liquefaction or providing extremely sophisticated crews in solitary places, but the subjacent idea is that *economy of scale can finally overpay* for all the diseconomies.

The ideas were mature and selfconsistant in 1972 when I wrote a long paper for Chemical Economy and Energy Review (CEER) that published it in 1973. the paper was on the potentials and the technique of a Hydrogen Economy, and the Energy Island was incorporated if only as a table (Figure 5).

One may giggle at the magic date of 1991. But people shrug targets too far apart in time. To stay in the magic 2002 is a good date for a demonstration plant.

The Japanese to whom I presented the H_2 economy concept in 1973 were flabbergasted by the Energy Island. They called it Coral Island project. They perceived a complete energetic independence for their country then whipped by the so-called oil crisis.

Their interest has been crucial *as they kept working since then, basically solving the three fundamental problems of the concept*: thermo-chemical water splitting, VHT reactors and uranium extraction from sea water.

Final disposal was not provided in the original concept although I had sunk already perhaps 5 M$ in developing the "hot mole" I will describe later.

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To have a reference place with geographical and geological connotates, I took a well-known if now almost uninhabited atoll, Canton Island. It has an airport that was used as a stepping stone when airplanes had lesser range, and the peculiar property of belonging to US and UK.

The atoll is depicted in Figure 6. The lagoon is fairly large and sufficiently deep for our reactor barges and H_2 tankers, obviously it can be excavated here and there. As common for atolls, the sea sinks rapidly all around, which will be very useful to fish for cold cooling water.

The reactors are HTR with gas-graphite balls. To have the very large powers I was expecting I thought of a *thorus reactor*, where one can have large volume with a given maximum size for the pressure vessel, as the current technology suggests.

My friends in Jülich consoled me as they had studied this configuration for other reasons. Helium HTR lend themselves to large sizes with moderate control as they have a large negative thermal coefficient and much reserve in the thermal resistance of their balls.

My idea was to have 200–300 GWT per reactor and to use the same procedures to make coated particles for fuel and for fission products, all with automatic processes. Coated particles and graphite ball seem to adapt well to automation and they do not have very stringent tolerances.

Fuel fabrication and reprocessing plus the water splitting plant had to be on the same barge for logistic reasons, bringing its weight to 5–10 MT or so (Figure 6).

I hear of a project of building a palace-ship for tax refugees (like the first emigrants to America) right in this ball park. Like oil platforms.

Incidentally at the time I reviewed all plant on barge projects, including a whole refinery and went to see the inventors of the floating city in Hawaii where I found much encouragement. With the latest developments in oil

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platforms I think all the necessary technology to build such behomoths is now in place.

Platform, reactor, and barge should be constructed in a wharf and towed into place, avoiding the technological solitude of far away sites. Also ground maintenance could be planned bringing the platform back and forth.

I piped hydrogen away to a somehow remote liquefying-storing-loading station where the tankers would land, charging LH_2 and possibly LO_x (Figure 7).

I also made some sketches for transporting H_2 part liquid part gas by huge dirigibles, oblivious of the Hindenburg story. It could work, but I did never spread the results. Sometimes I am careful not to overshock.

With all things in place Canton Island looks as in Figure 7. Pumps for cooling water are also included. As water comes from the deep, say 500 m, it is pretty cold, say 5°C.

For a good measure I operated the pumps using an OTEC process, so that they keep going even if all the system breaks down. This could be an astute measure in case of radioactive spillover as with reactors stopped the cool water sinks again bringing radioactivity into safe depths.

One of the characteristics that made the eyes of the Japanese gleam, is that the system can be self-sufficient in terms of uranium. Actually the oceans contain about $5\ 10^9$ tons of uranium in solution, if at the miserable concentration of 4.5 ppb.

However, if one looks at the flow of cooling water the reactors will require, he will be pleasantly surprised in finding that the flux of uranium carried by this water is an order of magnitude larger than that fissioned in the reactors.

MITI and the University of Tokyo and JAERI started working on this extraction (by absorption) in 1974 and kept going. They now have some

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processes based on mineral absorption, or on organic fibers that basically solve the problem. Cost is high, perhaps an order of magnitude more than uranium from the mines, but for breeders or quasibreeders this is immaterial.

The process brings a flavor of eternity in a society worrying for near next. The Pacific vertical circulation raises the waters by about one meter per year. Assuming 4,000 meters of mean depth, a practically unlimited amount of uranium fuel will be available for the next 4,000 years.

With all that uranium burned and reprocessed there will be a lot of fuel for Greenpeace to ram the atoll. But I reserved a little surprise for them.

When NASA put some electric generators on their satellites based on Pu or other dirty radioactive materials, they studied what happens if a misfiring brings them to earth.

The capsules containing the R-material certainly could take the impact, but what about the heat generated by the radioactive decay?

Computer modeling showed that the earth is a good insulator. So there is a good chance that the capsules will start melting the ground and, being denser, to sink down.

In fact, the computer models show that if you have fission products of sufficient concentration and capsule size, the capsule keeps sinking. E.g., with feasible conditions, down to 20 to 30 km.

It happened to me (and to SE Logan in US) that the process could provide a neat way to dispose high activity fission products in a very soft way and in an unretrievable configuration. It is a pity that the perseverant Japanese did not search into this line.

Actually in my Ispra Lab (Euratom) I could sink a few M$ to check the equations by sinking electrically heated capsules in rock and salt masses. They work. I still improved the scheme by sending down showers of balls,

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along a shaft filled with molten (or meltable) salt, down to a melting pot where they can collectively start the long journey into the rock.

This mixes the original idea of a large capsule, difficult to engineer, with the fact that the reactor processing and reprocessing easily produces balls.

Equipped with this facility Canton Island would appear as sketched in Figure 9, with all apparatus in place, sink holes included. Every megareactor has its own reprocessing facility and its own sink hole. To stop a recurrent critic, it must be clear that to start a volcano we would be short by perhaps ten orders of magnitude.

The process to split water assumed in the figure is one of Ispra's thermochemical cycles. The candidate No. 1 the UT-3 in development in the University of Tokyo (Figure 8).

The thermodynamic efficiencies of these processes were evaluated in 1970 to be in the 50% region. This means a considerable heat discharge at the site.

Just to cheat Greenpeace I proposed to pump cold water from the depths, at$\pm$5°C and release it at 20$\div$25° which is the temperature of surface waters at the Canton site. So no thermal plume would appear.

Concerning efficiency, however, chemical processes tend to become more efficient in time thanks to continuous refinements. The evolution of efficiency for nitrogen fixation, a large-scale chemical process is reported in Figure 11.

If we go to general considerations, however, efficiency does not play a key role even psychologically. Uranium is unlimited. The cost of hydrogen will be essentially defined by capital costs. Generation will be automatic with crews of engineers just for maintenance and repairs.

My original plan for these islands was to have about 10 of them to provide all the energy necessary for the world. The number 10 comes from

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an optimization of reserve, as in the case of electrical units (but LH_2 can be stored).

At present this would bring the scale of an island to about 1 TW output, more or less the equivalent of the whole Middle East.

Because this requires a lot of tankers shuffling I also did some reflections on tankers which, carrying a fluid about 10 times lighter than water, tend to travel upside down (Figure 12).

Inevitably many will ask about the political and strategic problems linked to the operation of such islands.

I tried to answer that in my dinner speech at the First Hydrogen Conference in Miami, "From the Primeval Soup to World Government".

As the title says, the speed of transportation and the unification of the energy system will lead to a global political system. Inevitably. In only 100 years.

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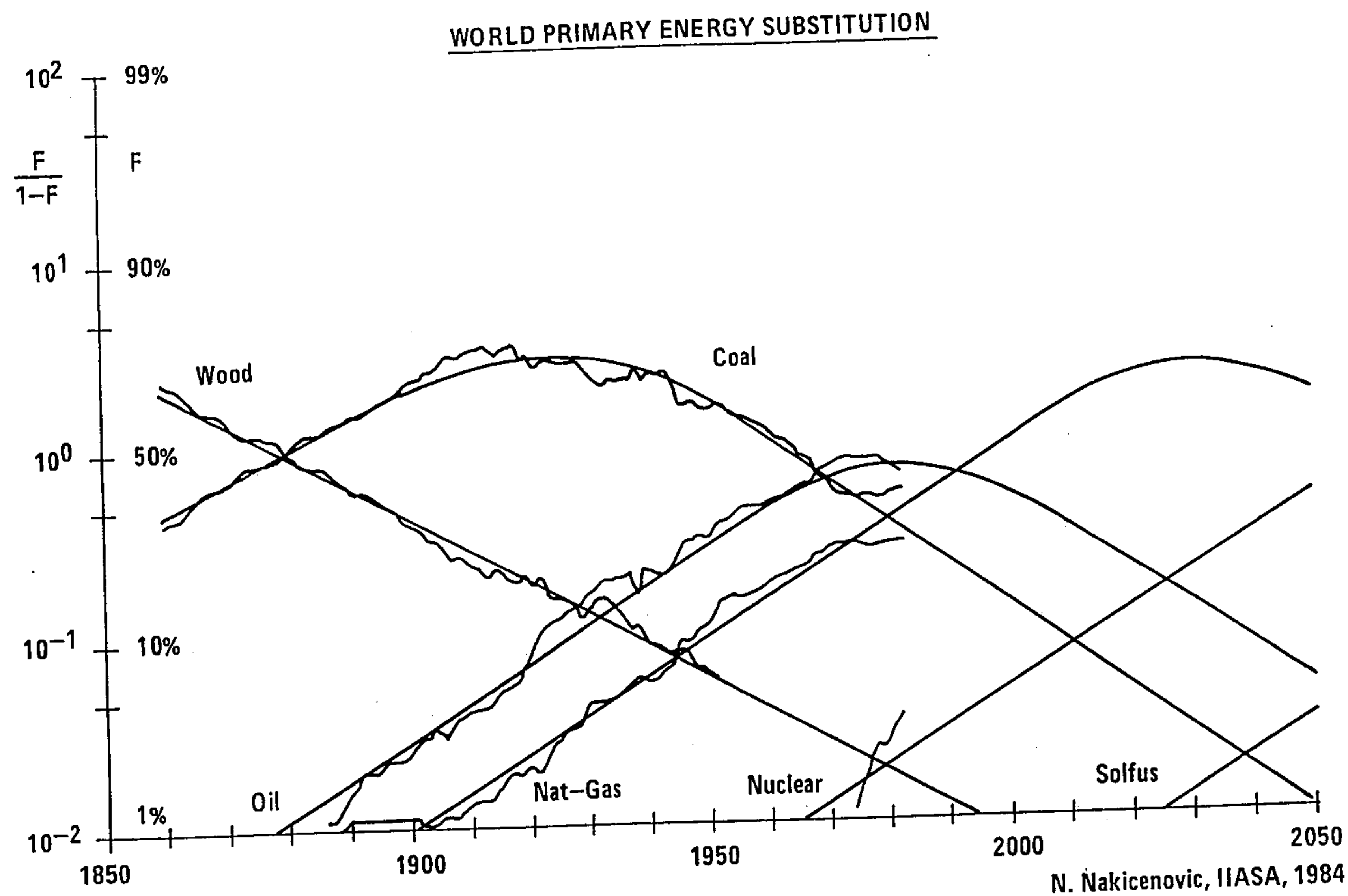

Figure 1.

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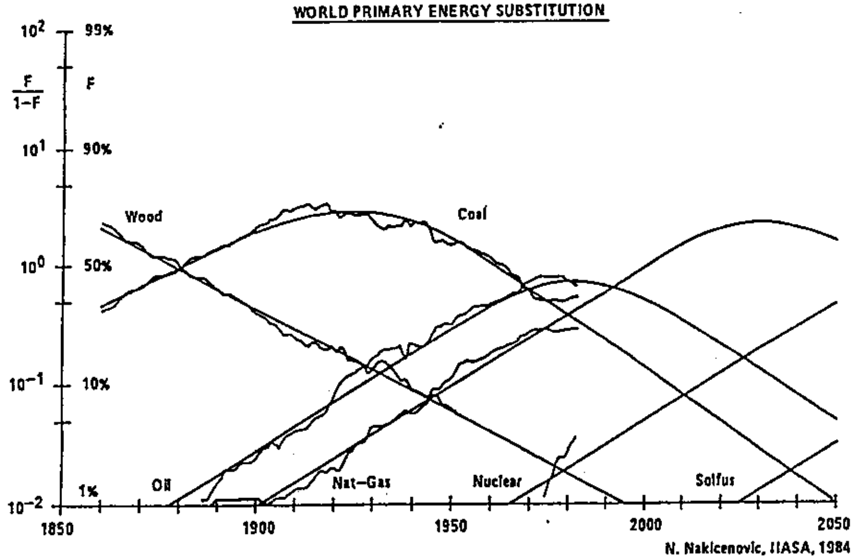
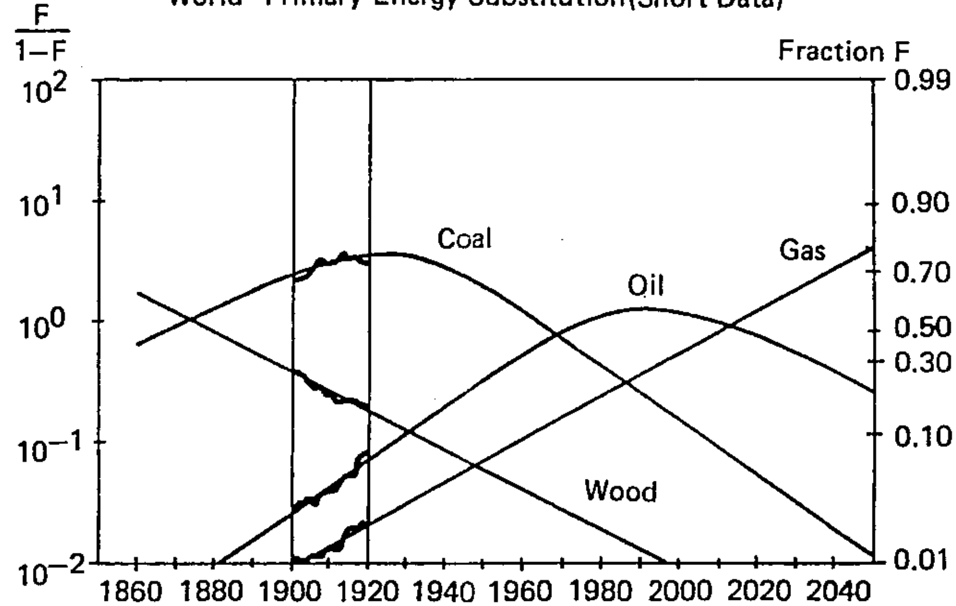
WORLD PRIMARY ENERGY SUBSTITUTION



World–Primary Energy Substitution (Short Data)



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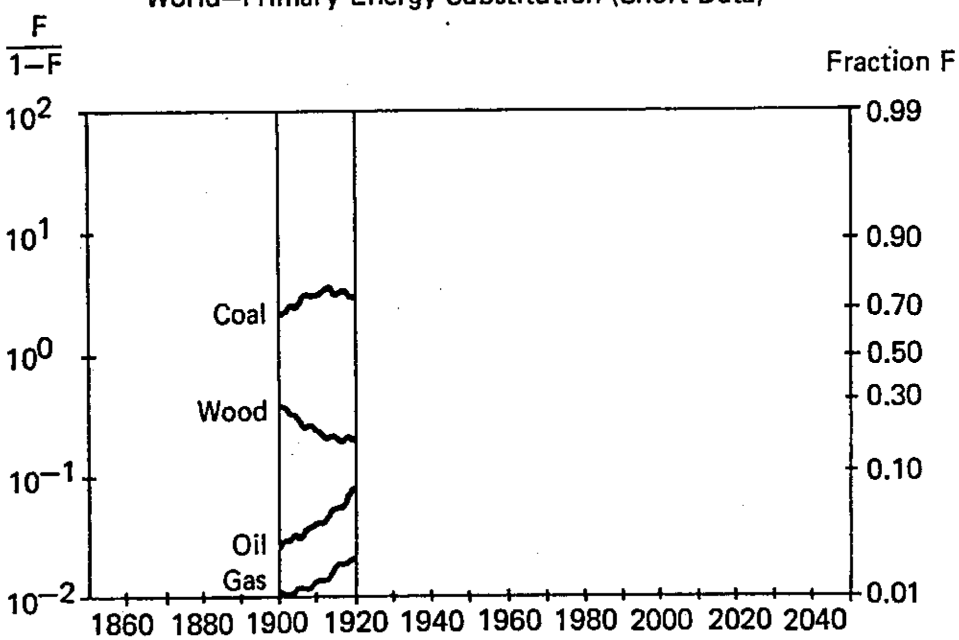

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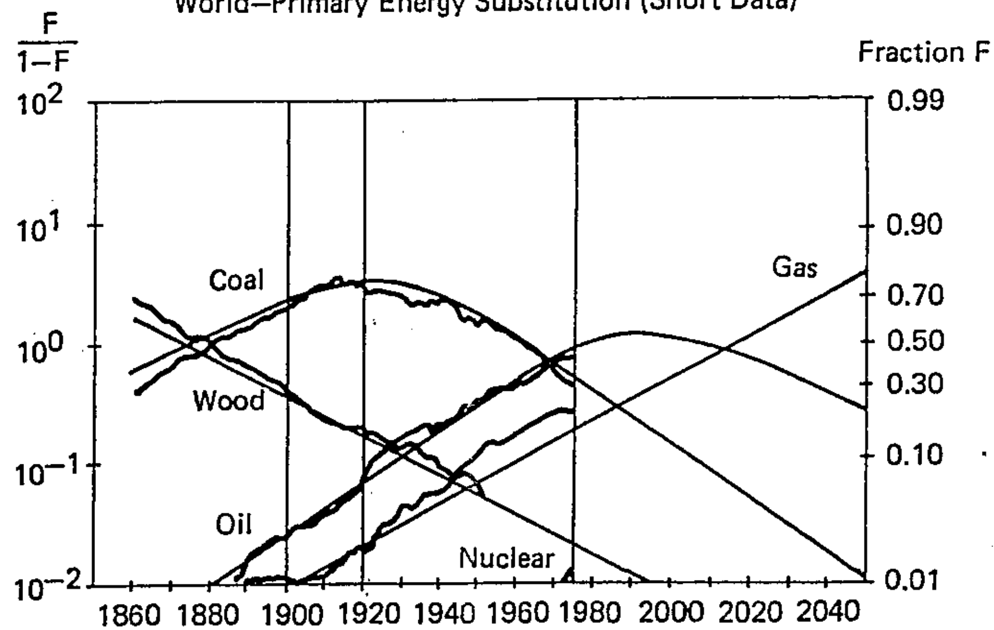

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INNOVATION WAVES AND THE START OF NEW ENERGY SOURCES

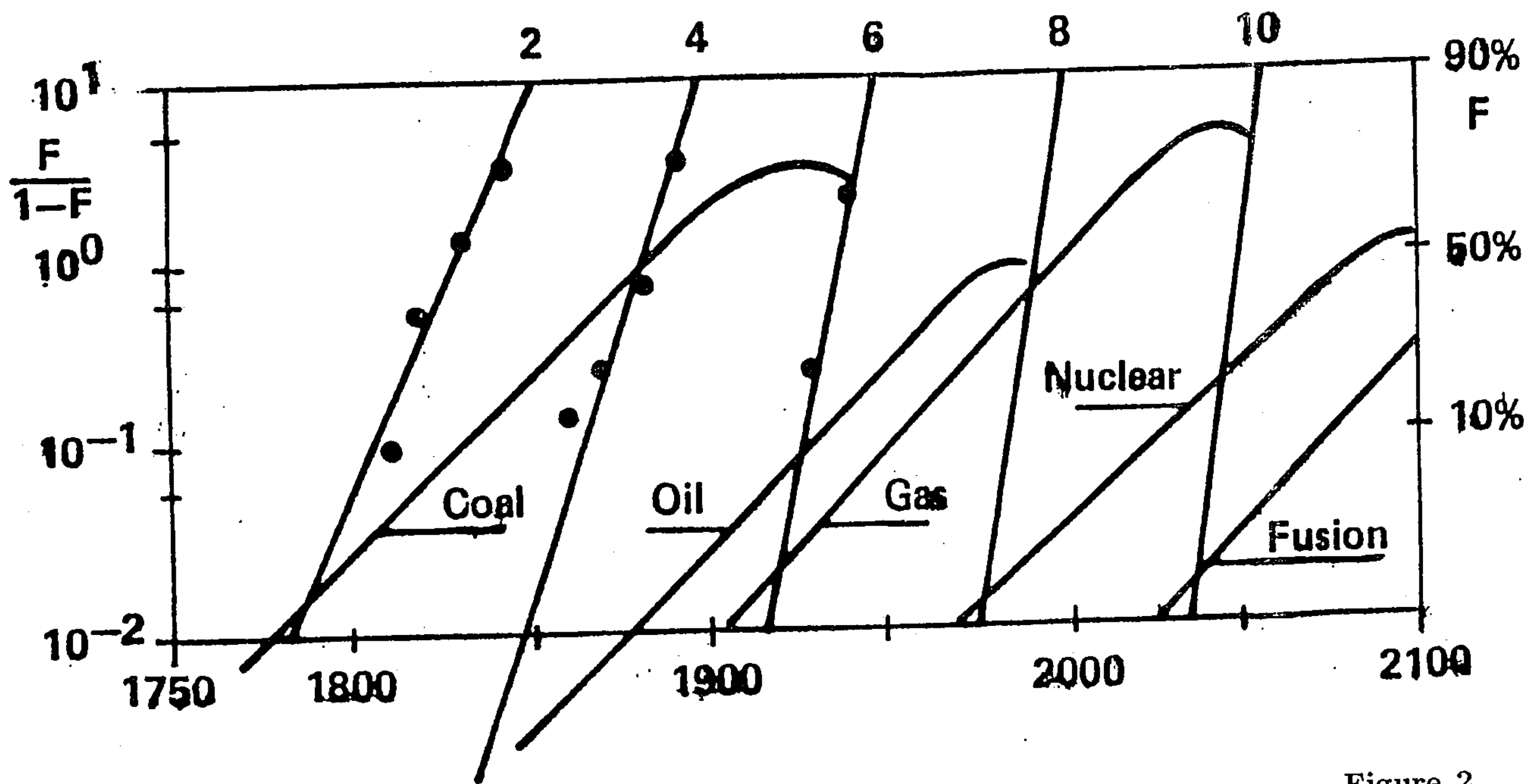

Figure 2.

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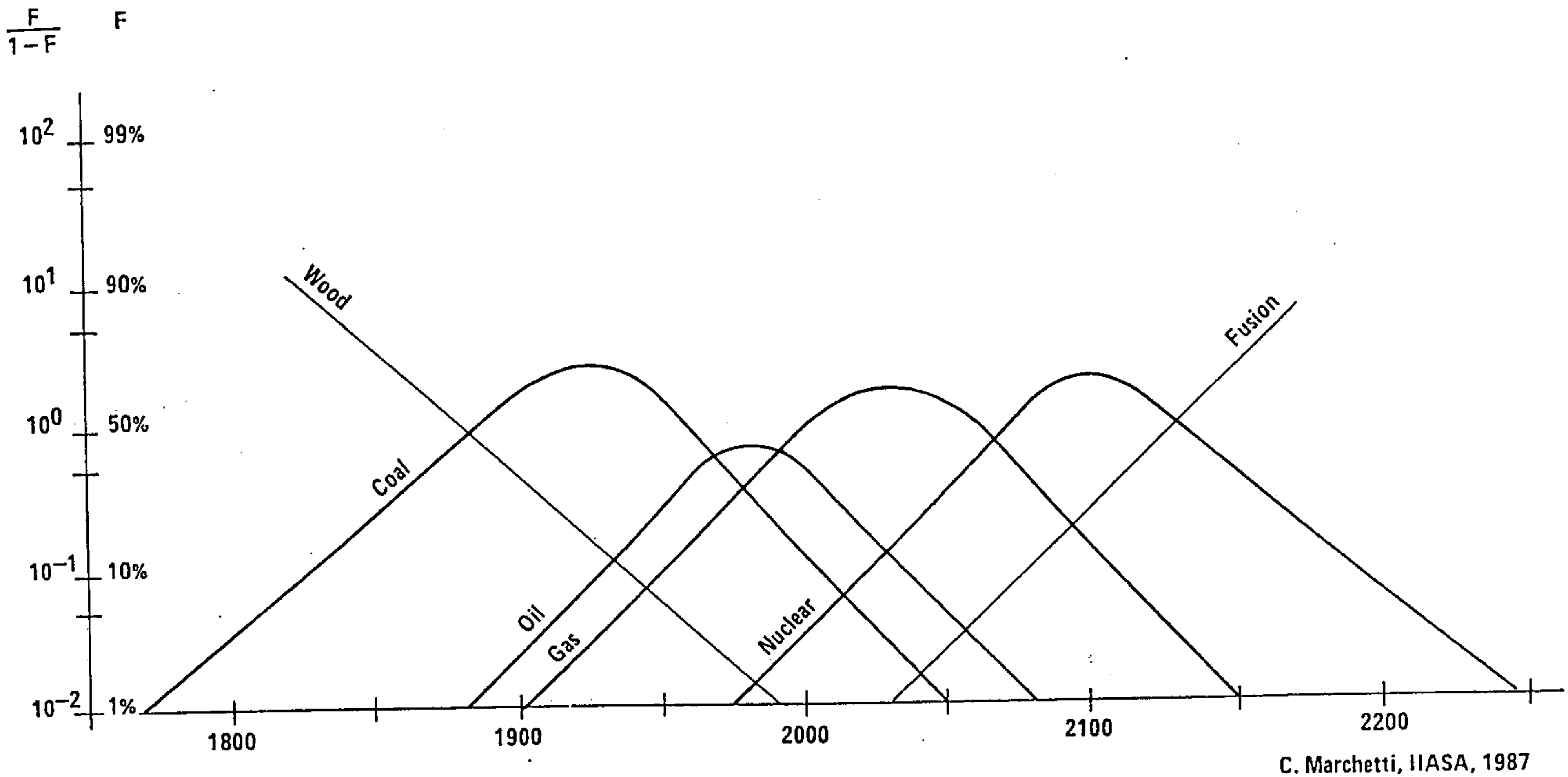

Figure 3.

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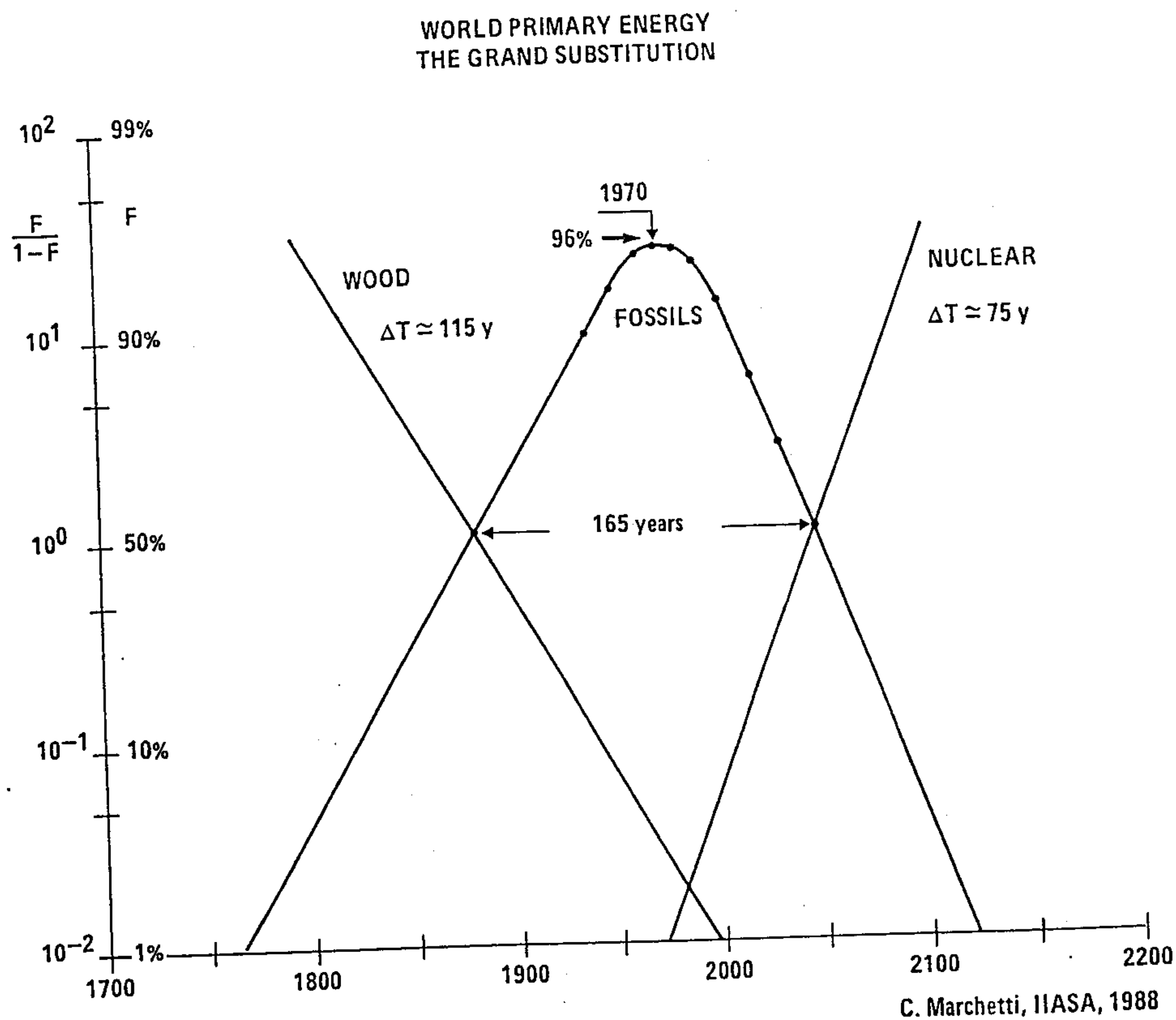

Figure 4.

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Target energy island

Year	$\boxed{1991}$
Site	Atoll in the Pacific
Reactors	5–10 HTGR + Breeders or HTG Breeders
Nuclear power	1 TWth (10^9kWth)
Efficiency	60% (lower heating value H_2 produced/heat consumed)
Hydrogen produced	500 million tons oil-equivalent/year
Lagoon size	$2,000 \times 2,000 \times 20$ meters
Cooling water	500 billion tons/year (500km^3) pumped from the deep and warmed up to surface water temperature
Uranium recovered	From sea water (50% effic.) 600 tons/year (dbsorption on Titanium dioxide)
Uranium consumed	In the plant (80% fissioned) 500 tons/year (nongrowing crossbreeding reactor system)
Transportation	Liquid hydrogen in tankers
Investement	10^9 kWth $\times$ 50\$/kWth = 50 billion \$. Includes: on site Uranium extraction, Fuel cycle, Liquefying plant.

From: C. Marchetti, CEER $\boxed{1973}$

Figure 5.

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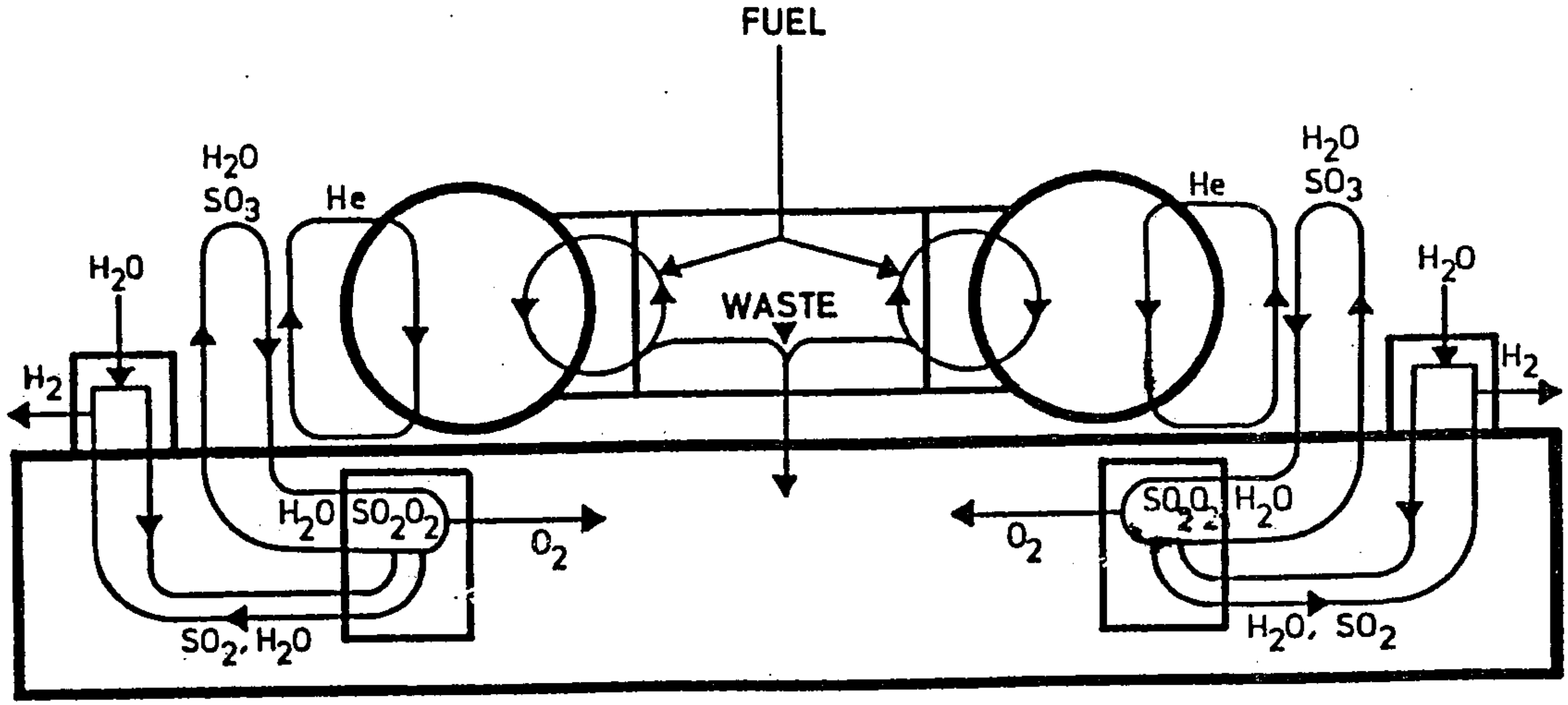

Figure 6.

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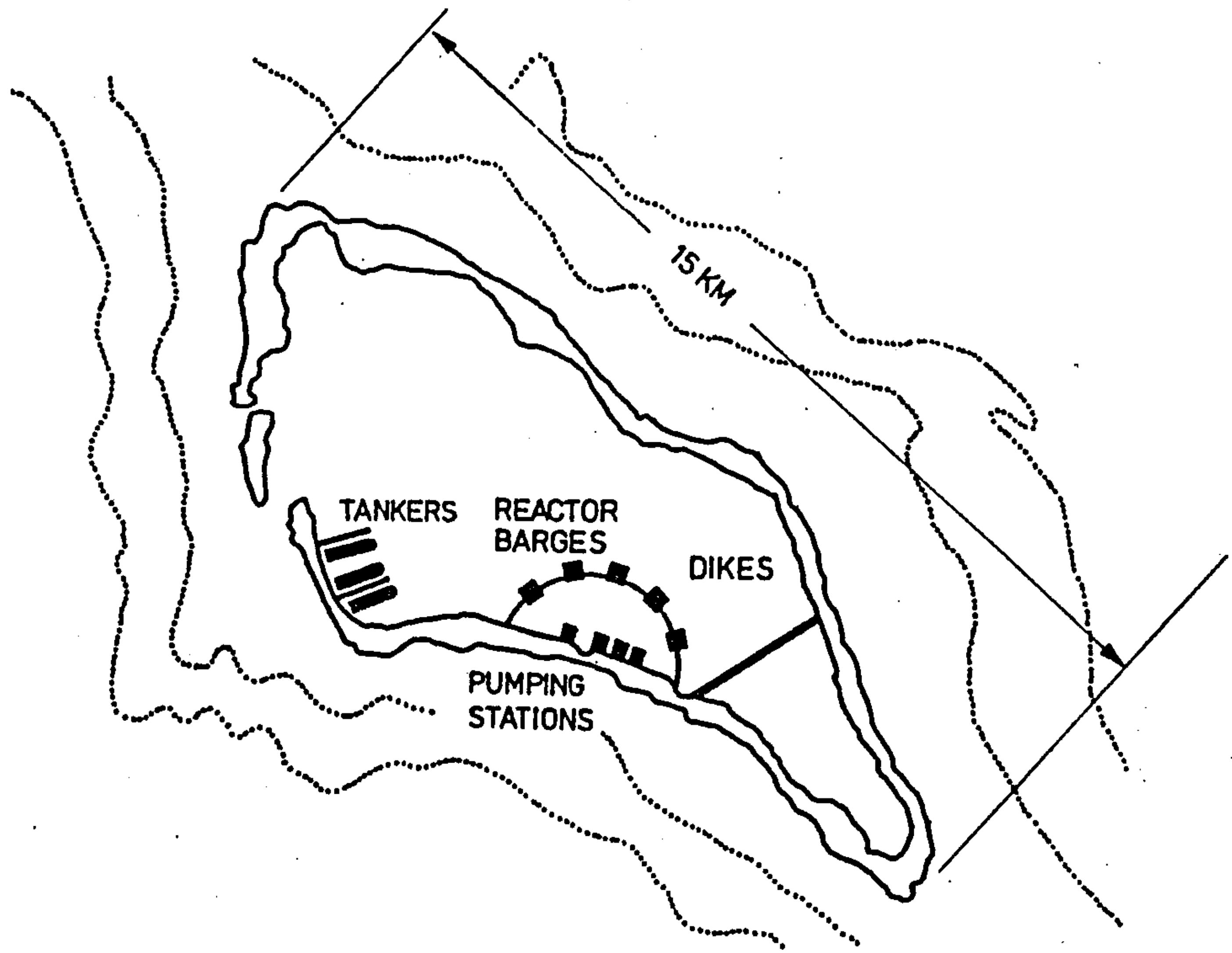

Figure 7.

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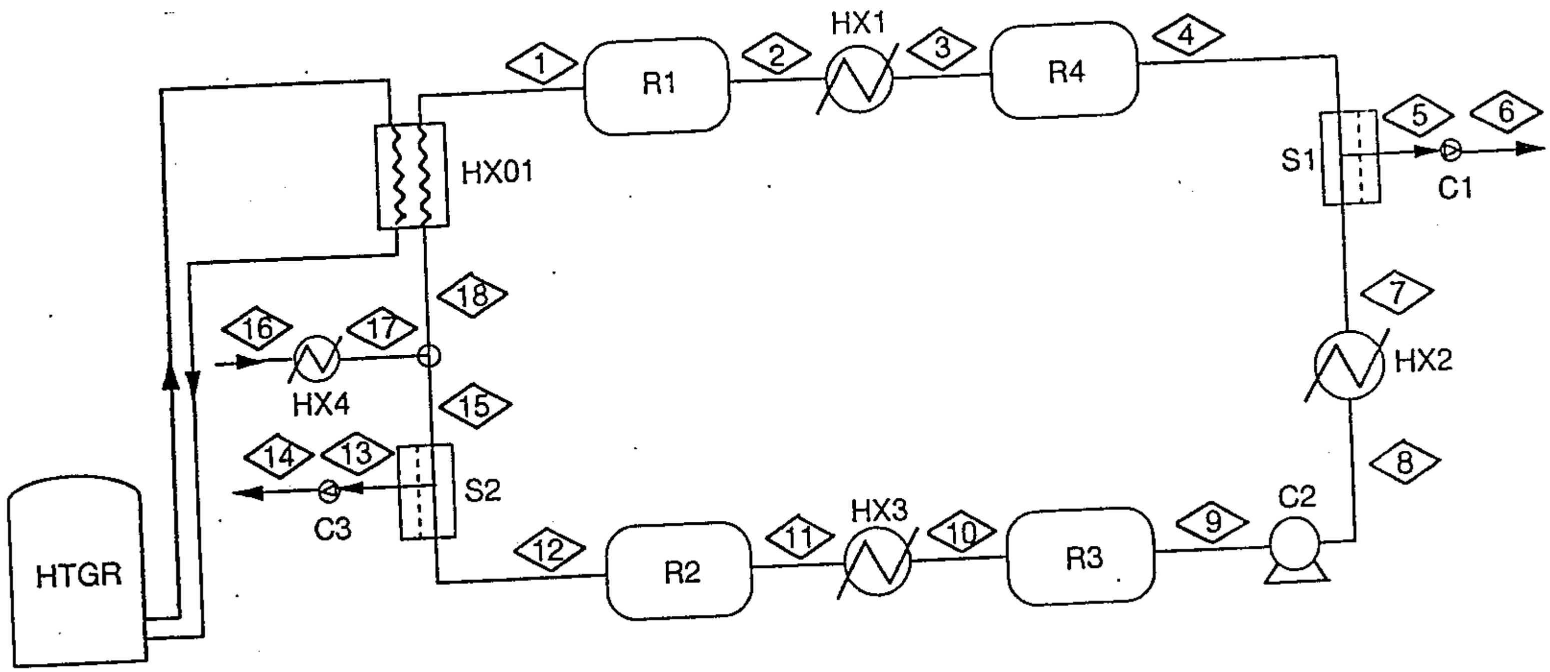
$$CaBr_2(s) + H_2O \xrightarrow{973-1033K} CaO(s) + 2HBr(g)$$

$$CaO(s) + Br_2(g) \xrightarrow{773-873K} CaBr_2(s) + \tfrac{1}{2}O_2(g)$$

$$Fe_3O_4(s) + 8HBr(g) \xrightarrow{473-573K} 3FeBr_2(s) + 4H_2O(g) + Br_2(g)$$

$$3FeBr_2(s) + 4H_2O(g) \xrightarrow{823-873K} Fe_3O_4(s) + 6HBr(g) + H_2(g)$$



adiabatic UT-3 thermochemical process

Figure 8.

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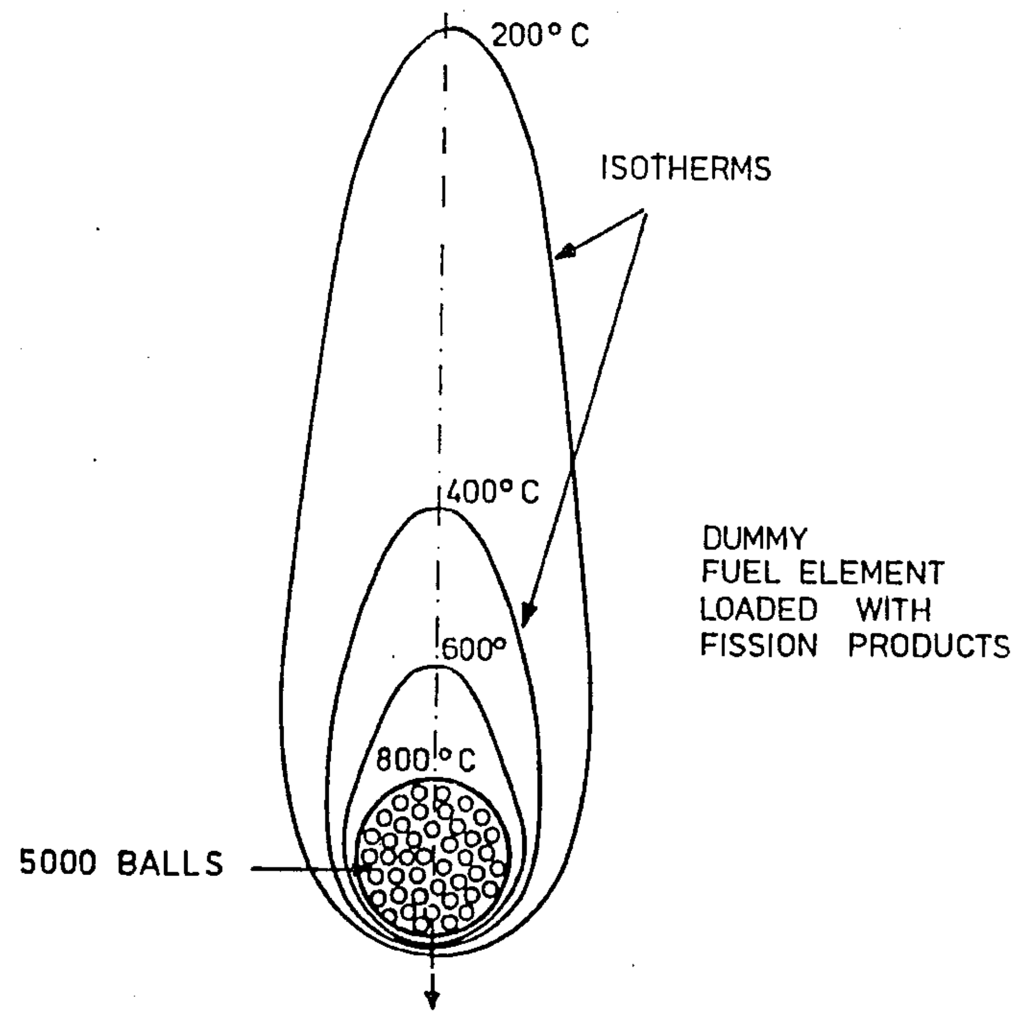

Figure 9.

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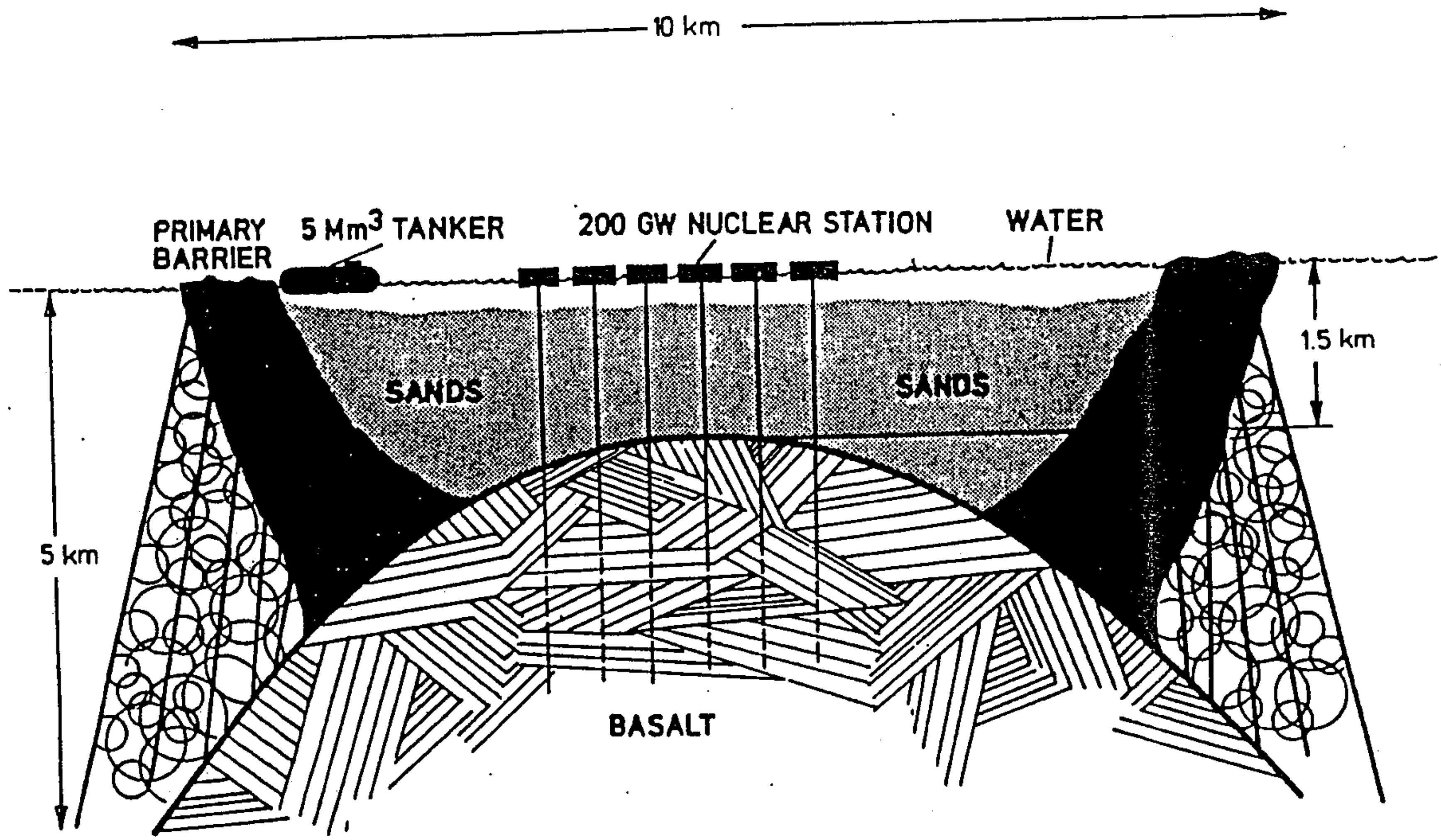

Figure 10.

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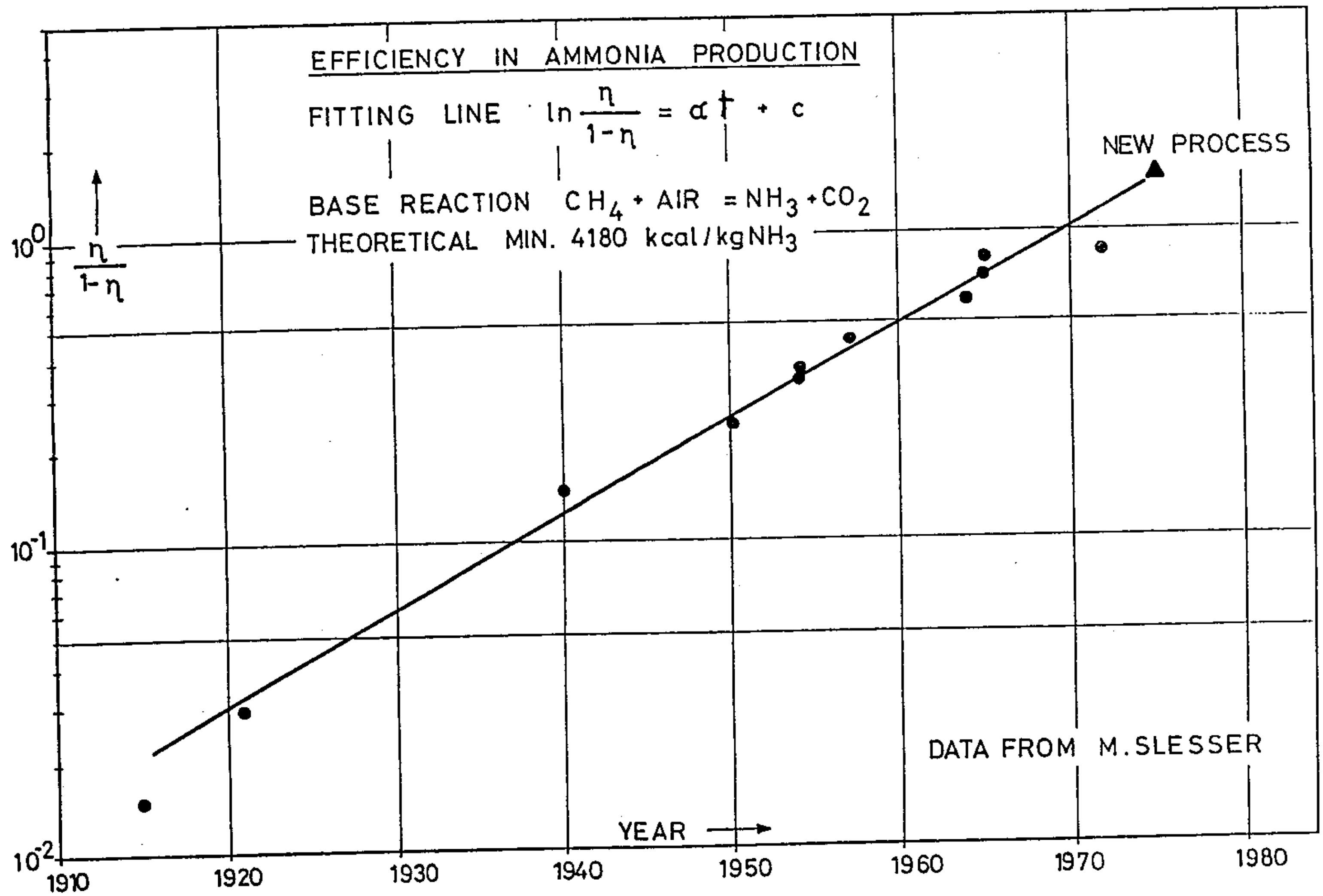

Figure 11.

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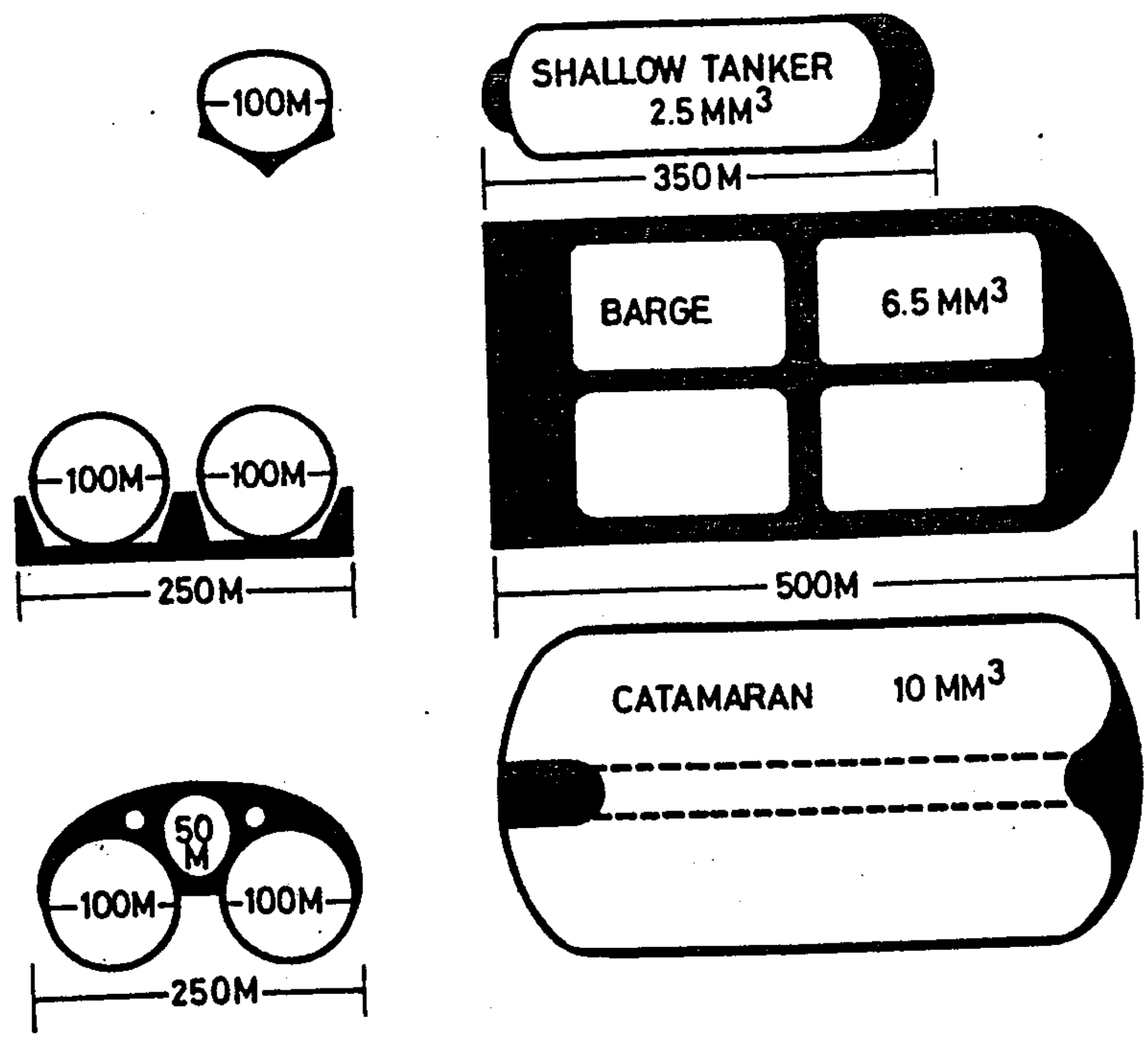

Figure 12.

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