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    These methods may produce goodness of fit to the data (in the sense that a parabola can fit an arc of a sine curve adequately), yet the coefficient may bear little relation in magnitude and may even be of opposite sign to coefficients obtained with the full, correct model. This occurs when an important variable is omitted or if nonlinearity is overlooked, in which case a bias can be introduced into all coefficients (the reason for the "correlation does not equal causation" warning). Tests of significance of coefficients against an alternative of zero cannot, therefore, be interpreted meaningfully unless one can place a bound on the possible bias in the coefficient that is attributable to the effect of excluded variables. Equally, the lack of statistical significance cannot be taken as evidence of lack of effect of the variable.
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Inherently Safe Reactors and a Second Nuclear Era

Alvin M. Weinberg and Irving Spiewak

David Lilienthal, in his book *Atomic Energy, A New Start* (*1*), was among the first to call upon nuclear technologists to design a reactor that was inherently safe. He saw such a device as being necessary for a new start in atomic energy. Without such a forgiving reactor, Lilienthal doubted that nuclear energy could regain the public's confidence, which had been so badly shattered by the Three Mile Island incident. The book appeared in 1980. At that time it was received with skepticism by the reactor community. The review of the book by one of us, for example, suggested that it was easy enough for a nontechnologist like Lilienthal to call for an inherently safe reactor, but that the fundamental characteristics of the fission process, in particular the afterheat, made such a goal all but unattainable (*2*).

Nevertheless, in May of 1980, the Institute for Energy Analysis, under the sponsorship of the Department of Energy, convened a 2-day workshop at which the possibility of designing a practical, inherently safe reactor was discussed. In attendance were many of those responsible for setting nuclear energy on its present course: M. Benedict of Massachusetts Institute of Technology, K. Cohen and E. Schmidt of General Electric, P. Cohen of Westinghouse, J. Dietrich of Combustion Engineering, M. Edlund of Babcock and Wilcox, P. Fortescue of General Atomic, K. Davis, then of Bechtel and later deputy secretary of energy, H. Kendrick of Department of Energy, U. Gat of Oak Ridge National Laboratory, and H. G. MacPherson, J. A. Lane, E. P. Epler, M. W. Firebaugh, and the authors, associated with the Institute itself.

We concluded that a serious study of more forgiving, or perhaps even inherently safe, reactors was a good idea, but the study would have to begin by assessing the safety of existing light-water reactors and of incremental improvements to light-water reactors (*3*). Most of the participants in the workshop believed that such a reexamination would confirm the widely held view that light-water reactors were as safe as any reactors that might compete economically with them.

A year later the Andrew W. Mellon Foundation granted the Institute for En-

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ergy Analysis $400,000 to conduct a 2-year review of the outlook for developing more forgiving or inherently safe nuclear reactors. Since our group at the Institute was so small, it enlisted the help of most of the major reactor vendors in the Western world and Japan: Babcock and Wilcox, Combustion Engineering, General Atomic, General Electric, and Westinghouse in the United States; the Central Electricity Generating Board in the United Kingdom; Atomic Energy of Canada, Limited; Kraftwerk Union in the Federal Republic of Germany; ASEA/ATOM in Sweden; and Hitachi in Japan.

Summary. The Swedish PIUS reactor and the German-American small modular high-temperature gas-cooled reactor are inherently safe—that is, their safety relies not upon intervention of humans or of electromechanical devices but on immutable principles of physics and chemistry. A second nuclear era may require commercialization and deployment of such inherently safe reactors, even though existing light-water reactors appear to be as safe as other well-accepted sources of central electricity, particularly hydroelectric dams.

Stored Energy and the Safety of Large Energy Systems

About 8 percent of the total energy released in fission results from radioactive decay of the fission products. Thus, even after the chain reaction in a 1000-MW electric reactor has ceased, more than 200 MW of heat continue to be generated. The radioactive heat decays gradually; at the end of a week 8 MW are still generated from a reactor that had operated for a long time. In consequence, the stored energy contained in a large nuclear reactor is sufficient, should the cooling fail, to cause the fuel to melt, releasing large amounts of radioactivity into the containment vessels.

That the residual heat source could not be turned off has always challenged, even tantalized, the reactor designer. Nevertheless, the first high-powered reactors at Hanford were not equipped with emergency cooling systems that could spring into action should the regular water cooling fail, nor were they housed in airtight containment domes. Instead, they were built in a remote part of the state of Washington, separated from each other by a dozen or more miles.

Modern light-water reactors operate at far higher power densities than did the Hanford reactors. Being very compact, their thermal inertia is small. Immediately after shutdown, the temperature of the water in a 1000-MW pressurized water reactor (PWR), if uncooled, would rise at the rate of 30°C per minute. The temperature rise would be accompanied by a rapid increase in pressure. Thus today's reactors must be equipped with emergency cooling systems that take over should the regular cooling systems fail; and the reactors are housed in airtight containment structures.

Failure of any one of the various emergency systems does not disable the entire reactor plant. Nevertheless, there is some probability that enough of the systems will fail so that the fuel will melt, or at least be seriously damaged. Though there is not enough reactor experience to determine the probability of a core melt empirically, several probabilistic risk analyses suggest that at the time of the Three Mile Island incident the probability of such a mishap was somewhat greater than 10^{-4} per reactor year, with at least a tenfold uncertainty (*4, 5*). The Three Mile Island incident occurred after some 500 reactor years had been accumulated: its timing therefore is almost consistent with the upper limit of core melt probability estimated by the best-known analysis (*6*).

We shall describe the progress that has been made in designing reactors that are "inherently safe"—that is, whose safety depends not on the intervention of humans or of electromechanical devices but instead depends on immutable and well-understood laws of physics and chemistry.

Technical Approaches

At present there are two well-thought-out ideas for inherently safe reactors: the Process Inherent Ultimately Safe (PIUS) reactor being developed in Sweden by ASEA/ATOM (*7*) and the modular High-Temperature Gas (HTG) reactor, proposed by GA Technologies (*8*) in this country and by Interatom, a subsidiary of KWU in Germany (*9*). Several other concepts have been proposed in addition, but none has been taken as seriously, or developed as fully, as the PIUS and the modular HTG reactors.

The PIUS reactor. The PIUS reactor is a 500-MW (electric) PWR where inherent safety is gained by immersing the reactor core in a large pool of cold borated water (Fig. 1). The pool of water is contained at full reactor pressure within a large prestressed concrete vessel (PCRV). The primary cooling system pumps and the steam generators are also immersed in the pool above the core, and all penetrations into the reactor are at the top of the PCRV. With such a configuration, it is impossible for any type of leak or equipment failure to uncover the radioactive fuel.

During normal operation, the hot primary cooling water is pumped through the core and the steam generators. The primary circuit is interconnected with the cold pool through pressure-balanced interfaces below the core and at the top of the vessel. If anything should interrupt the normal flow of primary coolant, borated water from the pool would immediately enter the primary circuit through natural convection, shutting off the nuclear chain reaction. Pool water is then available to remove decay heat, also. There is sufficient water in the pool to keep the core covered for at least a week, in the absence of external sources of water. Makeup water could then be added.

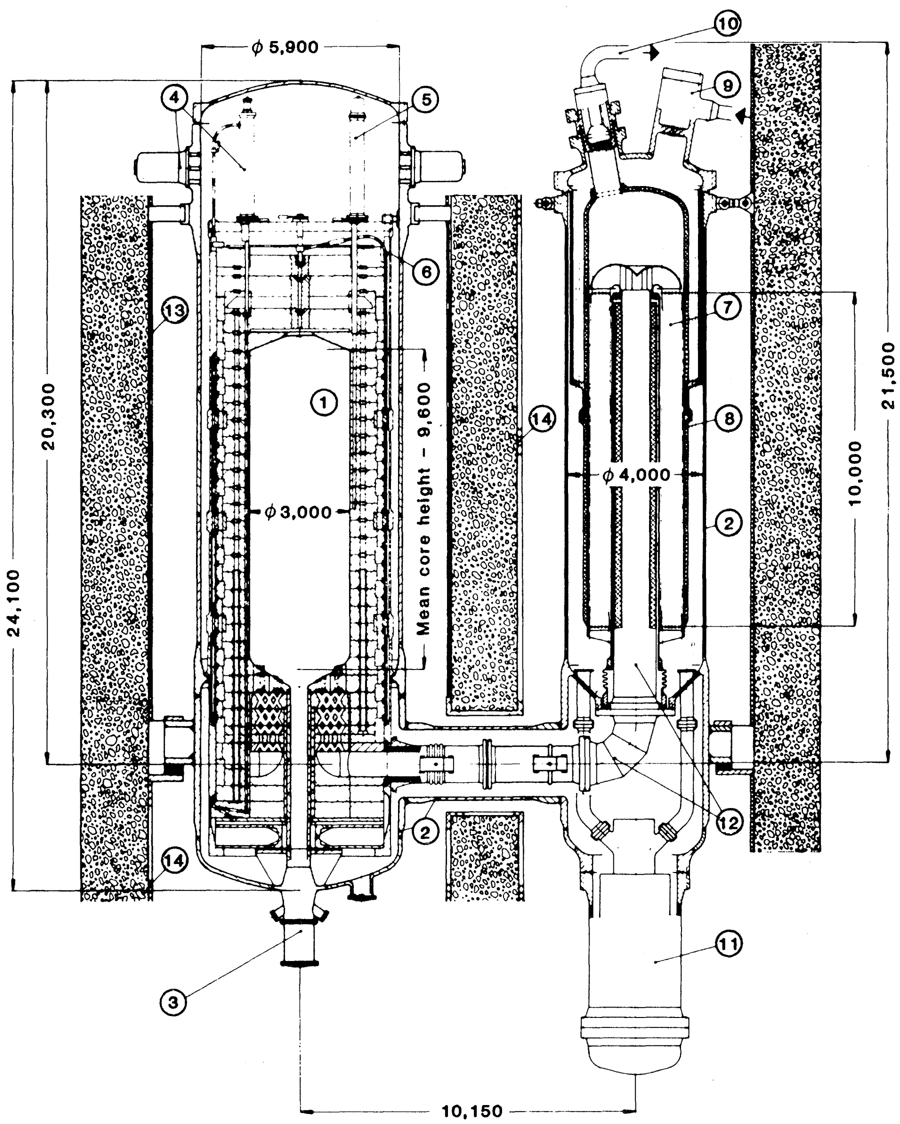
The protection against core meltdown is gained through passive physical principles without the intervention of active safety systems or reactor operators. The protection is effective not only against conceivable accidents caused by equipment or operator failures but also against external events such as earthquakes, sabotage, or attack with conventional explosives.

The PIUS reactor is being developed in Sweden both as a power reactor and, in a low-temperature version, as an energy source for district heating. A number of technical problems must be resolved to prove its operability and commercial worth. The stability of the interfaces separating primary coolant from pool water must be proven. Tools and procedures for refueling and maintaining the reactor efficiently must be devised. Steam generators must be developed. And overall costs must be estimated and shown to be competitive. Under favorable circumstances, ASEA-ATOM believes a demonstration plant could be put into operation in 8 or 9 years. A more realistic schedule for the United States would be 12 years.

The modular HTG reactor. The modular HTG reactor (Fig. 2) is a 100-MW (electric) graphite-core, gas-cooled reactor where inherent safety is gained by its small size and low power density. The power density of the modular HTG reactor is only 3 kW per liter; this compares to 6 kW per liter in a full-size HTG reactor and 100 kW per liter in a PWR. The reactor is cooled with helium, a chemically inert gas.

If the coolant were lost, the nuclear chain reaction would be terminated by the reactor's negative temperature coefficient after a modest temperature rise. The core diameter for the modular HTG reactor is limited so that decay heat could be conducted and radiated to the environment without overheating the fuel to the point where fission products might escape. Again, inherent safety is gained without the operation of mechanical devices or the intervention of operators.

Some of the fail-safe principles incorporated in the modular HTG reactor have been demonstrated in the Arbeitsgemeinschaft Versuchs-Reactor (AVR) in Germany. The AVR, a 15-MW reactor, was started up in 1968 and has operated at full power for extended periods. The physical principles of the modular HTG reactor can be considered proved. However, the major developmental challenge is reducing the capital cost of such reactors to be competitive with other sources of electricity. Extensive use of shop fabrication could lead to cost and schedule reductions and perhaps accomplish this objective.



1. Pebble bed
2. Pressure vessel
3. Fuel discharge
4. Boronated spheres
5. Reflector rod
6. Fuel loading
7. Pipe assembly
8. Outer shroud
9. Feed line
10. Live steam line
11. Blower
12. Hot gas duct
13. Surface cooler
14. Insulation

Fig. 1. Cross section of the PIUS reactor. [Courtesy of ASEA-ATOM, Västerås, Sweden]

How Safe Are Light-Water Reactors?

To develop and deploy a new reactor system such as PIUS or even the modular HTG reactor is a formidable undertaking. Before one embarks on such a course, one must therefore estimate the safety of current reactors: would an inherently safe reactor such as PIUS provide enough additional assurance against mishap to make its development worthwhile?

To answer this question, the Institute reviewed what is known about the core melt probability of light-water reactors, insofar as this probability is revealed by probabilistic risk analysis. Since the Three Mile Island accident, many such analyses have been performed on specific U.S. light-water reactors. In addition, Oak Ridge National Laboratory and Science Applications, Inc., have sifted through many thousands of licensee event reports to identify some 52 events which, had other systems failed, could have led to a core meltdown (*10*). Thus, we now have three separate risk estimates.

The original Rasmussen study found for two particular reactors, Surry (a PWR) and Peach Bottom [a boiling water reactor (BWR)], core melt probabilities of 6×10^{-5} per reactor year and 3×10^{-5} per reactor year, respectively; the uncertainty in these estimates is believed by Rasmussen to be a factor of 5 to 10 either way (*5*). Thus, on the basis of the Rasmussen study alone, one could not rule out a median core melt probability being as high as several times 10^{-4} per reactor year.

The study by Oak Ridge National Laboratory and Science Applications, Inc., is based on the analysis of operating data. It suggests that the core melt probability of reactors, before they had incorporated improvements mandated as a result of the Three Mile Island incident, was higher than 10^{-3} per reactor year, which was itself higher than Rasmussen's estimate (*5, 6*).

The analyses of reactors that have incorporated post–Three Mile Island improvements suggest that today's light-water reactors have core melt probabilities 1.5 to 3 times lower than Rasmussen predicted (*4, 6*). The probabilities are at most 10^{-4} per reactor year and probably lower.

These improvements have involved greater redundancy. For example, at Calvert Cliffs additional auxiliary feedwater trains were installed so that the likelihood of a loss of feedwater, which precipitated the Three Mile Island incident, would be much reduced. In addition, there is now a more positive indication of the state of closure of the power-operated relief valve, which was open during the incident although operators believed it to be shut. Operator training has been improved also, including guidance from the Institute of Nuclear Power Operations. Improvements of this sort, incremental but nonetheless real, have endowed the current fleet of reactors with a greater degree of safety than they possessed at the time of Three Mile Island.

Many of these improvements and more are being incorporated in the proposed Sizewell B reactor, the advanced PWR being developed jointly by Westinghouse and Mitsubishi, and the advanced BWR being developed by General Electric, Hitachi, and Toshiba (*11*). Probabilistic risk analysis leads to an estimated core melt probability of 1.1×10^{-6} per reactor year for Sizewell B; the estimated core melt probability for the advanced BWR is given by its sponsor, General Electric, to be around 5×10^{-6} per reactor year (*11*). The advanced PWR ought also to have very low estimated core melt probability though the value has not been published.

Thus, the core melt probabilities of the coming generation of American-, British-, and Japanese-designed light-water reactors ought to be lower than 10^{-5} per reactor year. This lowered probability, however, is obtained at the price of greater complexity and higher cost.

A serious core melt, such as at Three Mile Island, usually poses a much greater hazard to the owner of the malfunctioning reactor than it does to the public. In a majority of possible core melts, most of the fission products would be confined to the water inside the containment vessel. The matter is still somewhat controversial, though much evidence supports the view that the amount of radioactive iodine released at Three Mile Island (20 curies out of tens of million curies in the water) represents the likely outcome in most (though not all) reactor accidents in light-water reactors (*12*).

To summarize, then, the risk of the public receiving substantial radioactive dose from a core melt in a newly built light-water reactor, as judged by probabilistic risk assessment, is perhaps 10 to 100 times lower than is the likelihood that the reactor itself will be damaged severely. This latter probability is certainly less than 10^{-4} per reactor year and may be as low as 10^{-5} or even lower (*11*). The figure of 10^{-4} per reactor year is the safety goal recently promulgated by the Nuclear Regulatory Commission (*13*).

At present, with about 500 large reactors (operating or under construction) in the world, a core melt probability of 10^{-4} per reactor year implies an average accident frequency of one every 20 years. But if nuclear reactors are deployed more extensively—perhaps in response to heightened concern over carbon dioxide accumulation—then one might well contemplate a world with 5000 or more reactors. In such a "nuclear" world the estimated core melt frequency would be one every 2 years—almost surely too high. Thus the goal of 10^{-5} per reactor year, apparently achieved or surpassed in the advanced light-water reactors and in Sizewell B, would seem to be necessary.

Though reactors appear to be as safe as large dams, most Americans now seem to oppose nuclear energy (*14*); and a recent survey of utility operators of reactors reveals a widespread disaffection with nuclear power (*15*). Even though the probabilities seem favorable, at least in a 500-reactor world, a rebirth of nuclear energy, David Lilienthal's "New Start," will be very hard to initiate unless the public and the utility owners regain confidence in nuclear energy.

For the utility owners, nuclear energy, though in many cases a very good buy, in other cases has been a financial disaster. A prospective owner of a nuclear plant is understandably reluctant to go nuclear since he cannot initially know whether his plant will be one of the former or one of the latter! Would an inherently safe reactor remove these uncertainties that bedevil nuclear energy? Yes—but only if the inherently safe reactors could be built cheaply and with confidence. This implies that the Nuclear Regulatory Commission would greatly reduce its intervention in view of the inherent safety of the PIUS or the modular HTG reactors. On neither point can we be certain, though we have reason to be hopeful.

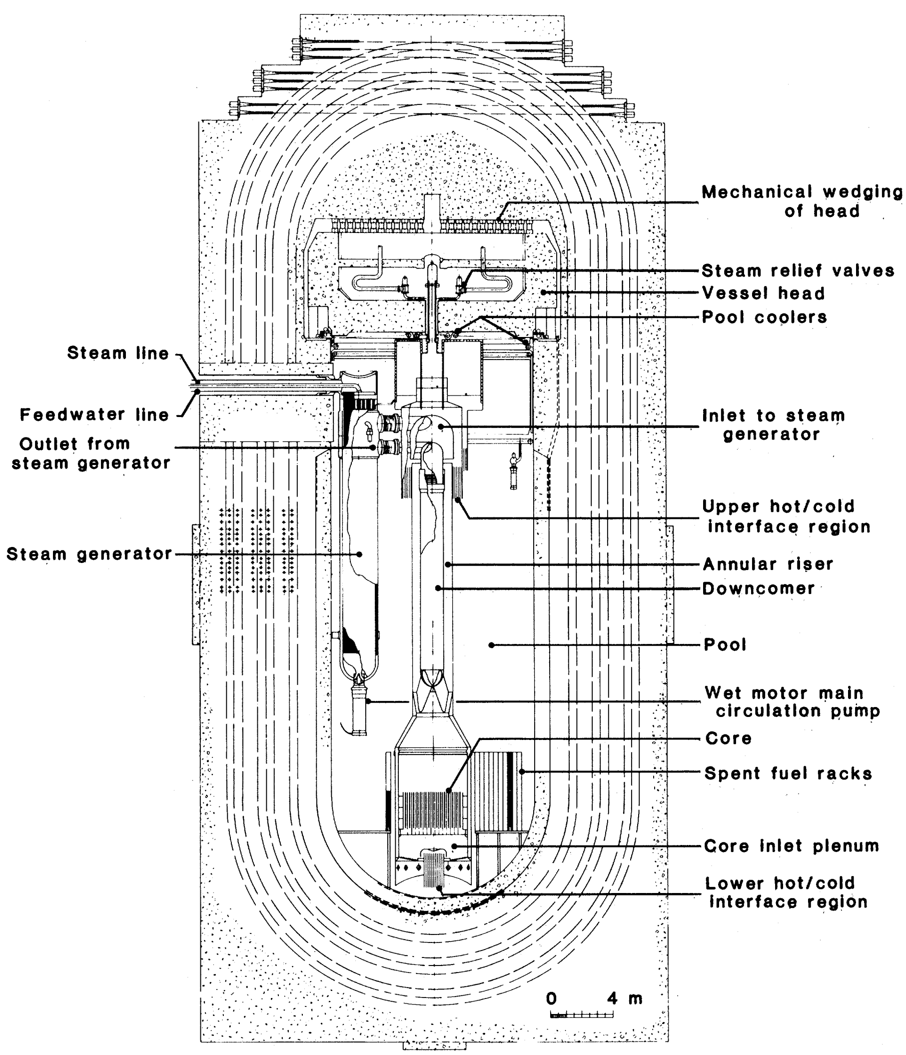


Fig. 2. Cross section of the modular high-temperature gas reactor. Dimensions in millimeters. [Courtesy of *Nuclear Technology* (*9*)]

For example, since there are no sequences that can release large amounts of radioactivity from PIUS, a high-pressure containment shell is unneeded. The elaborate emergency safety systems of a light-water reactor do not appear in PIUS, nor does the PIUS piping system require earthquake-proofing. For all these reasons, ASEA/ATOM believes that PIUS can be built for no more than the cost of a conventional PWR (*7*).

As to whether the Nuclear Regulatory Commission would simplify its mode of regulation, we can only guess. Three Mile Island resulted in a proliferation of regulations; whether, as reactors incorporate these safety features, the commission will return to a less prescriptive mode of regulation, no one can say. Certainly the economic success of a PIUS or a modular HTG reactor depends heavily on the commission's recognition that such reactors are fundamentally less prone to accident than current ones.

A Second Nuclear Era

The Institute for Energy Analysis has concluded that, yes, inherently safe reactors are surprisingly reasonable engineering devices (*11*). Yet before one can state this finding categorically, one must build a prototype—say, 100 MW (electric). We have proposed that the U.S. government undertake such a project, even though it might cost $500 million or more.

Why should the government, rather than the vendors themselves, take responsibility for such a project? In our view, because preservation of the nuclear option is in the national interest and transcends the interest of any particular utility. The United States is blessed with abundant coal: we could survive had fission not been invented, simply by burning more coal under utility boilers. But the environmental burden, including carbon dioxide, would become very heavy indeed were the nation to follow such a course.

Beyond this, should our nuclear plants last for 75 or even 100 years rather than the 30 years over which they are amortized then, because nuclear plants have such low operating costs, we could look forward to an era of cheap electricity based on amortized, but still operating, nuclear plants. The economics of nuclear power would then resemble much more the economics of hydroelectric dams than of diesel generators (*16*). But such long-term planning can hardly be expected of private industry. Only the government can plan for such a long term, as it does when it builds dams, interstate highways, and national parks.

Would inherently safe reactors render existing reactors obsolete? Would pressure to shut down existing reactors because inherently safe reactors are available become so strong as to abort the first nuclear era long before the current light-water reactors have been worn out? Again, it is difficult to say; but one can presume that, provided we do not repeat the Three Mile Island episode, the public will accept the presence of well-running nuclear power plants.

Should inherently safe reactors also be as cheap or cheaper than existing reactors, then of course economics would dictate the preference for the less expensive reactors over the more expensive. But we cannot predict these things. Only after some of these reactors have been constructed can we really decide if they can be built economically.

Future Prospects

In a sense, the PIUS and the modular HTG reactors, if proven to be practical, have let the genie out of the bottle. Are there other, equally clever, schemes for inherently safe reactors? And perhaps most important, can similar principles, or better ones, be adapted to the design of breeder reactors? Evidently the pool-type, liquid metal, fast breeder reactor, in which the reactor and intermediate heat exchangers are immersed in a very large pool of liquid sodium, possesses some of the features of PIUS. However, accident sequences that could destroy the core of these reactors have been identified. Could the principle of poisoning the pool and maintaining dynamic separation between pool and core coolant be applied in liquid metal, fast breeder reactors? Or even, could one invent inherently safe breeders, not necessarily fast breeders, based on other coolants and moderators and fuels—like gas, water, or molten salt—that can be made inherently safe? Perhaps the PIUS and the modular HTG reactors will, at the very least, serve to inspire the coming generation of reactor designers to devote their energies to the design of an inherently safe breeder reactor. Should they succeed in this endeavor, future generations will be forever grateful to them.

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