

UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

In the Matter of

THE REGENTS OF THE UNIVERSITY
OF CALIFORNIA

(UCLA Research Reactor)

Docket No. 50-142

(Proposed Renewal of
Facility License)

DECLARATION OF DR. JAMES C. WARF

I, James C. Warf, declare as follows:

1. I am Professor of Chemistry at the University of Southern California (USC), where I have been a member of the faculty for the last thirty-four years. Prior to that time, I spent five years with the Manhattan Project, mostly at Ames Iowa, and to a lesser degree at the University of Chicago and at Oak Ridge, Tennessee. I specialized in the chemistry of nuclear materials and was Group Leader of the Analytical Section and, part of the time, the Inorganic Section, at times with seventy people working under me. Directly after World War II, I played a role in the formation of the Federation of Atomic Scientists (later Federation of American Scientists). Nearly thirty years ago I helped found the Los Angeles Chapter of the Federation of American Scientists, which later became the Los Angeles Federation of Scientists and, most recently, the Southern California Federation of Scientists. I remain active with the organization to this day. A more detailed statement of professional qualifications is attached hereto.
2. I have reviewed certain documents related to the UCLA Argonaut reactor. These documents have included: (1) "Analysis of Credible Accidents for Argonaut Reactors" by S. C. Hawley, et al., particularly those sections dealing with explosive chemical reactions and graphite fire, (2) a draft analysis by David DuPont of the Wigner energy section of the Hawley report, supra, (3) "Fuel Temperatures in an Argonaut Reactor Core Following a Hypothetical Design Basis Accident (DBA)" by G.E. Cort, and (4) the fire response section of the March 1982 Emergency Response Plan for the UCLA Reactor, specifically the Los Angeles Fire Department fire response plan attached thereto as "Attachment A." Certain other relevant documents, identified below, have also been reviewed.

3. It is my understanding that, having operated for roughly twenty years, the UCLA Argonaut reactor is currently the subject of a safety review by the U.S. Nuclear Regulatory Commission as part of a license renewal proceeding. Such a review seems to me to be a sensible precaution, as occasionally some significant fact or facts, overlooked in an original analysis decades before, may be uncovered. And if nothing significant is found, a greater level of assurance of safety has been established. Thus, in my opinion, it would be prudent for such a safety review to take into account the following facts:

4. The original Hazards Analysis for the UCLA reactor dismissed the probability of damage from fire resulting in the release of fission products as "very small" in part because "none of the materials of construction of the reactor are inflammable." (1960 UCLA Reactor Hazards Analysis, p. 62, "Fire"). While other factors may affect the probability of fission product release from fire, the statement that none of the materials of construction of the reactor are inflammable is simply incorrect. A number of those materials--particularly the graphite, uranium, magnesium, and even the aluminum, among others--are, under the right conditions, most definitely combustible.

5. The first and most obvious of the combustible materials used in the Argonaut reactor is the graphite--used as moderator, reflector, and thermal column. Graphite will, under the right circumstances, most definitely burn, as the Hawley report correctly indicates. (Charcoal is, after all, a graphitic substance, and it will, of course, readily burn.)

6. On page 82 of the Proceedings of the 1958 Atomic Energy Commission and Contractor Safety and Fire Protection Conference, held at AEC Headquarters in Germantown, Maryland, June 24-25, 1958, held in part to analyze the implications for reactor safety of the Windscale accident in which the graphite moderator and the uranium fuel both caught fire, Dr. C. Rogers McCullough of the USAEC is quoted as saying:

By the way, this is an amusing point. The belief had grown up on the part of many people in this country that graphite will not burn. This is nonsense. Graphite is carbon, and anyone knows that carbon will burn if you get it hot enough. But this glib remark, that graphite will not catch on fire, had become prevalent.

While not having personal knowledge of any widespread belief in this country that graphite could not burn, I concur with Dr. McCullough's statement that it, of course, can burn in air, as the Windscale fire unfortunately so clearly demonstrated. A belief to the contrary would be neither correct nor prudent.

7. As to the matter of the ignition temperature of graphite, it is dependent upon a number of factors such as the purity and density of the graphite, the amount of air present and the velocity of the air, the particle size and surface-to-volume ratio of the graphite, and structural configuration influencing heat loss. Furthermore, there appear to be other uncertainties, as evidenced by Dr. McCullough's comments at the same page of the above-cited

proceeding:

Research work is going on; we are not satisfied that we know the ignition point of graphite. . . . At any rate, research is going on to learn more about the ignition temperature. It is a tough problem to solve, and we are exploring possibilities.

Thus, there are some uncertainties as to ignition temperature of graphite, and it might be wise from the point of view of a conservative safety analysis to place or establish the magnitude of error on whatever estimate of ignition temperature is used. However, I am not prepared at this time to suggest what error limits might be appropriate for any specific estimate of ignition temperature.

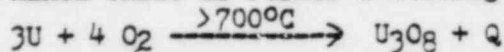
8. The Hawley report uses a figure of 650° C as the point at which graphite will burn readily if sufficient oxygen is supplied. That figure seems to me to be reasonable for reactor-grade graphite, although as I indicated in 7 above there are some uncertainties and some error limits might be appropriate. Any temperature estimate is valid only for a fixed set of parameters (density, purity, particle size, air supply, etc.)

9. Once ignited, self-sustained combustion of the graphite must be assumed if the air supply is adequate. Although this depends upon configuration, airflow, and the like, it appears to me that somewhere around 650° C is the critical temperature for induction of a self-sustained fire in the Argonaut reactor's graphite. This temperature is above a glowing red heat but below a white heat. The reaction is exothermic, so if some of the graphite were ignited, it could release enough heat to bring other graphite to the ignition temperature.

10. In addition to graphite, I understand the Argonaut reactor at UCLA employs metallic uranium in a uranium-aluminum eutectic, clad with aluminum. Metallic uranium readily burns in air if ignited, and under somewhat more restrictive conditions, so can aluminum. Aluminum gives off more heat, pound for pound, than uranium metal when burned, but it is somewhat more resistant to burning. The fact that the uranium and the aluminum are in a eutectic will not affect the ability of either to burn, although burning of the eutectic will give off slightly less heat than if the materials were not in a eutectic. However, the difference is insignificant. In addition, the fact that the eutectic melts at a relatively low temperature (640° C--Hawley, p. 18), will not affect the ability of the materials to burn. The metals can burn as well in a liquid form as a solid. In fact, molten metal can cause fresh aluminum, without the normal protective oxide layer, to be exposed to air, making burning far more likely.

11. As to ignition temperature for uranium metal, again there are some uncertainties. Charles Russell (Reactor Safeguards, Pergamon Press, Oxford, 1962, p. 115-116, citing W.C. Reynolds, Report NACA TN D-182, "Investigation of Ignition Temperatures of Metals") gives the ignition temperature of solid uranium metal in oxygen at 1 atmosphere as 608° F (320° C). Yemel'yanov and Yevstyukhin (The Metallurgy of Nuclear Fuel,

Pergamon Press, Oxford, 1969) state, "At a temperature above 700°C solid compact uranium burns in air and in oxygen emitting a blinding white light. Here uranium mixed oxide is formed according to the reaction



where $Q = 845.2$ kcal/mol." Turnings of reactor-grade uranium have ignited when being cut using a lathe, evidently from friction. Finely divided uranium ignites in air at room temperature. Thus the ignition temperature is a variable, depending on circumstances, but in general uranium metal must be considered more combustible than graphite. I have had no experience with uranium-aluminum eutectic, but the combustibility of the alloy certainly merits investigation, in both solid and liquid states.

12. It is my understanding that the control blades at the UCLA reactor are cadmium-tipped and protected by magnesium shrouds. Magnesium can also burn, and when it does so it gives off considerable energy. The ignition temperature of Mg metal is variable, depending on its particle size, etc. If you specify an ignition temperature you want, from 25° up, I can prepare a specimen which will ignite at that temperature. One should be aware that slow oxidation occurs below ignition temperature.

Cadmium metal is a low-melting metal with a relatively high vapor pressure. The Handbook of Chemistry and Physics reports its melting temperature as 320°C. If the control blades are made of the metal and not the oxide, it would thus seem prudent to analyze the reactivity and other possible consequences of an incident which resulted in the melting of the control blades. Furthermore, the volatility of cadmium could potentially result in cadmium vapor being released in a fire or other incident involving elevated temperatures. If so, the cadmium vapor or its oxide would likely rapidly condense in air as minute particles and could cause a potential hazard for fire-fighters or others due to the toxic nature of cadmium. This, too, should probably be considered, it would seem to me, in designing fire-fighting plans and analyzing potential accident sequences and consequences.

13. I also understand that UCLA is requesting a license for 2 curies of plutonium-239 in a plutonium-beryllium neutron source for the reactor facility. Were this Pu-Be source to become involved in fire, the consequences could verge on the catastrophic. Plutonium metal, of course, can burn, releasing minute particles into the air, dispersed by the energy of the fire. Fire-fighting would be extremely hazardous due to the presence of the plutonium oxide in the air, and the public health implications would be awful. (2 curies of Pu-239 is by no means an insignificant amount; placed near the skin, it will cause radiation burns in a few minutes; inhalation of even microgram amounts is exceedingly dangerous).

When Pu metal burns, it goes to PuO₂ in limited air, to Pu₂O₈ in excess air, just like uranium. Be is comparable to Al in its combustion, but is higher melting. Again, the chemical form of the material is important, i.e. whether in metal or oxide. BeO is volatile in steam at high temperatures.

14. The issue of how to fight a graphite-uranium fire, leaving aside the possibility of cadmium and plutonium particles being released, has no easy answers and would require considerable prior analysis of the problems inherent and preparation in advance in the form of emergency planning. There could be great danger, in particular, in employing either water or, to a lesser degree, carbon dioxide to put out the fire. In either case, an explosion might occur, owing to the formation of combustible gases.

15. Dr. McCullough's report on the Windscale incident, in the AEC document referred to above, describes how those fighting the fire tried various methods over a couple of days to put the fire out, which involved both uranium and graphite, all to no avail, and how they had to try, as a last resort, water:

Now they were faced with the decision either to use water or to let the fire burn up. They decided there was nothing left for them to do but put water in. There was some trepidation about this, as you can imagine, because they well knew that water on glowing uranium makes hydrogen. Water on glowing carbon makes hydrogen and CO; you have then a nice mixture of hydrogen, CO, and air, and you might have an explosion.

But they had no other choice.

They, in the end, followed techniques learned during World War II in extinguishing incendiary bombs, and fortunately the gamble paid off. But they had no other choice, and rightly were extremely worried about the potential for an explosion. The fact that one did not occur at Windscale, in my opinion, does not get one around the fact that such an explosion is clearly possible, could be quite dangerous, and that water should, if at all possible, not be used, or if used, used with the potential danger clearly thought out. As McCullough concluded:

I think it took a great deal of courage on the part of these people to put water on this reactor. They did it with fear and trepidation, and in talking with them they will not guarantee that they could do it a second time without an explosion.

I note also that the steam that ensued carried with it very significant quantities of fission products into the environment.

16. The potential for metal-water or metal-steam reactions should be examined in putting together fire-fighting plans. Aluminum, uranium, magnesium, and graphite all can react in a steam environment, producing large amounts of energy, liberating hydrogen which can cause explosion dangers. Russell indicates the Al-H₂O reaction liberates more than twice the energy of nitroglycerin, in calories per gram, and five times the energy of black powder; the magnesium-water reaction just slightly less than aluminum; and the U-H₂O reaction just somewhat less than black powder. (Al + NH₄NC₃ was used as a cheap explosive in Vietnam, "Daisy Cutter.")

17. I do not believe it likely that a group of firefighters arriving on the scene would have the competence to judge whether to use water, and if so, how, etc. Furthermore, it would seem most prudent for an emergency plan to have been considered in advance of the appropriate fire-fighting response, and for the requisite materials to be readily available for such fire-fighting. There are non-moderating materials that could be used to smother the fire that would not react explosively with burning core components; careful consideration should be given to the choice of these. My reading of the one-page fire-fighting plan included in the March 1982 emergency plan seems to me inadequate in these regards.

18. The use of CO₂ on such a fire could also be dangerous. Graphite is oxidized by CO₂, yielding carbon monoxide, which is also explosive in the presence of air.

19. Simple carbon tetrachloride extinguishers that formerly were used for lab fires have a host of problems associated with their use, notably the toxic phosgene they give off when used on fires. And even some chemical foams might have a favorable moderating effect that needs to be taken into account (this can be gotten around, perhaps, by the addition of boron-containing compounds to such foams).

20. Firefighters would also have to be prepared to deal with potentially toxic substances such as cadmium fumes in the air, and work in an environment possibly contaminated with fission products and perhaps plutonium. They would need good information as to what materials had been released in to the air and roughly in what concentrations, good detectors for those materials, and ability to read and interpret that information. They would need appropriate equipment to protect themselves from inhalation of the materials and from direct exposure.

21. As stated above, the one page plan by the LA Fire Department, in my opinion, does not adequately address the above potential problems. While one hopes that such an emergency never occurs, and trusts that adequate precautions will be taken to minimize any potential for such an emergency, an emergency plan must realistically deal with the conditions that could occur if such an emergency were to happen. The existing plans to control a reactor fire are, it seems to me, inadequate. A revised emergency response could profitably include the following: rapid determination of any radiation hazard, rapid evacuation of personnel, stockpiling of fire-fighting substances safe for reactor materials, and knowledge of access ports to the reactor. The fire-fighters should not have to locate and confer with any particular reactor personnel, who might not be available at once.

22. I understand that there is some question about positive temperature coefficients of reactivity for graphite. Such a positive effect has been known for a long time—certainly we in the Manhattan Project knew about it forty years ago.

23. As to the Wigner effect, the small size of the UCLA reactor does not necessarily mean that the amount of Wigner energy absorbed per gram of graphite is likewise small. In fact, were a large-sized reactor and UCLA's far smaller reactor to both produce 1 MW-day of energy, all other things being equal, the amount of Wigner energy absorbed in each gram of adjacent

graphite would be considerably greater in the UCLA reactor than in the larger reactor, for the simple reason that the larger reactor has far more graphite to absorb the same amount of energy, thus the energy absorption per gram of graphite is "diluted." All other things being equal, a large reactor with the same neutron flux as the UCLA reactor, run for the same length of time, would produce the same amount of energy absorbed per gram of graphite as the UCLA reactor. And it is the energy absorbed per gram of graphite that is the key to whether enough energy has been stored to bring any part of the graphite to ignition if enough air is present; and, given the proper configuration, one unit of graphite ignited could release enough heat to bring many additional units of graphite to the ignition point.

24. I have read the Hawley, et al, analysis of the Wigner energy matter, as well as Mr. DuPont's critique thereof. It appears to me that there is considerable disagreement as to how much Wigner energy can actually be absorbed, given operating limits, in the UCLA reactor. As I understand it, Mr. DuPont uses the same analytical method as Mr. Hawley, yet takes issue with some of the numerical values Mr. Hawley used in his calculations, particularly the neutron flux and number of MWD* of operation at UCLA and the appropriate cal/g absorption figure that should be used for exposures at low doses. It appears that, if Mr. Hawley's calculational method is correct and if Mr. DuPont's numerical values are the appropriate ones, the amount of Wigner energy that could be absorbed in the UCLA reactor's graphite would be roughly twenty times the amount Mr. Hawley indicates.

25. Mr. Hawley uses a neutron flux of 10^{12} n/cm²-sec. Mr. DuPont uses 1.5×10^{12} , taken from the UCLA Application for Relicensing at page III/6-5. Mr. Hawley's report takes the value 0.5 cal/g per MWD/AT as the best value for the rate of energy storage in graphite irradiated at 30°C. Yet Nightingale (p. 345) states, "More-accurate values derived from measurements at very low exposures range from 0.6 to 1.0 cal/MWD/AT." Mr. DuPont further takes issue with the Hawley study conversion to energy storage rate at 50°C; graphing the Nightingale data for the change in the rate of energy storage with temperature, Mr. DuPont finds 5/6ths the energy stored at 50°C than at 30°C, whereas the Hawley report uses a smaller fraction. Finally, the Hawley study indicates 12 MWD to-date at UCLA; Mr. DuPont says the correct figure is 17 MWD, and if the reactor were to operate its licensed limit of 5% per year through the proposed license period (until the year 2000), an additional 37 MWD could be produced. These modifications of the Hawley study calculations by Mr. DuPont seem reasonable, and raise a substantial question as to how much Wigner energy might be absorbed in the UCLA graphite.

26. In addition, there are some uncertainties in making such calculations, as they rely on employing empirically derived data from various irradiation locations in a few reactors and then extrapolating to another reactor of a different kind and configuration. Plus, I understand there is some uncertainty as to the past irradiation history of the UCLA reactor's graphite--whether, for example, it might have been previously used in another reactor prior to the construction of the UCLA reactor. In light of the foregoing, I suggest removing some of the graphite from different

* MWD means megawatt-days.

locations in the UCLA reactor core and experimentally determining how much Wigner energy has indeed been absorbed to date in the graphite. This could be done by any of a variety of methods--calorimetric annealing, X-ray diffraction patterns, heat of combustion measurements. (I understand the UCLA reactor is occasionally used to color diamonds. If this effect is due to changes in the diamond's crystalline structure and not to impurities in the diamond, this would be further evidence of this reactor's capability of causing radiation damage in graphite, as graphite and diamond are the two crystalline forms of carbon and would react similarly to neutron bombardment. I also understand there is some question as to whether the UCLA graphite has exhibited some swelling or dimensional change; if this is confirmed, it would also be evidence of Wigner energy storage and would lend further reason to the possible usefulness of making actual measurements.)

27. Both the Hawley and the Cort studies examine certain accident scenarios that could, by themselves, cause substantial temperature rises in the UCLA reactor. In both cases--the Hawley analysis of power excursions and the Cort analysis of coolant restriction following earthquake--the temperature did not reach that of the melting of the fuel eutectic or cladding. However, if substantial Wigner energy were stored in the graphite, such an incident could, conceivably, release that energy and substantially raise the temperature that could be reached. In addition, some experimental materials in the reactor core may have ignition temperatures below the melting point of the fuel, in which case fire could be initiated even though the initiating temperature did not approach the fuel's critical temperature. Thus, the significance of possible flammable characteristics of the reactor core contents and the true amount of Wigner energy that could be absorbed during the license period may well have significance in a safety review.

28. Much work has been done on the attack of uranium ingots, clad in aluminum, through a pin hole. At elevated temperatures, air or water enters the pinhole, reacts, and the resulting oxide swells. This breaks more Al skin, and the process continues faster; but so far as I know oxidation is retarded so much the ignition temperature is not reached. Powdered uranium (from decomposition of UH_3) can react with liquid water and glow red, forming UO_2 and H_2 . Massive U metal must be heated to react.

29. Uranium and aluminum can be separated chemically from their eutectic by any number of techniques. One method is to dissolve the eutectic in hydrochloric acid, and oxidize the uranium to uranyl ion using nitric acid. Addition of excess sodium hydroxide precipitates the uranium as sodium diuranate, but converts the aluminum to the soluble aluminate ion. Separation is effected by centrifuging. Alternatively, the uranyl nitrate can be extracted by ether or butyl phosphate, leaving the aluminum in the aqueous phase.

30. I might also add that as I read the Hawley, et al, analysis of "credible accidents" for Argonaut reactors, I had the impression that certain extremely unlikely scenarios were examined and then dismissed, with the conclusion then asserted that there are no serious credible accident scenarios

for Argonaut reactors, when scenarios more likely appeared not to have been analyzed whatsoever. Perhaps the above-described facts can be of use in a fuller review of potential accidents and consequences.

31. The above-cited facts might also be of use in mitigating consequences of or preventing accidents. For example, it might be prudent to consider use of a uranium oxide fuel, which would be far less susceptible to burning. A boron-based control blade might get around the low-melting temperature problem for the cadmium (if it is in the metallic form). Boron-based fire-fighting foams or other materials might ameliorate problems of using water alone. Sand or a silicate, as a clay, perhaps could be used to smother the fire. It might be best merely to close off the air supply mechanically, but the possibility that this might allow the reactor to overheat should be examined.

I cannot overstress consideration of the danger of using water on such a fire, should it ever occur. The use of water on such a fire could be disastrous. Careful emergency planning before such an event occurs should hopefully result in fire-fighters not having to face the terrible choices faced by those responding to Windscale.

I declare under penalty of perjury under the laws of the United States of America that the foregoing is true and correct to the best of my knowledge and belief.

James C. Warf

James C. Warf

Executed at Kota Kinabalu, Malaysia

This 17 th day of November, 1982.

DR. JAMES C. WARF
Professor of Chemistry
University of Southern California

Professional Qualifications

- 1939 B.S. degree in chemistry, University of Tulsa (Oklahoma)
- 1940-41 Research chemist, Phillips Petroleum Co.
- 1941-42 Instructor in chemistry, University of Tulsa
- 1942-47 Manhattan Project. Group leader of analytical section and, during the last years, of the inorganic chemistry section, mostly at Iowa State University, Ames, but frequently at the University of Chicago and other sites. Research on chemistry and analysis of nuclear materials, uranium, thorium, plutonium, fission products, etc.
- 1946 Ph.D. degree in inorganic chemistry, Iowa State University
- 1947-48 Guggenheim Fellow, inorganic chemistry, University of Berne, Switzerland
- 1948 to present Assistant, Associate, Full Professor of Chemistry at the University of Southern California, Los Angeles, California. Research: rare earth metals, uranium, solid state, crystallography, thermodynamics, liquid ammonia solutions.
- 1957-59, 1962-64, 1974-76, 1978-79, 1982- Visiting Professor of Chemistry at various universities in Indonesia or Malaysia
- 1969-70 Visiting Professor, Technical University of Vienna, Austria
- 1964-70 Consultant, Jet Propulsion Laboratory, Pasadena, California

Author of approximately 65 scientific papers or encyclopedia articles, 8 books on chemistry.