



Gary H. Loechelt

Accelerated Nuclear Decay in the Light of New Experimental Data

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One of the lines of evidence for accelerated nuclear decay promoted by young-earth creationists (YECs) is the high retention of helium in zircon crystals from a borehole in Fenton Hill, New Mexico, United States. More recent measurements of zircon samples from the Continental Deep Drilling Program, Germany, contradict this result. A model of the helium diffusion ages from that site shows that retention of helium is possible in these zircons for millions of years, consistent with the conventional radiometric age of the samples. A possible explanation for this discrepancy is the diffusion behavior of helium in zircon at relatively low temperatures below about 350 °C. The kinetic mechanisms of the low-temperature diffusion are discussed, along with possible implications for the accelerated nuclear decay hypothesis.

Radiometric dating methods pose a serious challenge to belief in a 6,000-year-old Earth held by young-earth creationists (YECs). Taken at face value, these dating methods indicate that Earth, and by implication the universe, is billions, not thousands, of years old. Not surprisingly, much has been written by the YEC community in an attempt to discredit radiometric dating.¹ Despite these efforts, compelling evidence remains that substantial amounts of radioactive decay have occurred in Earth's past. The simplest and most straightforward explanation for phenomena such as spontaneous fission tracks, the accumulation of radioactive decay products in rocks, and the overall trend of radiometric ages increasing with depth in the geologic column is that they are the result of nuclear decay. This evidence is so hard to dismiss that many young-earth creationists now concede that billions-of-years-worth of nuclear decay has occurred.

Two decades ago, a group of prominent YEC scientists initiated a research project called Radioisotopes and the Age of The Earth (RATE) to address this dilemma.

At the end of their eight-year study, these scientists concluded that one or more episodes of accelerated nuclear decay had occurred in Earth's recent past.² Don DeYoung eloquently articulates the RATE argument in his book, *Thousands ... Not Billions*:

One principle agreed on by all the RATE members is that the earth is young, on the order of 6,000 years old. This is not simply a working hypothesis to be tested as to whether it is true or false. Instead, it is a basic conclusion drawn from the biblical record of creation as written by the only One who was present, God himself ... A second guiding principle the RATE team realized from the start is that a large amount of nuclear decay has taken place in the past ... We assume that the earth was not created with an appearance of age at this microscopic level of detail. Alongside this principle,

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however, there is not the usual constraint that radioisotope decay has always been governed by today's measured nuclear half-life values. Instead, the RATE team concludes that there have been episodes of major acceleration of nuclear decay in the past.³

This explanation has been favorably embraced by many in the young-earth community,⁴ but not without criticism by some.⁵

Regardless of its popularity, in order for accelerated nuclear decay to be more than just a philosophical supposition invented to salvage a YEC religious belief, independent scientific evidence is required. Realizing this objection, the RATE team offered several lines of physical evidence: discordant radioisotope dates, radiohalos in granites, fission tracks, and helium retention in zircon crystals.⁶ Without going into detail here, many of these arguments are weak. For instance, most of the discordant radioisotope dates published by the RATE team disagreed by only 10–20%. It is hard to justify the six-order-of-magnitude increase in nuclear decay rates required by the RATE hypothesis from such a relatively small error. Regarding radiohalos, convincing evidence was made that a genetic relationship exists between uranium halos and polonium halos in many of the samples. The RATE team argued that this could be possible only if the polonium atoms were mobilized from uranium concentration sites by hydrothermal liquids in the cooling magma. Presumably, these hydrothermal liquids would only be able to create radiohalos over a narrow temperature and time window. However, an alternate explanation, which was not seriously considered, is that the mobile species is more likely radon in the uranium decay chain. Radon migration does not require the presence of hydrothermal liquids and can operate at low temperatures over long periods of time. The fission track argument is weaker still. No evidence for a young Earth was even given, only evidence for a substantial amount of nuclear decay. Above all, the common weakness in all three of these lines of evidence is that no alternate chronometer was proposed against which the age of the samples, and hence the rate of nuclear decay, could be measured. The one exception was the helium retention in zircon study, which used helium diffusion as an alternate chronometer.

In order to understand the helium retention in zircon argument, it is helpful to first consider some

basics of the diffusion mechanism itself and how it can be used as a chronometer. In a zircon crystal containing trace amounts of uranium and thorium, the α -particle decay of these radioactive nuclei will ultimately produce lead and helium as end products. One can use the amount of lead and uranium to calculate a radiometric age for the sample using conventional techniques. In principle, one could also use the amount of helium and uranium in the same way. In practice, using helium for radiometric dating is more problematic since helium, as a light noble gas, is more readily lost from the crystal. The process by which helium or other atoms move through a solid because of random thermal motion is called "diffusion." The question at hand is, how fast will a helium atom leave a zircon crystal? The speed of this diffusion process is quantified using a number called "diffusivity." Given a value for the diffusivity and other information, such as the dimensions of the crystal and the boundary conditions, the diffusion process can be modeled mathematically. If one can determine the amount of helium lost from a sample by comparing the concentrations of radiogenic lead and helium, this diffusion model can be solved for time, resulting in a model age for the sample.

In principle, then, the RATE helium retention in zircon argument is quite simple: calculate the radiometric age of the sample using conventional techniques and compare the results with the model helium diffusion age. According to the RATE researchers, a large discrepancy between the two ages was observed, with the "nuclear decay clock" indicating over a billion-years-worth of nuclear decay, and the "helium diffusion clock" indicating only about 6,000 years of diffusion. Taking the "helium diffusion clock" to be the more reliable measurement, the RATE team claimed that they had found physical evidence for both a young Earth and accelerated nuclear decay.

It is worth considering the assumptions behind this conclusion. The biggest one is that the "helium diffusion clock" is more reliable than the "nuclear decay clock." As DeYoung expressed earlier, questioning the constancy of nuclear decay rates was a fundamental premise of the RATE study, even though α -particle decay rates have been empirically determined to be constant over a wide range of environmental conditions. In contrast, solid-state diffusion rates are known to be affected by a multitude

of factors such as temperature, pressure, geometry, and crystal damage, just to name a few. The dependence on temperature is so strong that the system behaves more like a thermometer than a chronometer!⁷ In short, helium diffusion is not a good clock—there are far too many other factors which must be measured and controlled in order to get a reliable result. Several authors, including myself, have written about the numerous flaws in the RATE helium diffusion study.⁸ This article expounds upon what I believe to be the most serious one—a naïve misinterpretation of the low-temperature helium diffusion kinetics.

Figure 1, which shows a popular graph widely publicized by the RATE team, illustrates the concern. The solid circles depict the laboratory-measured diffusivities of helium through zircon crystals. The solid squares depict the diffusivities calculated from a diffusion model which assumes geologically long time, and the open squares without labels (that is, excluding the squares labeled “Hot” and “Cold”) show the corresponding young-earth diffusion model. Agreement between an extrapolation of the laboratory-measured data and the old-earth model is supposedly possible only when the model diffusivities are shifted to unrealistically low cryogenic temperatures (that is, open squares labeled “Cold”),⁹ which is clearly highly improbable. Note carefully, though, that this extrapolation is based upon the four lowest-temperature diffusivities. At higher temperatures, the curve bends steeply upwards. If an extrapolating line is drawn through these higher-temperature points, it would nicely intersect in the vicinity of the old-earth model, not the young-earth

model. In short, there is no discrepancy if the high-temperature diffusivity data are considered, or to put it another way, the young-earth argument rests entirely on just four low-temperature diffusion data points.

I spent several summers during my undergraduate years working on nuclear physics-related problems at the Hanford Nuclear Reservation in Washington State. After graduation, I transitioned into the semiconductor electronics industry, where I have been developing new technologies for the last twenty-five years. Solid-state diffusion is a bread-and-butter process in the manufacture of semiconductor devices, and I routinely run advanced diffusion simulation programs as part of my job function. Having worked in both the fields of nuclear physics and solid-state diffusion, I can say unequivocally that of the two phenomena, solid-state diffusion is much harder to model. The decades of research into solid-state diffusion invested by the semiconductor industry is a testament to this fact.

One cannot fully characterize complex solid-state diffusion phenomena using only a single experiment. It is surprising that the young-earth community makes such broad claims regarding the cosmic altering of fundamental physical processes on the basis of so little data. Perhaps their initial enthusiasm was excusable when the RATE team published their results back in 2005. However, since the publication of the RATE II book,¹⁰ no additional experimental work on helium diffusion in zircon has been performed by the young-earth scientific community. Meanwhile, the secular geochemical community has

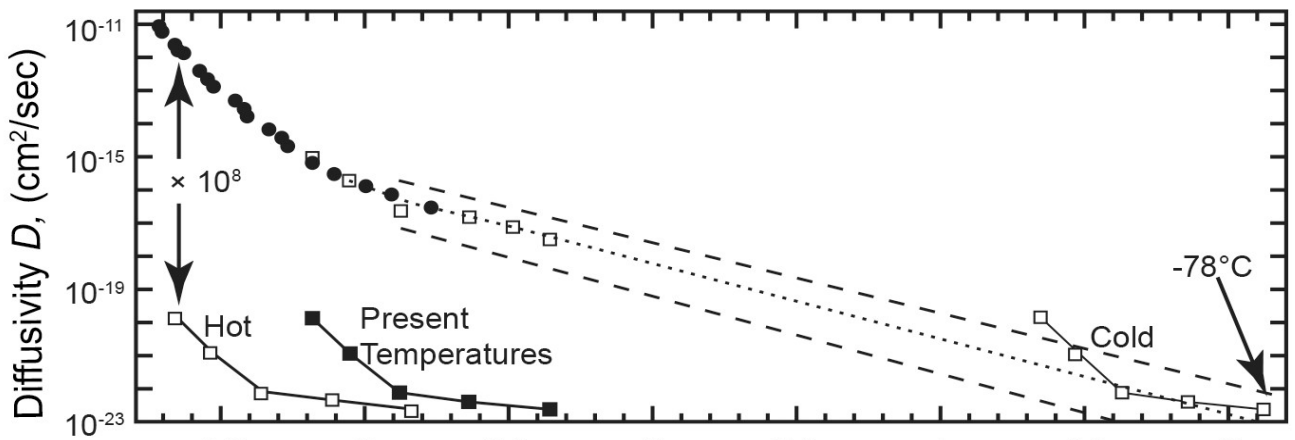


Figure 1. Arrhenius plot of helium diffusivity in zircon from the RATE study. Laboratory-measured data are filled circles. Model diffusivities from a young-earth model are open squares (not including the open squares labeled “Hot” and “Cold”). Model diffusivities from an old-earth model are filled squares. The dotted line is an extrapolation from the four lowest-temperature data points.¹¹

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been actively engaged in further research. This article summarizes essential findings of that scientific work and discusses its implications for the accelerated nuclear decay hypothesis.

Another Borehole

If an episode of accelerated nuclear decay has occurred at any time in Earth's recent past, one would expect the results of the RATE helium diffusion experiment at Fenton Hill, New Mexico, to be replicated at other sites around the world. In 2010, Wolfe and Stockli published results on helium diffusion from another borehole as part of the Continental Deep Drilling Program (KTB) of Germany.¹² One of the questions addressed by these researchers was, Can helium diffusivities measured in the laboratory be used to predict the retention of helium over geologic timescales in the field? In order to answer this question, they needed two independent chronometers, similar to the RATE study. For the nuclear decay age, they used the conventional helium/zircon radiometric (ZrHe) ages calculated from the measured helium content of the zircon samples. For the helium diffusion age, they used modeled ZrHe ages calculated using the laboratory-measured helium diffusivities and the known crystal geometry.

What does the accelerated nuclear decay hypothesis predict for the KTB borehole? According to secular geology, the basement rock experienced a major episode of faulting and uplift in the Late Cretaceous. In a young-earth Flood model, this event would be reinterpreted as a period of catastrophic uplift and cooling in the late Flood. According to the RATE hypothesis, accelerated nuclear decay occurred during the Flood, and roughly 70–90 million years (Ma) worth of radioactive decay, using current decay rates, would deposit helium in these rocks. Therefore, the measured ZrHe ages should be around 70–90 Ma and decreasing as one descends the borehole. As in the case of the Fenton Hill wells, deeper samples have a higher ambient temperature, and one would expect more helium loss and, hence, lower ZrHe ages. What is the prediction for the model ZrHe ages? Since zircon supposedly cannot retain helium for millions of years at any reasonable Earth temperature, one would expect an old-earth diffusion model to show severe helium loss at all depths. Consequently, the model ZrHe ages should be very small regardless of depth. This result would have created a major conundrum for the scientists. What did they observe?

Figure 2 summarizes the results of the Wolfe and Stockli study. The measured ZrHe ages are plotted as small squares, with averages for each depth plotted as large squares. Although there is some horizontal scatter in the data, the vertical trend is very clear. Near the surface of the borehole, roughly 85 Ma worth of helium was measured, assuming current decay rates. This quantity stayed constant until block C was reached. At a depth of just below 4000 m, the temperature rises sufficiently to cause some helium loss. By the time block D is reached at a depth of 7000 m, most of the helium is gone, and the measured ZrHe ages are close to zero. This trend matches the Fenton Hill samples, in which less helium was measured for the deeper and hotter samples.

To determine if the model ZrHe ages agree with the measured ZrHe ages, Wolfe and Stockli performed laboratory step-wise heating diffusion measurements on two zircon samples. The smooth curves with small solid circles and diamonds are the corresponding model ZrHe ages for samples ZKTB1516 and ZKTB4050, calculated using the zircon geometry and the measured helium diffusivity. In order to rule out the possibility of an error in their diffusivity measurements, they also calculated model ZrHe ages using helium diffusivities published by Reiners and others,¹³ represented by the cross-hatched region labeled "Bulk Diffusion Envelope" in figure 2. As can be seen, there is good agreement between measured and modeled ZrHe ages, especially for sample ZKTB4050. A discrepancy between the "nuclear decay clock" and the "helium diffusion clock" was not found at the KTB site.

A Possible Explanation

What happened at the KTB borehole? Why was there such good agreement between the "nuclear decay clock" and the "helium diffusion clock," when the accelerated nuclear decay hypothesis predicts that it should not be possible? Perhaps there was a mathematical error in the diffusion model. A point to note, though, is the remarkably good agreement achieved between measurement and model. The data define a characteristic curve. Upper samples in blocks A and B have been closed to helium loss since the uplift and cooling of the basement rock. Lower samples in block D are open to helium loss. In between, samples in block C define a classic partial retention zone, where helium loss is highly sensitive to small changes in ambient temperature. If Wolfe and Stockli

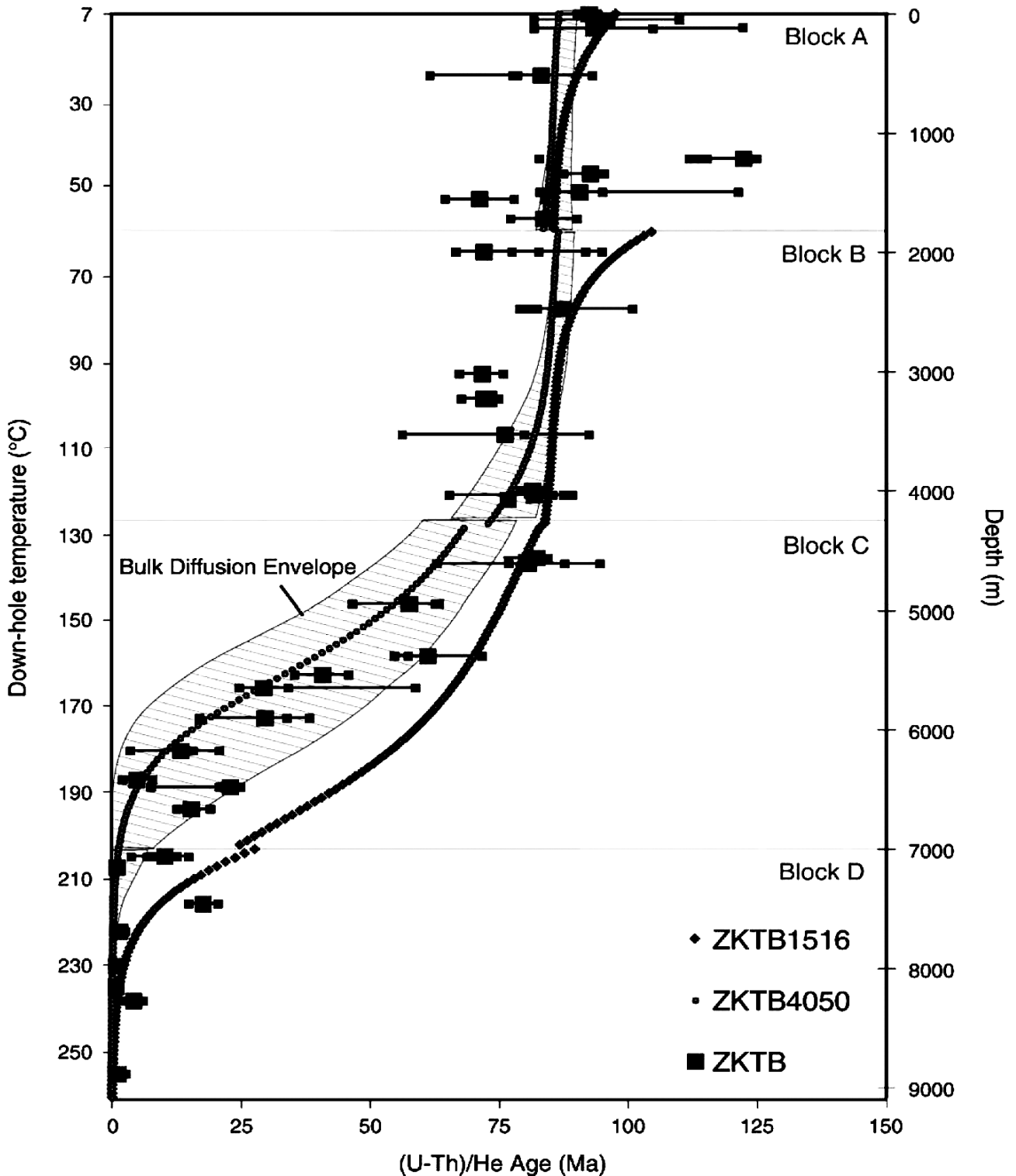


Figure 2. Comparison of measured helium/zircon radiometric (ZrHe) ages to helium diffusion model ages. The samples are from the Continental Deep Drilling Program (KTB) of Germany. Measured ZrHe ages are plotted as individual ages (small squares) and average ages (large squares) with the error bars representing the maximum age spread. The smooth curves with small solid circles and diamonds are the corresponding model ZrHe ages calculated using laboratory-measured helium diffusivities from two different samples, ZKTB1516 and ZKTB4050. The cross-hatched region labeled “Bulk Diffusion Envelope” covers the range of model ZrHe ages calculated using helium diffusivities published in the literature. Blocks A through D delineate different fault-bounded crustal blocks intersected by the drill hole. The overlap of measured and modeled ages demonstrates that there is a good correlation between the “nuclear decay clock” and the “helium diffusion clock.”¹⁴

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made a fundamental modeling mistake, they were very fortunate to have the results come out so close to measurement.

Was there perhaps an error in the measured ZrHe ages? This possibility is even less likely. Both the secular model and the accelerated nuclear decay hypothesis predict that about 85 Ma worth of radioactive decay should have occurred. The samples above 4000 m support this prediction. The eventual loss of helium with respect to increasing depth and temperature is exactly what would be expected.

A remaining possibility is that there is a difference in the measured helium diffusivities between the Wolfe and Stockli study and the RATE study. Since diffusion is the long-range effect of random atomic motion, it is highly sensitive to temperature. The higher the temperature, the faster atoms move. The faster atoms move, the greater the diffusion. Diffusivity is often graphically displayed on an Arrhenius plot, which is a plot of the logarithm of the diffusivity versus the inverse absolute temperature. The theoretical motivation behind the Arrhenius plot is that thermally activated processes such as diffusion often have the following temperature dependence,

$$D = D_o \exp\left(\frac{-E_a}{RT}\right) \quad (1)$$

where E_a is the activation energy of the process, D_o is the prefactor, T is the absolute temperature, and R is the universal gas constant.

Graphical elements of a curve on an Arrhenius plot have direct physical meaning. The slope of the curve gives the activation energy. Think of helium atoms as being bound in the zircon crystal at certain sites. In order for them to move, enough thermal energy must be supplied to break this bond. The activation energy represents the strength of this bond. The y-intercept of the curve gives the prefactor and represents the speed of the process at essentially infinite temperatures. Once the thermal energy is sufficient to break the bond holding the helium atoms, the limiting factor to the speed of the diffusion process is the prefactor. Figure 3 illustrates these relationships.

If the diffusivity data fall along a single straight line in an Arrhenius plot, it indicates that the process operates by a single mechanism. When multiple slopes appear on the plot, as is sometimes the case with helium diffusion in zircon, it indicates that more than one mechanism is present. Multiple diffusion mechanisms complicate both the modeling of the long-term retention of helium in a sample and the interpretation of the laboratory measurement itself.

Table 1 compares the helium diffusivity measured in the RATE study with that of the Wolfe and Stockli study. Included are additional measurements from Reiners and others, Cherniak and others, and Guenther and others.¹⁵ Since the RATE data had a two-slope behavior on an Arrhenius plot, separate lines in the table are given for the high-temperature

Table 1: Comparison of published helium diffusion activation energies (E_a) and prefactors (D_o) to the results from the RATE experiment. The diffusivity at 87°C extracted from the low-temperature RATE diffusion data differs by about five orders of magnitude from similar diffusivities extracted from data found in the literature.

E_a (kCal/mol)	D_o (cm ² /s)	D ($T = 180^\circ\text{C}$) (cm ² /s)	D ($T = 87^\circ\text{C}$) (cm ² /s)	Reference
13.9	1.7E-10	3.1E-17	5.7E-19	Humphreys (low-temperature data) ¹⁶
38.1	3.1E-01	1.3E-19	2.3E-24	Humphreys (high-temperature data) ¹⁷
40.4	4.6E-01	1.5E-20	1.4E-25	Reiners ¹⁸
34.9	2.3E-03	3.4E-20	1.5E-24	Cherniak, Watson, and Thomas (perpendicular direction) ¹⁹
35.4	1.7E-01	1.5E-18	5.8E-23	Cherniak, Watson, and Thomas (parallel direction) ²⁰
38.2	3.0E-02	1.1E-20	1.9E-25	Wolfe and Stockli ²¹
33.0	2.7E-02	3.2E-18	2.5E-22	Guenther et al. (Mud Tank, parallel) ²²
39.7	2.3E-02	1.6E-21	1.8E-26	Guenther et al. (RB140, parallel) ²³
38.9	2.7E-02	4.5E-21	6.4E-26	Guenther et al. (M127, parallel) ²⁴

and low-temperature data. The first two columns give the activation energies and diffusion prefactors extracted from the measurements. These parameters were used in the Arrhenius formula to calculate the diffusivities at 180°C and 87°C in the next two columns (see eq. 1). The last column gives the references.

There is a striking consistency in the diffusivities measured in all of these studies with the exception of the low-temperature RATE data. At a temperature of 87°C, there is a five-order of magnitude difference in diffusivity. Interestingly, a temperature of 87°C corresponds to the upper end of where the helium partial retention zone begins in the Wolfe and Stockli

study. Figure 1 illustrates this difference graphically. The extrapolation in this figure is through four low-temperature data points. The rest of the data lie upon a line with a much steeper slope, consistent with what other researchers have published. The conclusions of the RATE study rely heavily upon these four data points. It is crucial, therefore, to understand the diffusion kinetics of the helium-in-zircon system in this low-temperature regime.

Since these diffusion experiments all follow a procedure that was developed by Fechtig and Kalbitzer for the diffusion of argon in potassium-bearing solids, it is helpful to see how these authors handle the case

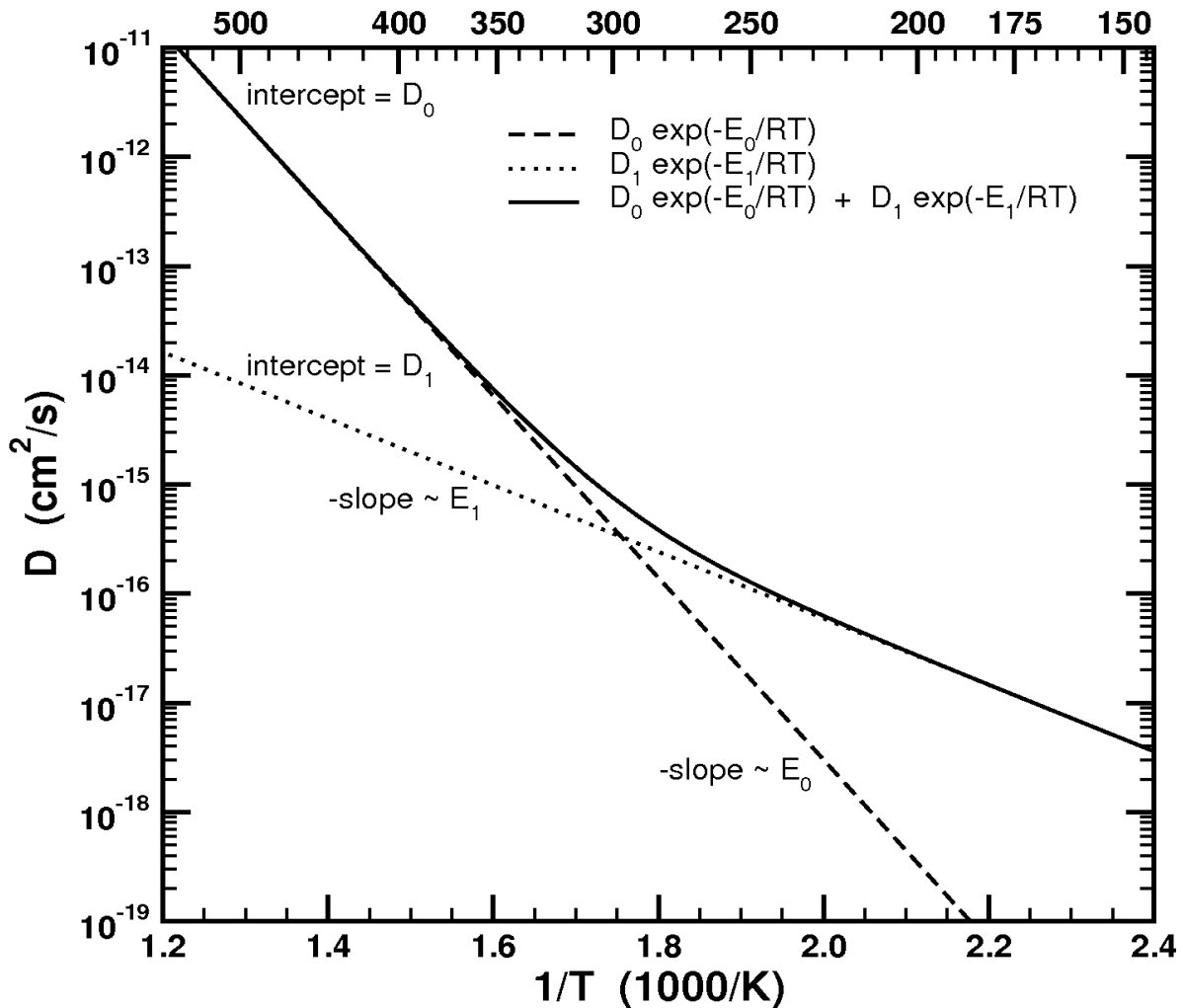


Figure 3. Examples of temperature-dependent diffusivities graphed on an Arrhenius plot. The expressions $D_0 \exp(-E_0/RT)$ and $D_1 \exp(-E_1/RT)$ plot as straight lines, with the negative slopes being proportional to the activation energies E_0 and E_1 , and the y-intercepts equal to the prefactors D_0 and D_1 . The sum of these two expressions plots as a curve in which the diffusion mechanism with the highest prefactor D_0 dominates at high temperatures and the diffusion mechanism with the lowest activation energy E_1 dominates at low temperatures. Values for E_0 and D_0 come from the Humphreys high-temperature data and values for E_1 and D_1 come from the Humphreys low-temperature data in Table 1.

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of a diffusivity curve that does not follow a simple Arrhenius trend. They use the archaic term “non-volumic diffusion” to describe the phenomenon:

Sometimes fractions of weakly bound argon are found in diffusion experiments. At lower temperatures a flat curve in the Arrhenius plot is observed, characterized by rather low activation energies ... In crystals, where the potassium is a regular constituent, the existence of loosely bound argon may be explained by higher structural defects (such as dislocations, grain boundaries, etc.), in which case the argon will diffuse out easily.²⁵

In general, they advise extrapolating the high-temperature data to lower temperatures rather than using the low-temperature data directly.²⁶ A good summary is given in their conclusions:

Although the situation is quite complex one can say that at least for minerals which have K homogeneously distributed throughout the mineral practically all the argon can escape only by volume diffusion, if we do not take into account any metamorphism. For such minerals it is, therefore, allowed to extrapolate the straight line which represents the volume diffusion [i.e. high temperatures] down to the temperatures investigators are most interested in [i.e. low temperature].²⁷

The situation can be complex. I previously presented a similar argument during an online debate program.²⁸ Humphreys, the lead RATE scientist on the helium diffusion study, challenged my interpretation of Fechtig and Kalbitzer in his later reply.²⁹ His primary argument regarding experiments on the K-halide system was the following quote:

These results on this “simple” system clearly show that the diffusion of argon at low temperatures should not be calculated from high-temperature measurements, but that measurements have to be performed in the temperature interval of interest.³⁰

Humphreys claims that this advice is a general principle which would reasonably apply to most situations. On the contrary, Fechtig and Kalbitzer never made such broad-reaching claims. The particular quote in question pertains to diffusion experiments on the K-halide system, which is highly unusual in that its high-temperature activation energy is lower than its low-temperature activation energy. This behavior is the exact opposite of the “non-volumic diffusion” effect described above. Such an unusual situation does not apply to the helium diffusion in zircon cases considered in this article.³¹

What is the rationale for the procedure of extrapolating the high-temperature diffusion data to lower temperatures when the low-temperature data deviate from an Arrhenius trend? Basically, laboratory experiments cannot measure diffusivity directly. Instead, only the gas release at a given temperature step can be measured. The challenge is to relate the measured amount of gas release back to the diffusivity. This connection is done by means of a model. If the assumptions of the model hold, then the diffusivity that is calculated is meaningful. If the assumptions of the model do not hold, then the diffusivity that is calculated does not relate to a real physical quantity. One of the assumptions of the Fechtig and Kalbitzer model is that all the gas comes from a single gas reservoir defined by a single activation energy. What happens if the gas comes from multiple reservoirs with different activation energies, as in the RATE diffusion experiment? In that case, the measured gas release at any given temperature step is some unknown combination of the two sources, and the diffusivity that is calculated is some weighted average of the individual diffusivities with unknown coefficients. This is the situation at low temperature when there are multiple diffusion mechanisms involved, and the problem is intractable.

At higher temperatures, however, the problem becomes tractable again. Once the temperature becomes high enough to mobilize all the helium atoms in the sample, the activation energy is no longer a limiting factor. Instead, at sufficiently high temperatures, the rate of diffusion is mostly determined by the prefactor, and the dominant mechanism with the highest prefactor will always win. What was intractable at low temperatures becomes manageable at high temperatures (see fig. 3).

As a side note, the RATE team outsourced their helium diffusion experiment to a well-respected researcher at a secular university. In the RATE publications, they mention, on multiple occasions, how they insisted that this researcher take more measurements at lower temperatures. In contrast, in the publications of this researcher and his students, they never go to the same low-temperature regime in their own experiments. Note the practical consequences of Fechtig and Kalbitzer’s advice. If low-temperature diffusion data are problematic, then it is not worth wasting valuable experimental resources taking data there.

Some Implications

Before considering the implications of the low-temperature diffusion mechanism on the helium retention ability of zircon samples in the field, a couple of points need to be emphasized in order to avoid potential misconceptions. First, strictly speaking, none of the laboratory experiments cited in the previous section actually measured the helium diffusivity. Diffusivity is not a directly accessible material parameter. One does not have a “diffusometer” that can be placed in a sample like a thermometer. Instead, the directly accessible measurable quantity is the amount of gas released at a given temperature over a given time. Inferring a diffusivity from this gas release requires a model built upon underlying assumptions. If the assumptions of that model are not met, then the number that is calculated is not representative of the actual diffusion kinetics, regardless of how accurately the experiment was performed. This point should not be overlooked.

Second, any inference regarding the ability of a rock or mineral sample to retain helium over time scales on the order of the age of Earth requires the extrapolation of these laboratory measurements over time and temperature, often by orders of magnitude. Consider a simple example. If one wants to definitely know by direct observation if a mineral sample can

retain a certain amount of helium for 6,000 years, the experimenter would have to put that sample in a laboratory instrument and wait that long. Clearly this is not practical. At best, a typical step-wise heating diffusion experiment will run over the course of many hours or perhaps even a few days in some instances. The challenge is how to best use data that were acquired over a relatively short period of time in the laboratory to predict the behavior that is expected over a longer period of time in the field. For this reason, a solid theoretical understanding of the underlying diffusion mechanism is invaluable.

Guenther and others performed one of the most thorough and rigorous studies of helium diffusion in zircon that has been published in the literature.³² Some of their samples showed low-temperature diffusion behavior similar to what was observed in the RATE experiment (fig. 4). They attributed the diffusion mechanism in this low-temperature regime to “grain-boundary-like sites.” Here is what they mean. Empirically, they observed in their diffusion experiments that the majority of the helium released from a sample was due to a diffusion mechanism with a high-activation energy, and only a small fraction of the remaining helium in the sample was released due to a diffusion mechanism with a low-activation energy. A high-activation energy indicates a tight

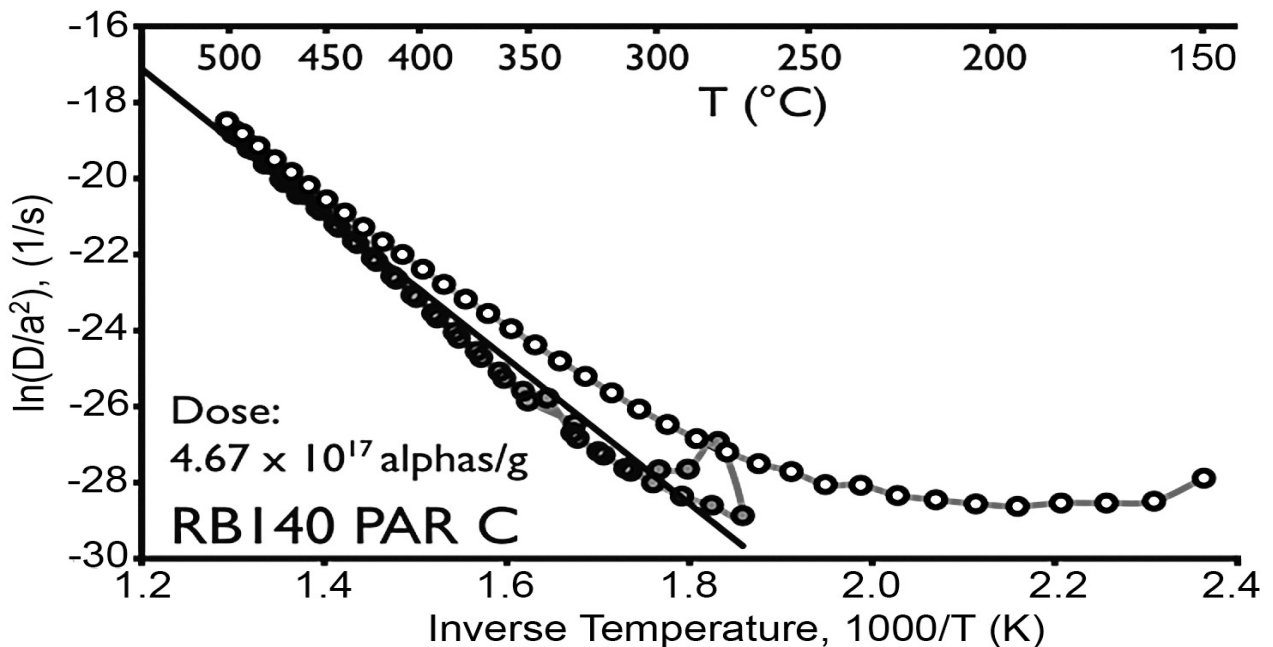


Figure 4. Arrhenius plot of helium diffusivity in zircon. Data measured during the initial rising temperature ramp are designated using open circles. Data measured after the maximum-temperature step are designated using grey-filled circles. Note the persistence of nonlinearity in the low-temperature diffusivity even after the initial temperature ramp. This behavior is similar to what was observed in the RATE experiment (compare with fig. 1). Guenther and others attributed this low-temperature diffusion behavior to a small fraction of helium loosely bound to “grain-boundary-like sites” that were partially refilled with helium during the previous high-temperature steps.³³

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binding between the helium atoms and the crystal, whereas a low activation energy indicates a loose binding. Although Guenther and others could not identify the exact nature of these loose-binding sites, they drew an analogy to polycrystalline systems in which there are crystalline grains separated from each other by grain boundaries. Even though this is probably not a perfect analogy, it illustrates an important point. The majority of the helium atoms are locked up in the crystal lattice "grains" and only the small minority that are wandering in the "grain-boundary-like sites" can diffuse at lower temperatures.

The findings of Guenther and others open up new insights into the possible diffusion mechanism for helium in zircon at low temperatures in a step-wise heating experiment. The high diffusivity observed at lower temperatures could be from a small fraction of helium loosely bound to grain-boundary-like domains.³⁴ Although most of this loosely bound helium would be released from the sample during the initial heating ramp of the experiment, the release of helium from the tightly bound lattice sites at high temperatures partially refilled these loosely bound sites. Later in the experiment, helium in these loosely bound sites continued to be released, resulting in the high diffusivity that was observed. Contrary to the assumptions of the RATE researchers, this diffusion mechanism cannot account for any substantial amount of helium loss for samples held at these lower temperatures. The accelerated nuclear decay hypothesis cannot be supported in light of this preponderance of experimental work performed by Wolfe and Stockli, Reiners, Cherniak, Guenther, and many others.

Reflections

Consider the RATE helium diffusion experiment. Take a rock sample from deep underground. Crush that rock and remove tiny zircon crystals. Place those bare crystals, which were previously surrounded by other minerals under high pressure, in a vacuum system. Heat the crystals up to high temperature and cool them down. Repeat this process a second time, measuring the amount of helium that is released at each temperature step along the way. After excluding the initial temperature ramp, the high-temperature steps above 350°C accounted for over 22% of the total helium in the system, whereas the

four low-temperature steps below 275°C accounted for only 0.0008% of the total helium in the system, or about eight parts per million.³⁵ What do these eight parts per million of helium release tell us about the age of Earth? Very little, in fact.

The RATE authors considered these eight parts per million of helium release to be strong evidence for accelerated nuclear decay. Why? Because time on their "nuclear decay clock" disagreed with time on their "helium diffusion clock." Supposedly, nuclear decay rates had been drastically altered by an act of divine intervention. In making this supposition, they tacitly assumed that helium diffusion is a more reliable chronometer than nuclear decay. But is it? The α -decay of uranium is governed by the strong nuclear force and is insensitive to environmental influences such as temperature and pressure. The diffusion of helium in zircon is governed by long-range electromagnetic forces and is highly sensitive to environmental influences which include not only temperature and pressure, but other factors as well, such as crystal structure, surface boundary conditions, and the type and density of radiation damage and extended defects. In the final analysis, the RATE helium diffusion study tells us more about the properties of the zircon crystal than the age of Earth.

Epilogue

A manuscript similar to the one above was previously submitted to the *Journal of Creation*. Unfortunately, it was rejected. Knowing that the position of the paper would not be popular, I strongly encouraged the editors to conduct a fair and impartial review. In my opinion, their review of my manuscript was neither fair nor impartial. The young-earth creationist community will not gain any respect outside of their narrow circle if they refuse to engage in civil discourse with their fellow brothers and sisters in Christ who hold different views.

Acknowledgments

I would like to thank Steve McRae for his support and encouragement of this work. Kevin R. Henke and Jon Fleming assisted with the bibliography. Jon Fleming assisted with the figures as well. The review of my manuscript by them and many others is also appreciated. Finally, my deepest gratitude goes to those who have strengthened me through their prayers.

APPENDIX A: ADDING DIFFUSIVITIES

One of the central themes of this article is that, when attempting to model solid-state diffusion, it is vitally important to understand the diffusion kinetics of the material system of interest. I have faced this challenge many times over my last twenty-five years of experience in the semiconductor electronics industry. Because of its commercial value, diffusion in the silicon system has been studied better than just about any other material, and silicon diffusion models can become very complex, especially in a low-temperature regime where there are interactions with extended crystal defects.

Therefore, it was with a bit of surprise that I saw the following equation in the RATE literature:³⁶

$$D = D_0 \exp\left(\frac{-E_0}{RT}\right) + D_1 \exp\left(\frac{-E_1}{RT}\right) \quad (\text{A1})$$

This simplistic equation represents the combined diffusion of a species (helium in this case) for a material with both an intrinsic and defect diffusion mechanism (zircon in this case). The first term (with leading D_0) represents diffusion from the intrinsic mechanism and the second term (with leading D_1) represents diffusion from the defect mechanism. The problem with this naïve equation is that one typically cannot add diffusivities from two separate mechanisms any more than one can add velocities from cars traveling on two parallel highways. The diffusing species will be in either one state or the other, just as a traveling car will be on either one highway or the other, not both at the same time. This insight is the motivation behind multidomain diffusion models.³⁷ In multidomain diffusion models, the diffusing species is partitioned into separate domains. Each domain has a separate diffusion model with a unique concentration, diffusivity, and particle flux. After modeling the diffusion in each domain, the results are combined. In multidomain models, concentrations and particle fluxes can be added, but diffusivities, in general, cannot.

In a recent online debate program, I challenged Humphreys to defend his use of equation (A1) with either a derivation or reference.³⁸ Humphreys obliged by providing a derivation,³⁹ a critique of which is given here. If equation (A1) is graphed on an Arrhenius plot, a two-sloped curve results, with the intrinsic term creating a high-sloped line at high temperatures and the defect term creating a low-

sloped line at low temperatures. A corner or knee forms at intermediate temperatures where these two lines intersect (see fig. 3).

Humphreys attempted a derivation of equation (A1). After several algebraic steps, he arrived at the following expression for the natural logarithm of the diffusivity:

$$\ln D = \left(\ln D_0 - \frac{E_0}{RT}\right) + \left(\ln D_1 - \frac{E_1}{RT}\right) \quad (\text{A2})$$

This equation supposedly represents the two-sloped curve described by equation (A1) and plotted in figure 3. The problem is that equation (A2) is not the natural logarithm of equation (A1), and it does not describe a two-sloped curve on an Arrhenius plot. A simple way to see this mathematical error is by regrouping the terms in equation (A2) as follows:

$$\ln D = (\ln D_0 + \ln D_1) - \frac{(E_0 + E_1)}{RT} = b - a\left(\frac{1}{T}\right) \quad (\text{A3})$$

This equation describes a simple straight line on an Arrhenius plot, not a two-slope curve with a high-slope intrinsic line and a low-slope defect line. Not only did Humphreys fail to give a rigorous physical derivation of equation (A1), he also failed to do the algebra correctly.

APPENDIX B: UNPUBLISHED EXPERIMENTAL DATA?

An important point made in this article is that scientific theories should be established by multiple experiments whenever possible. As was discussed earlier, the Wolfe and Stockli study does not support the accelerated nuclear decay hypothesis.⁴⁰ Table 1 demonstrates that the low-temperature diffusivity data from the RATE study are inconsistent with published results from multiple researchers. Since the RATE conclusions rest heavily upon only four low-temperature data points from a single diffusion experiment, it is worth taking inventory of the experimental work performed by the RATE team.

The first helium diffusion data published by the RATE team was in a 2003 paper in the Fifth International Conference on Creationism (ICC).⁴¹ Although the results were tantalizing, these data were considered to be inconclusive because they did not extend to low enough temperatures. The following year, results from another experiment were

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published in the *Creation Research Society Quarterly* (CRSQ).⁴² Since the low-temperature diffusion data overlapped predictions from their young-earth model, the RATE team claimed that they had found definitive evidence for accelerated nuclear decay. No follow-up experiments to confirm their findings have been performed.

However, it is possible that additional unpublished experiments were performed. The 2004 CRSQ paper reviews the history.

Then we sent both the biotite and the zircons to our experimenter. He sieved the biotite sample to get flakes between 75 and 100 μm , but he used all the zircons Kapusta extracted, regardless of size. Size of crystals (effective radius) is important in converting the raw data into diffusivities. He sent us the raw data [which was later published in 2003 ICC] in 2002 ...

After that, in the summer and fall of 2002, we tried several times to get lower-temperature data. However, we only discovered several wrong ways to make such measurements. First, we asked the experimenter to do new runs on the same batch of zircons, but at lower temperatures. The results were ambiguous, an effect we decided was due to exhaustion of helium from the smaller zircons in the batch (Fechtig and Kalbitzer, 1966, § 2.5, p. 72).

Second, we sent the experimenter a new set of zircons from the same depth in GT-2 and asked him to sieve out crystals in the 50–75 μm size range. Before sieving, he decided to leach the crystals in cold concentrated hydrofluoric acid (HF) to remove flecks of biotite clinging to them. Though the technique was new, it seemed reasonable. However, the values of D/a^2 he then obtained were over fifty times higher than all previous zircon data, both ours and published. Scanning electron microscope images done later (see next section) revealed severe pitting and cracking in the HF-treated zircons. That would allow helium to leave the zircons much faster than normally.

These were all the data we had by February 2003, the deadline for the final version of our conference paper (Humphreys et al., 2003a).⁴³

The diffusion data for the 2004 CRSQ paper did not arrive until July 2003, well past the deadline for the 2003 conference. This history is fascinating for several reasons. First, it suggests that more than two helium diffusion experiments were performed by the RATE team. Second, apparently only data from

the first experiment were published in the 2003 ICC paper,⁴⁴ even though all the data except for the last run were available prior to the conference deadline. Third, data from these intermediate experiments were not published in either the 2004 CRSQ paper or the 2005 RATE II book.⁴⁵ Finally, the argument for not using at least some of the data from these intermediate experiments was that the results were “ambiguous.” It is not clear what the authors meant by this term, but because they attributed the effect to “exhaustion of helium from the smaller zircons in the batch,” it may indicate that the diffusivity came out lower than expected. Perhaps this ambiguity is an indication that the RATE helium diffusion results are not reproducible?

In order to gain a better understanding, I requested the data for these intermediate diffusion experiments from Humphreys through Steve McRae, who was facilitating our dialogue for his Great Debate program. Below is Humphreys’s uncooperative response.

Sorry that I’ve given this such a low priority. I’m reluctant to spend several hours watching the Hanke [sic, Henke]/Loechelt videos, because I have a strong feeling that they have said nothing new or worthwhile. For example, I think I’ve published (in the RATE II book) all the diffusion data that Dr. Loechelt is asking for, along with all the relevant parts of the lab reports we received. See particularly the appendices to my chapter in the book. Thus it seems to me that Dr. Loechelt is grasping at non-existent straws, which implies to me that he’s got nothing substantial. That in turn un-motivates me for spending more time on him.⁴⁶

So according to Humphreys, all the diffusion data were published in the RATE II book. Yet, according to the 2004 CRSQ paper, additional experiments were performed. This mystery remains unresolved.

∞

Notes

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²¹Wolfe and Stockli, "Zircon (U-Th)/He Thermochronometry in the KTB Drill Hole, Germany."

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²⁶Ibid. Examples of extrapolating the straight line which represents the volume (high-temperature) diffusion down to lower temperatures are given on pp. 82–83, 91, and 96–97.

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²⁸Steve McRae, "Dr. Kevin Henke and Dr. Gary Loechelt on Creationist Claims about He Diffusion Rates (LIVE) – Part II," Great Debate Community video, 2:18:14, January 19, 2018, accessed October 20, 2019, <https://greatdebatecommunity.com/2018/01/19/dr-kevin-henke-and-dr-gary-loechelt-on-creationist-claims-about-he-diffusion-rates-live-part-ii-2>.

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³⁰Humphreys, "Young Helium Diffusion Age of Zircons Supports Accelerated Nuclear Decay," 84.

³¹Compare figure 12 of Fechtig and Kalbitzer, "The Diffusion of Argon in Potassium-Bearing Solids," with the figures of this article.

³²Guenther et al., "Helium Diffusion in Natural Zircon: Radiation Damage, Anisotropy, and the Interpretation of Zircon (U-Th)/He Thermochronology."

³³Figure reproduced from Fechtig and Kalbitzer, "The Diffusion of Argon in Potassium-Bearing Solids," fig. 3, sample RB140 PAR C with permission of the *American Journal of Science* by J. D. & E. S. Dana, in the format Journal/magazine via Copyright Clearance Center.

³⁴Essentially equivalent is the concept of "non-volumic diffusion" used by Fechtig and Kalbitzer in "The Diffusion of Argon in Potassium-Bearing Solids" (p. 74) to explain similar nonlinear Arrhenius behavior observed in the potassium/argon system.

³⁵Calculated from Table II of Humphreys et al., "Helium Diffusion Age of 6,000 Years Supports Accelerated Nuclear Decay," 6. Also in Table 2 of Humphreys, "Young Helium Diffusion Age of Zircons Supports Accelerated Nuclear Decay," 45. From the high-temperature steps (10–13 and 21–27), 306 ncc of helium was released (22.58%). From the low-temperature steps (16–19), 0.0106 ncc of helium was released (0.0008%). From the initial temperature ramp (1–9), 56.5 ncc of helium was released (4.16%). From the remaining intermediate temperature steps (14–15 and 20), 0.118 ncc of helium was released (0.0087%). After the initial temperature ramp, the vast majority of helium was released from the high-temperature steps. Total helium yield, including final fusion step, was 1356 ncc.

³⁶Equation (3) of the RATE II book (Humphreys, "Young Helium Diffusion Age of Zircons Supports Accelerated Nuclear Decay," 34). Note sign error later corrected in Humphreys, "Answer to a Persistent Critic of RATE Helium Research."

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³⁹Humphreys, "Answer to a Persistent Critic of RATE Helium Research."

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⁴¹Humphreys et al., "Helium Diffusion Rates Support Accelerated Nuclear Decay."

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⁴⁶D. R. Humphreys, private communication, May 24, 2018.

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