# The Re-Construction of The Great Pyramid at Giza

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**1. INTRODUCTION.** Unfortunately, it is a mystery as to how exactly the Great Pyramid at Giza was constructed; also mystifying is its completion time. Pyramidologists have spoken to many of the ancient Egyptian builders' descendants, but cannot rely solely on oral accounts that may have become skewed over the generations. Several individuals, who take interest in pyramid construction, have attempted to re-create the ancient Egyptians' processes in order to come to the conclusion of construction time using the most efficient methods. Specifically, in 1997, Peter Prevos, an engineer from Australia, composed a step-by-step study on the construction of the Great Pyramid at Giza. He did this from the perspective of a civil engineer. Prevos drew most of his hypotheses from Peter Hodges' book, *How The Pyramids Were Built*, a builder's perspective on pyramid construction. Although Prevos' essay is fairly consistent, Ernest Moyer criticized some of its aspects. Most of these criticisms can be justified in favor of Prevos, however Moyer does manage to make one good point. I was also able to find a couple of blemishes in Prevos' methods, however I feel that his study is one of the most accurate reconstructions that one can find. In the following essay, we will take a look at how the Great Pyramid at Giza may have been constructed, meanwhile dissecting the points that seem to be flawed using Ernest Moyer's observations along with my own.

**2. BACKGROUND AND ORIGINAL SPECIFICATIONS.** The Great Pyramid was built for the Egyptian King Khufu during Egypt's Old Kingdom, Dynasty IV (2680-2560 B.C.E.) and is part of a group of three pyramids [**5**, p. 252]. Khufu's pyramid was completed around 2560 B.C.E. [**4**, p. 37]. Occasionally, the Great Pyramid is referred to as "Khufu", as a common trend is to refer to a pyramid by its honored king, and not by who built it. Presently, there exist a little over 70 surviving large pyramids, but the largest and perhaps the most recognizable of all is the Great Pyramid at Giza, which also represents the only surviving Wonder of the Ancient World [**1**, p. 22], [**3**, p. 5].

Merriam-Webster defines a pyramid as, "A polyhedron having for its base a polygon and for faces triangles with a common vertex" [**8**]. In the Great Pyramid's case, the base polygon is a square with sides originally measuring 230.362 meters and currently measuring 227 meters, due to the weathering that took place over the millennia. The common vertex formed by the four triangles is called the pyramid's apex. The height from the base to the apex was originally 146.16 meters, as marked by an iron post erected on the summit, but is now about 137 meters tall [**6**], [**5**, p. 115].

There were approximately 2,500,000 total blocks that made up the pyramid. This number varies a lot because of the pyramid's erosion through the years and the removal of the casing stones, which will be discussed later on. On average, the stones weigh about 3 tons each, although some may have weighed about 15 tons [**4**, p. 37]. Their average volume is one cubic meter [**6**].

There were approximately 209 layers, or courses, to the Great Pyramid [**3**, p. 95]. Many pyramid researchers noticed that as the levels increase (from the ground up), the blocks tend to get smaller, so the larger stones tend to be towards the bottom [**7**, p. 74]. Therefore, it is easy to infer that the height of the lower courses tends to be greater than the upper courses.

**3. PREVOS' RECONSTRUCTION SPECIFICATIONS, LABOR TIME AND EQUIPMENT USED.** Prevos chose parameters that are very close to those of the original pyramid. For the height at the apex, he chose 146 meters. For the side length, he chose 230 meters. In order to simplify some math, he chose for the pyramid to be composed of 200 courses. The block, or element, size is .73 meters high by 1.17 meters wide by 1.17 meters long, giving a volume of .999 cubic meters—so very close to the Great Pyramid's average. Prevos specifies that the step size for the pyramid, i.e. where the ancient Egyptians would have stepped to walk up the pyramid, is .575 meters. The re-constructed pyramid will be completely solid as the chambers and passages are calculated to take up only approximately .07% of the volume of the entire pyramid [**6**].

The Great Pyramid is composed mostly of Egyptian-quarried limestone. The large granite slabs will not be taken into account, as they are only found in the king's chambers and some passages leading to the chambers. The density of limestone varies between 2.5 and 2.7 tons per cubic meter. Prevos chooses the mean of the densities, 2.6 tons per cubic meter, and with this we can calculate the weight of each stone element. Using high school physics, D * V = M, we come up with:

2,600 tons/$m^3$ * .73 m * 1.17 m * 1.17 m = ~2.6 tons. This is very close to the average given by several pyramidologists [**6**].

Regarding the time parameters, Prevos seems to do a good job in assuming how long and when the ancient Egyptians worked. For this reconstruction, the builders, masons and quarrymen will work 350 days per year. This way, they can celebrate the holidays and other religious events that mattered to them. They also had a 12-hour workday, as the "Average daylight per day, measured over a year, is 12 hours." The ancient Egyptians had no way of employing artificial light—a modern amenity; therefore they worked from sunrise to sunset. I feel that some of the work could have been done by firelight, or torches, so that construction time could be minimized. For example, transportation of the elements from the quarry site to the construction site could have been done by firelight. Finally, with regards to time, we will utilize an efficiency factor of 70%. This is used because not everything will go as planned. Workers will get sick, they will take lunch breaks and bathroom breaks, and no one is ever *always* able to give their all, or 100%, at the work place [**6**].

Prevos prefers the use of levers for vertical and even horizontal transport while constructing the courses of the pyramid. He refers to vertical transport as "jacking-up" and elects Hodges' "paddling" method for horizontal transport. Prevos uses levers made completely out of wood, which make more sense than the levers with metal feet that Hodges proposed. I feel that he used the wooden levers without the feet because the only known metal used by the ancient Egyptians was copper—a very soft metal [**7**, p. 23]. This would obviously not hold up against a 2.6+ ton limestone mass. The length of the levers is 2 meters, the size of the fulcrum is 10 centimeters by 10 centimeters and, the wood was tapered so that the men "jacking-up" the stones would have an easier grip. "When assuming that the leverage point is at 0.1 meters from the end, and the maximum downward force to be applied by one person is 600 N the upward force on the other end is 1.9 * 600 / 0.1 = 11,400 N. The actual bending stress in the lever will be 6.84 N/mm$^2$ which is allowable for most timber. Three levers would be sufficient to lift a 2.6 [ton] element, but for reasons of stability four levers have to be used." [**6**].

Apparently, Ernest Moyer does not agree with the lever usage, with respect to the amount of people it would take to lift a 2.6-ton element. He states that 600 Newtons is equivalent to about 135 lbs, or 60 kilograms, of force [**9**]. Moyer then questions how a 5’5”, 150 lbs, ancient Egyptian could manage to exert such a high force. He sets up his own scenario with the builders lifting 60 lbs of force, or about 267 Newtons [**10**]. The 60 lbs is conservative even to Hodges’ own experiments where he believes that a man should be able to apply 80 lbs of pressure [**7**, p. 5]. However, Hodges does make a point in saying that “…the effort is only required in short bursts, and in rhythm” [**7**, p.139]. Moyer’s guess seems a lot more feasible, but we will not concern ourselves with Moyer’s observations, as most of them are pretty far-fetched. We will see later on that four men are still used to “jack-up” the 2.6-ton stones.

**4. PREPARATION OF THE CONSTRUCTION SITE.** Now that we have our basics, we can start with the complex analyses of the steps before, during, and after the actual pyramid construction. Firstly, we will take a look at how Prevos proposes the clearing of the area on which the Great Pyramid will be built. One man will take two hours to clear one square meter. Therefore, if we have 230 men clearing one square meter each, it will take those 230 men * 2 hours = 460 hours to clear the whole foundation. With the efficiency factor and time constraints taken into consideration, it should take approximately 9 weeks for completion [**6**].

I find it very hard to believe that in only 9 weeks the entire site would be leveled and ready for construction. It seems that many other details must be taken into account when leveling, other than simply “clearing and cutting” [**6**]. According to David

Macaulay, the ancient Egyptians must have created levels using water-filled trenches. They would first mark off, with metal stakes, the area on which the pyramid was to be built. Then the masons would chisel narrow trenches, fill them with water, and then mark off where the water calmed. Finally, they would use these marks as the level points for the rest of the chiseling away of the area [**2**, p. 25].

Another time-increaser would be the accurate orientation of the pyramid. We all know from history classes that the ancient Egyptians had a deep knowledge and understanding of the skies and celestial tendencies. This would aid them in getting the pyramid's four sides to face each cardinal direction almost perfectly. The way the "orienters", mostly priests, found true north was by first constructing a circular wall as close to the center of the site as possible. The walls were high enough so that only the sky was visible to the person standing inside. The level blocks at the top of the stone wall formed a perfect horizon line. "In the evening a priest stood in the center of the circle and watched for the appearance of a star in the east. Its position was marked as it rose above the wall and a line was drawn from that point on the wall to the center of the circle. He watched the star as it moved in an arc through the sky and finally set in the west. As it dropped behind the wall its position was marked again and another line was drawn to the center of the circle. Because stars appear to rotate around the north [star], the priests knew that a third line drawn from the center of the circle through the center of the space between the first two lines would point directly north" (See Figure 1) [**2**, p. 22].

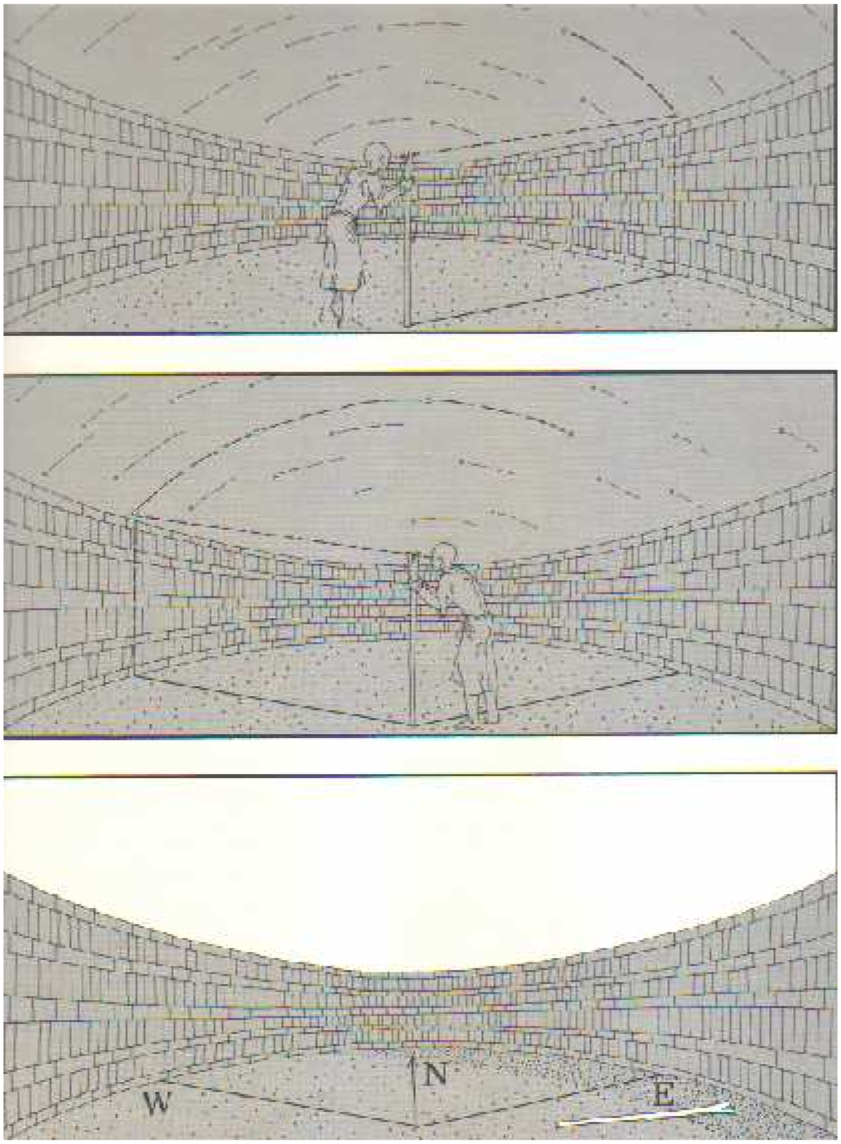

Figure 1 [**2**].

I do not know exactly how much of an increase these leveling and the orientation would add to Prevos' estimation of 9 weeks. However, I do feel that these need to be taken into consideration when so much more needs to be done to the site then simply "clearing and cutting".

**5. CONSTRUCTION OF THE CORE.** As soon as the area is cleared and leveled, we can begin the re-creation of the core of the Great Pyramid at Giza. The builders will be using levers, as mentioned above, for both the vertical and horizontal transport. Prevos chooses the wooden lever method although many pyramidologists, like Ernest Moyer, believe that "jacking-up" with levers using his parameters was and still remains impossible.

Two sides of the pyramid will be utilized for the vertical transport. Prevos acceptably justifies this in saying that the use of one side would not be very time efficient. With the use of three sides of the pyramid, the workers that place the elements would get in each others' ways. Finally, if all four sides are utilized, there would be no effective way to get the builders back down the pyramid so that they could start over. Therefore, we will see that the same teams that move the elements vertically will then be in charge of moving them into their horizontal position. They will then go back down the unused pyramid sides, and start up again with the vertical transport of a new element [**6**].

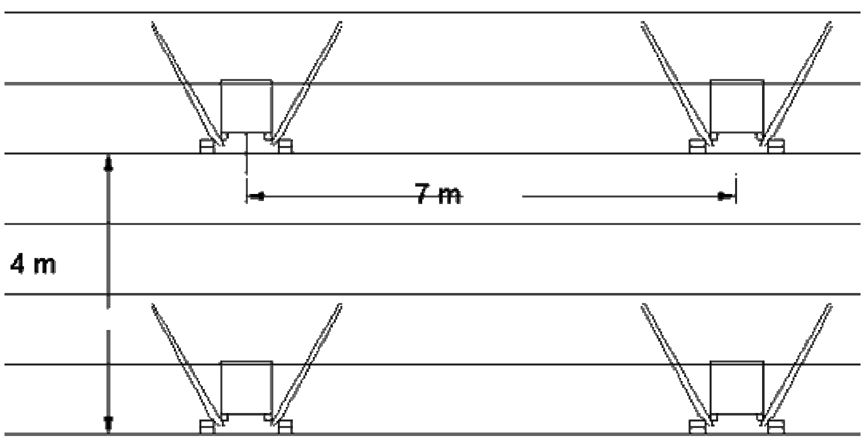

Figure 2 [**6**].

In order to have a constant flow of materials to the pyramid, the vertical spacing between jack-up teams is 4 meters. Similarly, the horizontal spacing between the jack-up teams is 7 meters (See Figure 2). Each jack-up team will consist of seven men. As mentioned before, there will be one man per lever (four levers per stone), two men to pack the timber under each vertical lift, and one overseer. Hodges calculated, with his levering trials, that it takes approximately 25 seconds to complete one vertical lift—including packing the timber.  Each lift will be 10 centimeters, therefore if we remember the element height of .73 meters, we see that it will take eight vertical lifts per layer before we can move the stones horizontally and prepare for the next lifts (See Figure 3) [**6**].  The vertical traveling speed would be: 25 seconds * (8) - ten centimeter lifts = 200 seconds per 80 centimeters, or 250 seconds per meter.  With the efficiency factor of 70%, this will take 357 seconds per meter, or more commonly 10 meters per hour.  I do not see where Prevos derives his vertical transport of 5.12 meters per hour, but that is the speed we will use in our future calculations.

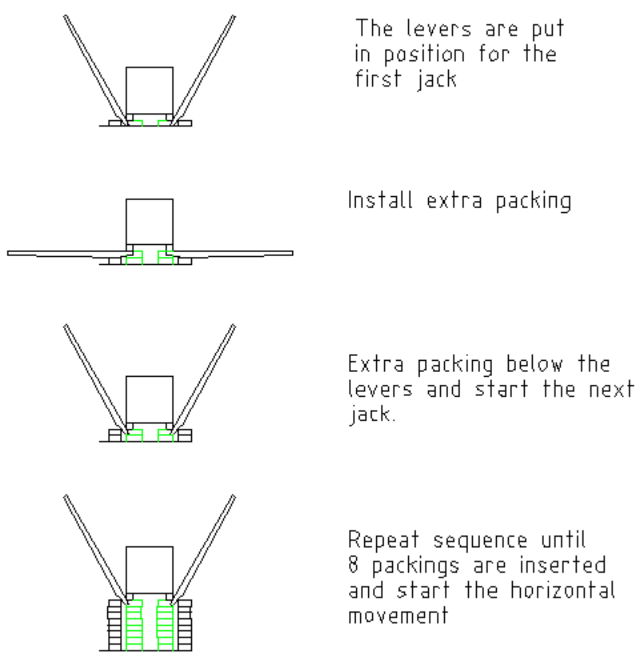


Figure 3 [**6**].

To see how long it takes to transport each element horizontally per level, remembering our step size of .575 meters, we can take this proportion: 13 meters / 3600 seconds = .575 meters / X seconds. We see that this results in almost 159 seconds. Now to find the speed, we take the following proportion: 159 seconds / .575 meter = 3600 seconds / X meters. This results in a speed of about 13 meters per hour. The 13 meters per hour is exactly what Hodges proposes, now we must take 70% of the speed to get 9.1 meters per hour, as given by Prevos [**6**].

In regards to the distance between two teams on the platform, during horizontal movement), we find the distance to be 9.10 meters per hour * 4 meters / 5.12 meters per hour = 7.11 meters.

Now, let us show a summary of the abovementioned parameters so we can create some equations.

| | |
|---|---|
| W - Width of the pyramid [230 m] | $V_h$ - Horizontal speed [9.10 m/h] |
| H - Height of the pyramid [146 m] | $S_v$ - Vertical spacing [4 m] |
| z - Element height [0.73 m] | $S_h$ - Horizontal spacing [7 m] |
| l, b - Element size [1.17 m * 1.17 m] | $S_p$ - Spacing on the platform [7.11 m] |
| $V_v$ - Vertical speed [5.12 m/h] | n - Layer number [1 to 200] |

So, for each layer n, we have:

The height, h(n) = $n * z$

The width, w(n) = $\frac{W(H - h(n))}{H}$

And the number of elements to be placed, e(n) = INT $\left[\frac{w(n)^2}{b * l}\right]$.

To find the total elements, we can take: $\sum_{n=1}^{200}\left\{\left[\frac{w(n)^2}{b * l}\right]\right\}$ = 2,556,998 blocks.

Let us find the height, width and number of elements to be placed for course 55:

h(55) = 55 * .73 m = 40.15 meters

w(n) = $\frac{230m(146m-40.15m)}{146m}$ = 166.75 meters

e(n) = $\left\lceil \frac{(166.75m)^2}{1.17m*1.17m} \right\rceil$ = 20,312 elements.

Now we need to look at some more numbers so that we can come up with the construction time per layer. After every $S_v$ / $V_v$ = .78 hours, a new batch of elements arrives, and this will be repeated until the last row, or ½ w(n) / b, is placed. We must also take into account the horizontal movement of the elements so that the rows can be filled. Their average distance of movement will be ½ $S_h$ meters, and must be repeated $S_h$ / l times to fill the platform. The total construction time can be calculated by finding the time from when the first row of stones is placed and the moment the last row has been placed. We can do this by taking the summation of Prevos' construction time per layer, or: $\sum_{n=1}^{200}\left\{\left[\left(\frac{\frac{1}{2}w(n)}{b}*\frac{\text{Sv}}{\text{Vv}}\right)+\left(\frac{\frac{1}{2}\text{Sh}}{\text{Vh}}\right)\right]*\frac{\text{Sh}}{l}\right\}$. This is calculated to be 45,684 hours or 10.88 years, of course taking into account the efficiency factor, 350-day year, and 12-hour workday [**6**]

I feel that the core construction time would be increased pretty substantially had we factored in the construction of the internal passages and chambers. Even though Prevos decided their addition would *not* take up a large amount of volume, their intricate assembly and the transportation/vertical lifting of their huge granite slabs *would* take up a large amount of construction time.

As mentioned above, Prevos' parameters for usage of levers for "jacking-up" can be assessed. I agree with both Prevos and Hodges in their use of levers for vertical transport; however I find it hard to visualize a .73 meters high by 1.17 meters wide by 1.17 meters long element being balanced on a .575 meter step. Ernest Moyer elaborates more so on the specifics and does not believe that the ancient Egyptians could "push" 600 Newtons of force each [**10**]. Since he considers this impossible to do, more men would be necessary per transported element. As I said, there is not a lot of space on the pyramid step for the "jacked-up" stone, let alone four men lifting with four levers. Moyer proposes the use of more men—but there just is not enough room for the men to stand using Prevos' parameters [**10**]. I feel like Prevos should have taken this small step size into account when completing his study, but I am still convinced by Hodges' trials that levering is the best method.

**6. CASING OR TRIMMING.** In order to achieve a pyramid with smooth sides, the Egyptians either had to add a casing, or "shell", to the core of the pyramid; or they had to chip away at the core to smooth out the blocks, called trimming. Smyth believed that the Egyptians used casing that was, "…smooth, polished, dense white lime-stone, almost like marble, in a sloping plane…" [**3**, p. 2]. However, most pyramidologists and Prevos, believe that the latter occurred for the Great Pyramid at Giza.

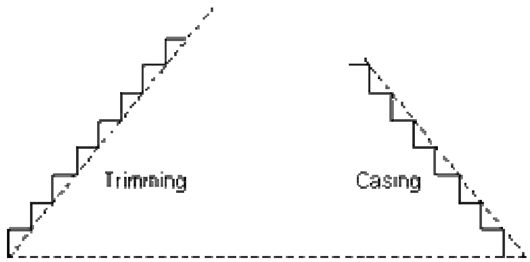

Figure 4: Casing or trimming [**6**].

Most importantly, trimming begins right after the last element is placed on the pyramid during core construction, and the stone masons work their way down the pyramid, trimming as they go along. Trimming requires that there be more core material placed around each layer. Prevos proposes that every layer should be 1.15 meters wider. Since there are 200 courses and they are each 1.15 meters wider, one extra layer equivalent to 230 meters by 230 meters needs to be constructed. Using Prevos' "elements placed per course" equation, those dimensions are equal to 38,644 elements. Again using Prevos' "construction time per course" equation, we get a construction time of 460 hours. This will be added to the core construction time from above to get 45,684 hours + 460 hours = 46,144 hours, or 10.99 years [**6**].

Now, say that one stone mason can chip away .5 cubic meters per day and the masons are positioned every two meters. Therefore, it will take one day to complete one layer and 200 days to complete the entire pyramid. With Prevos' efficiency factor of 70%, it will take 286 days, or 40.8 weeks, to trim the Great Pyramid [**6**].

**7. PRODUCTION OF THE ELEMENTS.** Currently, there is not a lot known about the quarries from which the ancient Egyptian builders got their limestone blocks. While Prevos was completing his desk study, he stated that at that time he did not know the distance from the quarries to the construction site, nor did he know how many quarries existed [**6**]. May I add that it is also hard to determine how the elements were transported to the construction site. When we calculated the above core construction time, we were assuming that the quarries would be yielding just the right amount of blocks so that the "jack-up" teams would not be left waiting. This is a pretty unlikely outcome being we have no, or some varying, answers to the abovementioned unknowns. In order to take the unknowns into account, Prevos utilizes a method he calls "leveling".

It is very easy to realize that the less output the quarries have, the more time it will take to construct the Great Pyramid. Conversely, the more output the quarries have, the less time it will take. Using Prevos' Appendix 1, we see that our average placing capacity is 56 elements per hour. Prevos prefers an output of 30 elements per hour because, "A higher quarry capacity is not very likely and [an] even lower capacity will increase the construction time [considerably]." We see that in order to produce the 2,556,988 (core elements) + 38,644 (elements added to core for trimming) = 2,595,632 elements, we must do the following time calculations:

2,595,632 elements / 30 elements per hour = 86,521 hours and

86,521 hours / 12 hours per day = 7,210.1 days. Using our 350-day year, the element production will take 20.6 years or about 1,030 weeks [**6**].

Now the leveling of the construction of the core can take place. Since we are far below our maximum placing capacity of 84 pieces per hour, as seen in Prevos' Appendix 1, we can increase the vertical spacing of the "jack-up" teams to compensate. Prevos proposes a new vertical spacing of 7.5 meters, which will in turn make the use of labor minimal, however there will be a reduction in the builders that are just "hanging around" the construction site. To find the new total core construction time we can again take the summation of Prevos' construction time per layer, but use $S_V$ = 7.5 meters:

$$\sum_{n=1}^{200}\left\{\left[\left(\frac{\frac{1}{2}w(n)}{b}*\frac{\text{Sv}}{\text{Vv}}\right)+\left(\frac{\frac{1}{2}\text{Sh}}{\text{Vh}}\right)\right]*\frac{\text{Sh}}{l}\right\} = 97{,}758 \text{ hours} + 460 \text{ hours (to trim the pyramid)},$$

1,169 weeks, or 23.4 years [**6**].

**8. IN SUMMARY.** We can briefly summarize the reconstruction of the Great Pyramid with the following:

i. The preparation of the work area will take 9 weeks to complete.

ii. The "leveled" construction of the core will take 1,169 weeks to complete

iii. The trimming of the pyramid will take 41 weeks to complete

iv. The production of the elements, or stones, will take 1,030 weeks to complete.

Prevos also mentions giving the builders a 2 week holiday between the finishing of the core and the commencement of the trimming. Knowing that the production of the elements will take place during the construction of the core and that the core construction time is greater than the element production time, we need only add the following to conclude the total construction time of the re-creation Great Pyramid:

9 weeks + 1,169 weeks + 2 weeks + 41 weeks = 1,221 weeks or 24.4 years [**6**].

**9. CONCLUSION.** Although Prevos has received some criticism, I feel his process is the most thorough. This is most likely due to the fact that he is an engineer who was influenced by Hodges' experiments and book that they gave rise to. Pyramid construction, especially that of the Great Pyramid, was a long and arduous task. Luckily, the pyramids have remained intact, enabling research and the realization of the unbounded capabilities of the ancient Egyptians. We concluded that the immense structure may have taken about 25 years to build, yet has lasted over 4500 years. It will have a lasting impact on future generations due to its incredible craft and workmanship. The Great Pyramid is truly a *great* pyramid.

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