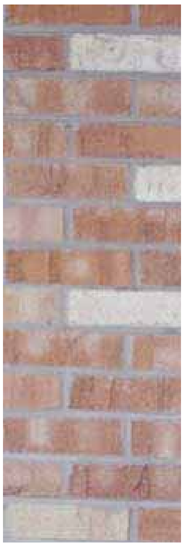
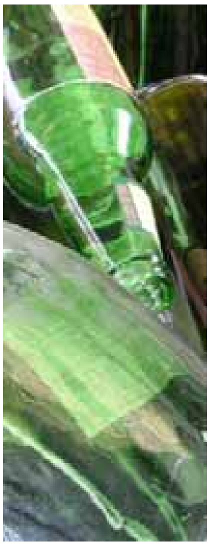
Potential Energy Savings From the Use of Recycled Glass in Brick Manufacturing

Robert Kirby




CENTER FOR ENVIRONMENTAL ECONOMIC DEVELOPMENT

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Abstract

A research project, sponsored by the California Department of Conservation and managed by the Center for Environmental Economic Development (www.ceedweb.org), was undertaken to determine whether energy savings were possible from substituting 12 mesh recycled soda lime container glass for ceramic grog in brick manufacturing. 12 mesh is the grade of recycled glass currently being processed for use by fiberglass manufacturers. The Chief investigator for the project was Robert Kirby of Seattle, Washington (kirbgood@earthlink.net).

ASTM C-1272-05a, "Standard Specification for Heavy Vehicular Paving Brick" was chosen as the applicable standard. Bricks containing 50 percent glass were fired until a kiln profile was found that produced bricks with average cold water absorption less than 6 percent. 50 percent glass bricks meeting the absorption standard were made with the following kiln profile:

Heat from 350°F to 1850°F at a ramp rate of 1000°F per hour
Hold at 1850°F for 20 minutes.

Then the minimum weight glass/clay brick was found that, when fired to the schedule above, also met strength standards for heavy vehicular paving bricks. The minimum weight brick meeting the strength standard consisted of

700 grams 12 mesh recycled glass
700 grams dry Redart Fireclay.

As a control, bricks were made using the same dry clay, but with conventional ceramic grog. The minimum firing profile using conventional grog was:

Heat from 350°F to 2125°F at a ramp rate of 1000°F per hour
Hold at 2125°F for 30 minutes.

The conventional bricks meeting the strength standards consisted of

800 grams Christy grog
800 grams Redart Fireclay

Energy analyses of the kiln and firing profile gave the following results:
Energy to make glass/clay brick (per 4x8 brick):

Including kiln	7717 btu’s per brick
Without kiln losses	1456 btu’s per brick

Energy to make a grog/clay brick:

Including kiln	11,085 btu’s per brick
Without kiln losses	2382 btu’s per brick

The percentage of energy saved:

Including kiln losses	30.4%
Brick only	38.9%

In addition to the firing energy savings, the fired glass/clay bricks weigh 11 percent less than the conventional bricks, resulting in transportation energy savings.

Potential Energy Savings from the Use of Recycled Glass in Brick Manufacturing

Introduction

This sub-project, to determine whether energy savings are possible from substituting recycled soda lime glass for other ceramic raw materials in brick manufacturing, was part of a grant from the State of California Department of Conservation, Recycling Market Development Division. The grant was managed by the Center for Environmental Economic Development of Arcata, California.

The idea of using glass as a brick flux has been researched and reported on for many years. In a sense, one could say that the concept goes back hundreds of years. In the competition to replicate Asian porcelain, early researchers added glass frit to clay formulas to attain translucence and density. Some formulas for Irish Belleek pottery claim that it was 50 percent glass frit[1]. The Italian Medici porcelains of the 16th century also contained large amounts of glass[2].

On a more pragmatic level, after the energy crisis of the early 1970's, the United States Bureau of Mines sponsored research to see whether energy could be saved using ground glass as a brick flux[3]. In the 1990's the Clean Washington Center sponsored research on the viability of glass in clay bodies as a strategy to improve recycled glass markets.[4] Very recently, the government of the United Kingdom sponsored studies and trials to investigate glass as a brick flux, both to save energy and to improve markets for recycled glass[5]

Real-world industrial results are more difficult to find. Universal Ground Cullet UGC) of Ohio, a glass processor, claimed to be selling ground glass as an additive to ceramics manufacturers[6]. This is impossible to verify because UGC is no longer in business. Quarry Tile of Spokane, WA, and Fireclay Tile of San Jose, CA, both use very fine recycled glass in their clay tile bodies and advertise the environmentally friendly aspects of the practice.

There is anecdotal evidence that some fine baghouse dust from large recycled glass processing operations has been used by large tile manufacturers as a flux. It is difficult to confirm this because both the glass processors and the tile manufacturers consider the information to be proprietary.

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[1] Peterson, Susan, The Craft and Art of Clay, Overlook Press, 1996, page 149.
[2] Rado, Paul, An Introduction to the Technology of Pottery, Pergamon Press, 1988, page 181.
[3] Tyrell, M. E. and Goode, Alan H., "Waste Glass as a Flux for Brick Clays," U. S. Dept. of the Interior Report of Investigations 7701, 1972.
[4] "Glass Clay body Flux," CWC Report GL99-1, 1999.
[5] "To demonstrate the commercial viability of incorporating ground glass in bricks with reduced emissions and energy savings," Waste & Resources Action Programme Project GLA2-018, 2004.
[6] Conversation with Robert van Buskirk, Sr.

All of the reports, studies, and products above share one thing: they focus on the use of very finely ground glass. While it has been well established technically that adding very finely ground glass lowers firing temperatures, there are a number of problems associated with extending the practice into brick manufacturing:

1. High levels of glass reduce the workability of moist clay bodies for several reasons:
   - Although the glass particles are fine, they are huge compared with ceramic particles. The rigid glass particles can bridge the fine clay particles, interfering with plasticity.
   - The glass particles tend to be cubicle and sharp-cornered compared with platy clay particles, and hence stiffen the clay mixes.
   - Soda lime glass in contact with water leaches alkalinity directly proportional to the surface area of the exposed glass, which is significant with very fine glass[7]. The alkalinity can affect clay electrolytic conditions and water requirements. PH levels higher than 10 have been confirmed in run-off from piles of finely ground glass[8].
2. The amount of fine glass available as baghouse dust from glass processing operations is adequate as an additive for tile manufacturing, but not adequate for brick manufacturing. A moderate-sized brick manufacturer might make 250,000 tons of finished bricks per year. The 25,000 tons a ten percent addition would require is simply not available as a by-product.
3. Processing glass uniformly to very fine (200 mesh and finer) material in thousand ton volumes is expensive compared with using mined brick raw materials.

Now consider: how would the issues above change if glass was treated as a grog rather than as a fine industrial mineral?

1. It is easy and inexpensive to crush glass to 8 mesh and finer particles. In fact, hundreds of thousands of tons of 12 mesh glass is currently being made annually by large glass processors for the fiberglass industry. There is also off-the-shelf small, medium, and large-scale equipment to efficiently perform this kind of processing for less than $10 per ton.[9]
2. Traditional grog particles are sharp-cornered and large, but industry has developed equipment and gradations to optimize the particle packing between the very fine clay and the very coarse grog and to use the characteristics of grog for accelerating drying and reducing shrinkage. Properly graded glass can do the same thing. In fact, since glass particles have zero absorption, if properly used they work better than grog to accelerate drying.

Availability of Recycled Glass

It is impossible to name a typical price for recycled glass because price and availability varies enormously across the country. On average, American consumers use about 80 pounds of glass per person per year. So the consumption of glass is demographically

[7] Clark, Pantano, and Hench, Corrosion of Glass, Books for Industry, 1979, page 36ff.
[8] Ibid, page 38.
[9] Conversation with Cynthia Andela, Andela Systems, Richfield springs, NY.

rather than geographically distributed. A city of 500,000 people, like Seattle, consumes about 20,000 tons of glass containers per year. As a nation, the United States consumes about 12 million tons of glass and recycles about 25 percent, but collection rates vary from zero to 60 percent, largely dependent upon the availability of local markets.

Because of deposit laws, minimum content product requirements, and the number of container and fiberglass plants, California has both the highest deposit glass container collection rate, 58%[10], and the most robust recycled container glass markets in the United States. In California, the good news is that there is plenty of processed glass. The bad news is that there is also plenty of competition for the glass.

However, one kind of glass is available in large quantities inexpensively in California. Over the last ten years glass processors have been installing automated optical-pneumatic sorting equipment, which reduces hand labor and lowers the amount of ceramic contamination in the sorted glass. The sorting systems work by breaking the glass into large (3/8-inch and larger) pieces. Optical scanners are then able to sort colors and pick out contaminants. One limitation of the sorters is that they are only able to sort down to about 3/8-inch. All of the 3/8-inch and finer mixed color glass is a waste in the system.

Thousands of tons of this mixed broken glass are being hauled away as solid waste. This waste glass, which also contains up to 2 percent by weight organic contamination, and some inorganic contamination in the form of ceramics and small pieces of metal, can be reduced to 12 mesh size and works fine in this process. Organics burn out and inorganics become a part of the brick body. This is not surprising since brick makers have been putting crushed corncobs into some bricks for porosity and crushing all kinds of inorganic materials, especially old bricks, to reduce the amount of clay needed in new bricks for generations.

Throughout most of the rest of the country, recycled glass markets are very spotty. For example, virtually all of the glass being collected in the state of New Mexico is being crushed at glass processing installations in Santa Fe, Albuquerque, and Taos, and being given away as construction fill or as daily cover at landfills[11].

Glass as a Ceramic Grog

This project tests 12 mesh and finer glass as a grog for making bricks. As part of research on barriers to more use of recycled glass by ceramics manufacturers, a bag of dry brick clay mix was obtained from a brick manufacturer in California. The mix contained approximately 50 percent 30 mesh and coarser sand and grog. The brick manufacturer stated that about 16 percent water was added to the mix before extruding into bricks.

[10] California Dept of Conservation Biannual Report, dated May 11, 2006.
[11] Conversation with a New Mexico recycling manager.

Crushed soda lime glass, in approximately the same gradation as the temper and grog, works well as a grog in reducing water requirements, accelerating drying, and minimizing shrinkage. Then, at temperatures in the range of 1700 to 1850°F, the glass can be made to fuse without distorting the formed piece, forming the "glue" that holds the ceramic piece together. The function of the clay part of the composition is therefore to provide workability, to facilitate forming at room temperatures, and to hold the shape throughout the fusing process.

Since the glass is in granular rather than powdered form the workability is not affected as it is with powdered glass. Also, because this is a viscosity change rather than a chemical evolution, the speed of the process is limited to the speed with which heat can be driven into the green glass/ceramic piece.

So the glass is the grog at room temperature, then becomes the main source of strength at elevated temperatures. During this project this phenomenon has been named the "Principle of Reactive Aggregate."

Test Set-up

Tests were run on 50 percent glass/clay mixes. Among dry commercial medium-fire clays, Redart Fireclay, made by Resco, most closely replicated the brick clay in water requirement and workability.

The standard brick mix for this project was:

- 50 percent 12 mesh glass
- 50 percent dry Redart Fireclay
- 16.5 percent water

For control, a mix was developed using the same Redart Fireclay with commercial grog:

- 50 percent dry Redart Fireclay
- 25 percent Christy Grog 12M
- 25 percent Christy Grog 20M
- 16.5 percent water

For good energy monitoring in a small kiln, a special electric kiln was built for this project. Rather than resistance elements, quartz halogen tubes were used as heating elements. The quartz tubes provide a nearly instantaneous 100 percent radiant heat transfer source in the near infra-red range. Since heat transfer is a function of the fourth power of the difference between black body surface temperatures, the high temperature equivalent black body source (near 3000°F for the quartz tubes) helps to remove "delta T" as a variable to be corrected for when analyzing energy usage while firing to different temperatures.

Experience has also shown that the quartz bulbs begin emitting energy at quite low amounts of input energy, compared with resistance elements, which appear to send out no measurable heat below ten percent of maximum output. The consistent power-in to power-out relationship helps with energy data collection.

A Fuji proportional-integral-differential (PID) controller was used with a type K thermocouple. A Hobo data acquisition system by Onset enabled the monitoring of the 4-20 milliamp signal between the controller and the silicon-controlled rectifier (SCR). Transferring the data from the Hobo into a spreadsheet enabled a correlation to be developed between the control signal and the actual output to the elements. Unfortunately, the relationship between the control signal and the SCR output are never linear, so a look-up table was developed empirically, using an ammeter and manually stepping the control signal across the full range to develop the table.

Making the test bricks

A relatively uniform system was needed to make the bricks. A manual press was developed. The wet clay was place into a 4”x8” wooden mold with a liner:

Press-mold box with slide-out liner

After a lid was placed on the box, the brick was pressed in a bottle-jack press:

Bottle jack press

The depth of the mold was calibrated to be self-leveling. Using this method, there were no pressing rejects.

After pressing, the green bricks were dried on a warming plate with a surface temperature of about 200°F. After drying for two hours, the bricks could be placed into a resistance element kiln and dried for two hours at 300°F. Then the bricks were placed in the firing kiln.

Using this procedure, it was no problem to start with dry raw materials at 7:00 am, and remove warm bricks from the kiln the same day at 9:00 pm. After removal from the firing kiln, the bricks were weighed, then submerged overnight, then weighed again in the morning. The difference between the wet and dry weights was the cold water absorption.

Standards

A standard by which to judge a “good brick” needed to be chosen. The forming method only allowed for solid, flat bricks, so ASTM C-1272-05a, "Standard Specification for Heavy Vehicular Paving Brick" was chosen as the standard.

In particular, the most stringent standard within C 1272 is for Type F bricks, which are bricks set in sand rather than concrete, so they carry the full vehicular load. The standards of interest are Breaking Load and Cold Water Absorption. The standards are as follows:

1. Cold Water Absorption less than 6% for an average of 5 bricks.
2. Breaking Strength greater than 475 pounds-force per inch of width for an average of 5 bricks, with the weakest brick exceeding 333 pounds per inch of width. The bricks being made for this test are nominal 4 inches wide, so for convenience a minimum average breaking strength of 4x475 = 1900 pounds was assumed, with the weakest brick exceeding 4x333=1332 pounds.

From previous experience making glass-bearing bricks, 1-1/2-inch thickness is tried first to meet the strength standards. Commercial paving bricks available from a local home center are 1-1/2 inches thick, so convenient comparisons will be possible.

Test sequence

Cold water absorption gives the resistance to freeze/thaw and a sense of whether a brick is fully fired. High porosity often correlates to low strength. Also, the equipment to test cold water absorption is available in the production laboratory while strength testing needs to be scheduled at a certified lab.

So cold water absorption is chosen as the initial test. 1600 grams is found to be the brick weight that closely makes a 1 1/2 inch thick brick. The initial standard mix is:

- 800 grams dry Redart Fireclay
- 800 grams 12 mesh glass
- 264 grams water (16.5 percent of total dry weight)

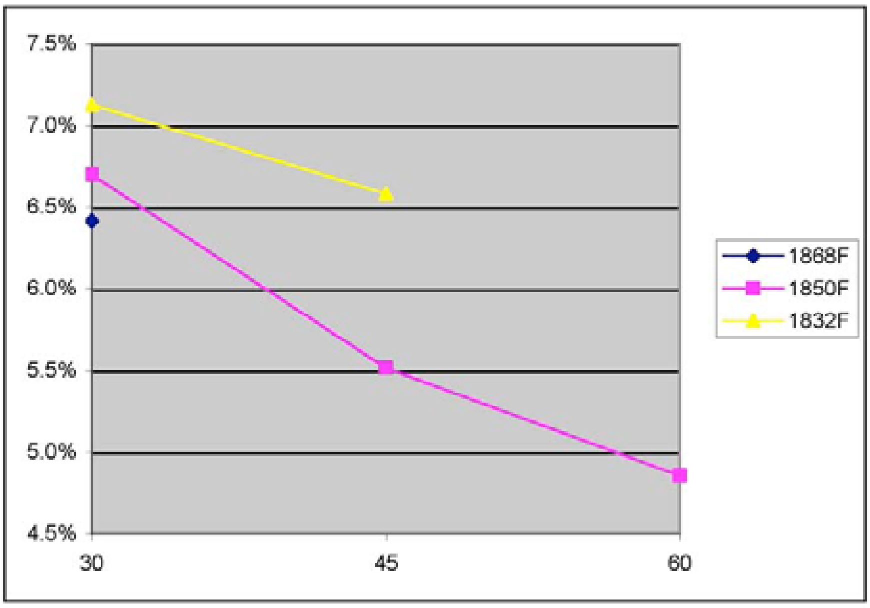
After losses during the manual brick-making process and loss on ignition, the fired bricks weigh about 1500 grams.

The first task is to find the firing profile that will result in cold water absorption less than 6 percent and a brick with no visible defects.

The test kiln is very fast. And since this project is ultimately about minimizing the energy to make a brick, the first bricks are fired as quickly as possible. Here is a typical firing schedule:

- Ramp up from 300°F to 1100°F in one minute
- Hold at 1100°F for 30 minutes for burn-out
- Ramp up from 1100°F to 1850 in four minutes
- Hold at 1850 for 30 minutes

Correlating maximum temperature soak time to cold water absorption gives the following:



Vertical scale is absorption, horizontal scale is soak time at max temp.

Only one data point is shown for 1868 maximum soak temperature because at that temperature particles of glass are being forced out onto the surface of the brick. So 1850°F is taken to be the maximum temperature for firing the bricks.

However, at these fast ramp times, small cracks are apparent along the edges of the bricks:

Small firing crack along the edge of a brick

A series of tests is then run, slowing down the ramp time until the cracks disappear.

The fastest ramp rate at which no cracks are seen is 1000°F per hour. And a serendipitous byproduct of slowing the ramp time down is that no soak is needed at 1100°F for burn-out.

So the standard firing schedule is:

- Ramp up from 350°F to max temp at 1000°F per hour
- Hold at max temp for minimum time needed to reach Absorption standard

Bricks are fired in pairs. Zeroing in on the firing standard:

Dry weight	Wet weight	Absorption	Average Absorption
Hold for 30 minutes at 1825°F:			
1499	1594	6.3%	6.3%
1505.5	1599	6.2%	
Hold for 20 minutes at 1850°F:			
1488	1574	5.8%	5.95%
1462	1551.5	6.1%	
Hold for 30 minutes at 1850°F:			
1476	1551	5.1%	4.8%
1477	1544	4.5%	

Testing Standard Profile

The 20 minute soak is so close to the ASTM standard that the 30 minute soak is chosen as the standard. The standard firing profile is therefore:

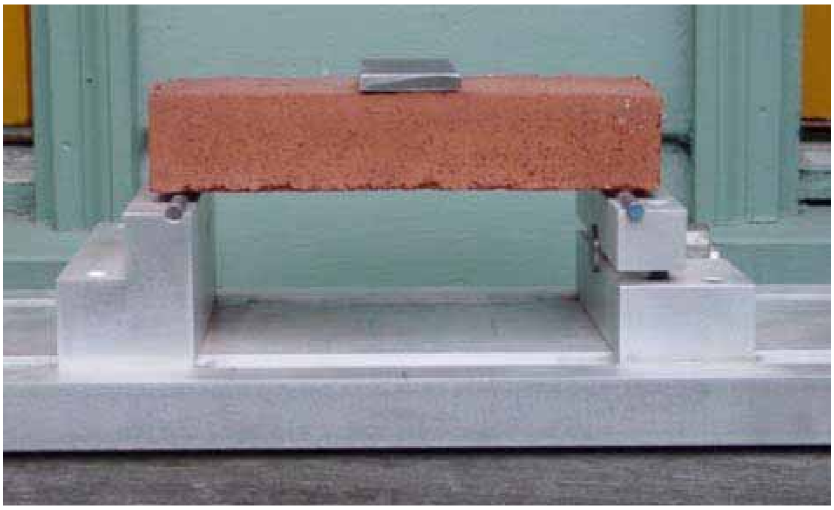
- Ramp up from 350°F to 1850 at 1000°F per hour
- Hold at 1850°F for 30 minutes
- Cool naturally
- Open kiln at 500°F to cool in air

A set of ten bricks are made at the firing standard. Absorptions are as follows:

Dry weight	Wet weight	Absorption	Average Absorption
1473	1537	4.3%	4.1%
1472	1534.5	4.2%	
1463.5	1518	3.7%	
1484.5	1555	4.7%	
1479.5	1537	3.9%	
1479	1532.5	3.6%	
1495	1547.5	3.5%	
1472.5	1533	4.1%	
1481	1552	4.8%	
1475.5	1540.5	4.4%	

An important note is that these ten bricks were made and fired over three days, with NO rejections, during either fabrication or firing. This would seem to indicate that brickmaking with crushed glass is a fairly robust process.

The Instron test machine at the University of Washington Department of Mechanical Engineering is used for the strength test. A test fixture is built meeting the procedure in ASTM C67-05, "Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile:"



Test fixture with test brick in place

The results of the strength tests:

Dry weight	Absorption	Strength	Average Strength
1473	4.3%	3207	2725.8
1472	4.2%	2503	
1463.5	3.7%	2670	
1484.5	4.7%	2627	
1479.5	3.9%	2873	
1479	3.6%	3155	
1495	3.5%	2488	
1472.5	4.1%	2878	
1481	4.8%	1844	
1475.5	4.4%	3013	

The average breaking strength far exceeds the required average of 1900 lbs-f.

Because the 1850°F 20 minute soak also met the standard for Cold Water Absorption, those bricks are also tested for strength:

Dry weight	Absorption	Strength	Average Strength
1499	5.8%	2508	2535
1505.5	6.1%	2562	

Although this set of two does not meet the statistical standard, it is apparent that the 20 minute soak also makes an adequate brick. At an average breaking strength of 2535, the 20 minute soak bricks exceeded the strength standard by

2535/1900 = 1.334:1

Flexure strength is proportional to the square of the depth, so it may be possible to make bricks exceeding the 1900 pounds strength standard with a thickness of

1/(1.334)^.5 = .866

times the thickness of the first set of bricks.

The first bricks used 1600 grams of dry raw materials, so the new set will weigh

.866*1600 = 1386 grams dry.

But one thing is noticed during the testing. The broken faces of the brick look like this:

Broken brick face

It is apparent that the clay/glass bricks have not fused all of the way to the middle. Since the bricks pass the standard for both strength and absorption, this is not pertinent to the test result, but since the middle of the brick is not completely fused, an even thinner brick can probably be made with the same strength.

So for the second test run, 1400 grams of dry material is used. The standard mix for this run is:

- 700 grams 12 mesh glass
- 700 grams Redart Fireclay
- 231 grams water

A set of five bricks is made and tests as follows:

Dry weight	Absorption	Ave. Absorption	Strength	Ave Strength
1302.5	5.6%	5.74	1769	1914
1302	5.8%		1942	
1318.5	5.9%		1921	
1321	5.6%		1913	
1307	5.8%		2026	

So this set of bricks meets the ASTM standard for both Absorption and Strength.

Testing Grog Bricks

In order to have data for energy comparison, control bricks using standard brickmaking materials are needed. Bricks are made with the following standard composition:

- 800 grams dry Redart Fireclay
- 400 grams Christy Grog #12M
- 400 grams Christy Grog #20M
- 264 grams water

Using the same firing schedule:

- Ramp up from 350°F to max temp at 1000°F per hour
- Hold at max temp for 30 minutes
- Cool naturally

pairs of bricks are made and tested for Cold Water Absorption:

Max Temperature	Dry weight	Wet weight	Absorption	Average Absorption
1850°F	1503	1658	10.3%	10.4%
	1498	1654	10.4%	
1875°F	1500	1653	10.2%	10.2%
	1495	1647	10.2%	
1900°F	1496.5	1645	9.9%	9.9%
	1504	1652	9.8%	
1925°F	1492	1634.5	9.6%	9.5%
	1516	1660	9.5%	
1950°F	1492	1628	9.1%	9.2%
	1510	1649	9.2%	
1975°F	1497	1622.5	8.4%	8.5%
	1508.5	1637.5	8.6%	
2000°F	1516	1640	8.2%	8.1%
	1500.5	1622	8.1%	
2025°F	1506.5	1621	7.6%	7.6%
	1504	1617.5	7.5%	
2050°F	1504	1609	7.0%	7.0%
	1504	1610.5	7.1%	
2075°F	1495	1589	6.3%	6.4%
	1505.5	1604	6.5%	

2100°F	1512	1598	5.7%	5.8%
	1512	1601	5.9%	
2125	1468	1545.5	5.3%	5.3%
	1478	1556.5	5.3%	

So the minimum firing temperature meeting Absorption standards using Christy grog is 2100°F. The strength test results for the bricks fired at maximum temperatures of 2075°F to 2125°F were:

Max Temperature	Dry weight	Absorption	Strength	Average strength
2075°F	1495	6.3%	1440	1397
	1505.5	6.5%	1354	
2100°F	1512	5.7%	1740	1808.5
	1512	5.9%	1877	
2125°F	1468	5.3%	1918	1979
	1478	5.3%	2040	

The 2125°F bricks meet both standards (albeit not statistically valid), so they will be used as the reference for energy used to make a brick.

Out of curiosity, some commercial paving bricks were purchased at a home center and tested for absorption and strength. They were not labeled as meeting any standard, but the test results were the following:

Designation	Dry weight	Absorption	Strength
Home Center	1577	6.7%	1650
	1594	6.1%	1683

So the small sample from the home center bricks met neither absorption nor strength standards.

Energy consumption

Published estimates for the energy it takes to make a brick vary widely. One federal government sustainable building database puts the number at 1238 btu's per pound.[12] A book of technical ceramic articles published in 1980 put the number at 1760 btu's per pound[13]. A National Industrial Competitiveness through Energy, Environment, and

[12] "Building for Environmental and Economic Sustainability" (BEES 3.0 – NISTIR 6916), October, 2002, page 57.
[13] Energy and Ceramics (Elsevier Press, 1980), article "Economy in Fuel Consumption of Bricks Manufacturing Plants," by E. Facincani.

Economics (NICE3) study estimated a high-efficiency natural gas kiln's energy usage at 2180 Btu/pound of product.[14]

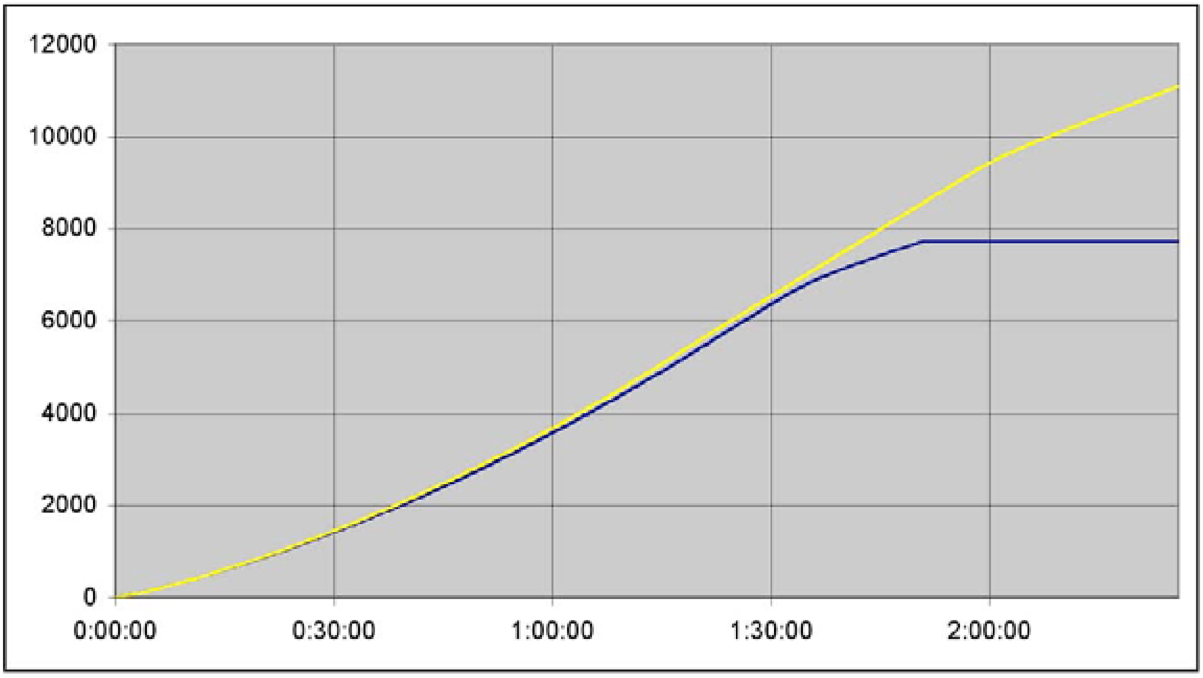
Summarizing:_

BEES	1238 btu/pound
Facincani	1760 btu/pound
NICE3	2180 btu/pound

Of these figures, the NICE3 figure might be the most reliable, since it is based on real-world experience with a relatively new furnace installation. In that study, bricks were made on a 48-hour cycle, very fast by historical standards but typical today.

Energy savings will be developed in two ways: with and without the kiln wall losses. As mentioned previously, the percentage of energy into the kiln was monitored through the 4-20 milliamp control signal. Then a correlation was developed between the control signal and the actual energy input to the kiln.

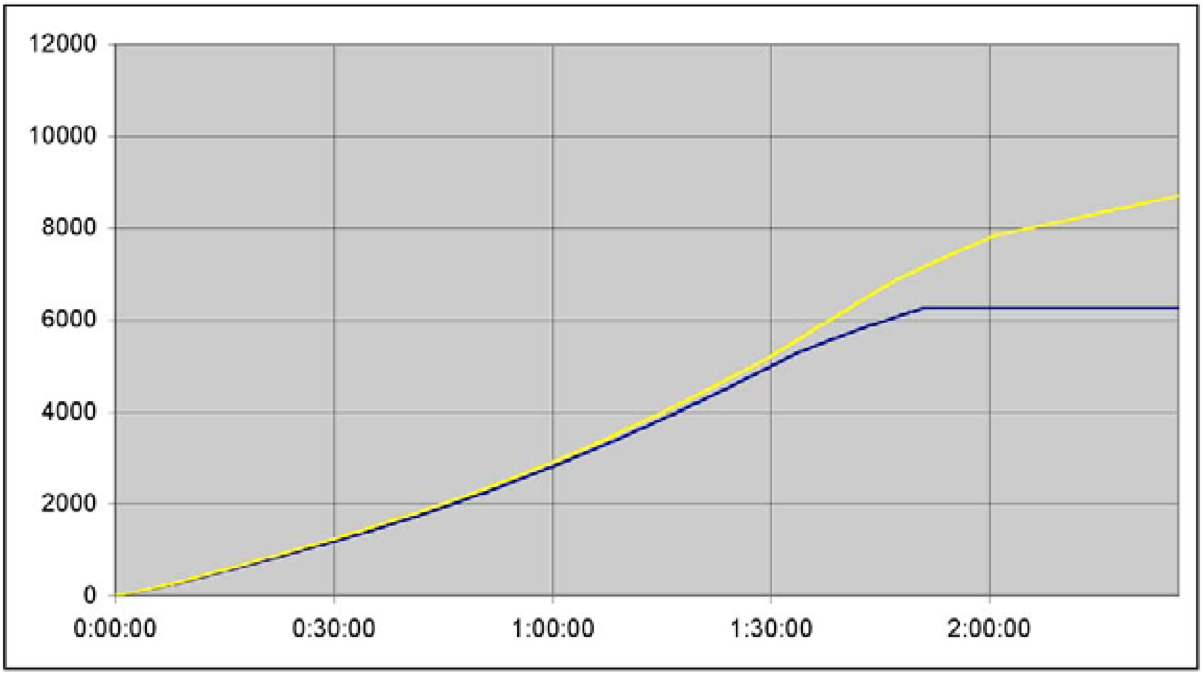
Two bricks were made per kiln run. All data are calculated as energy per brick. Energy usage, including both the kiln and the brick, looked like this:



Blue line is glass/clay brick, yellow line is grog/clay brick. Left scale is btu's per brick.

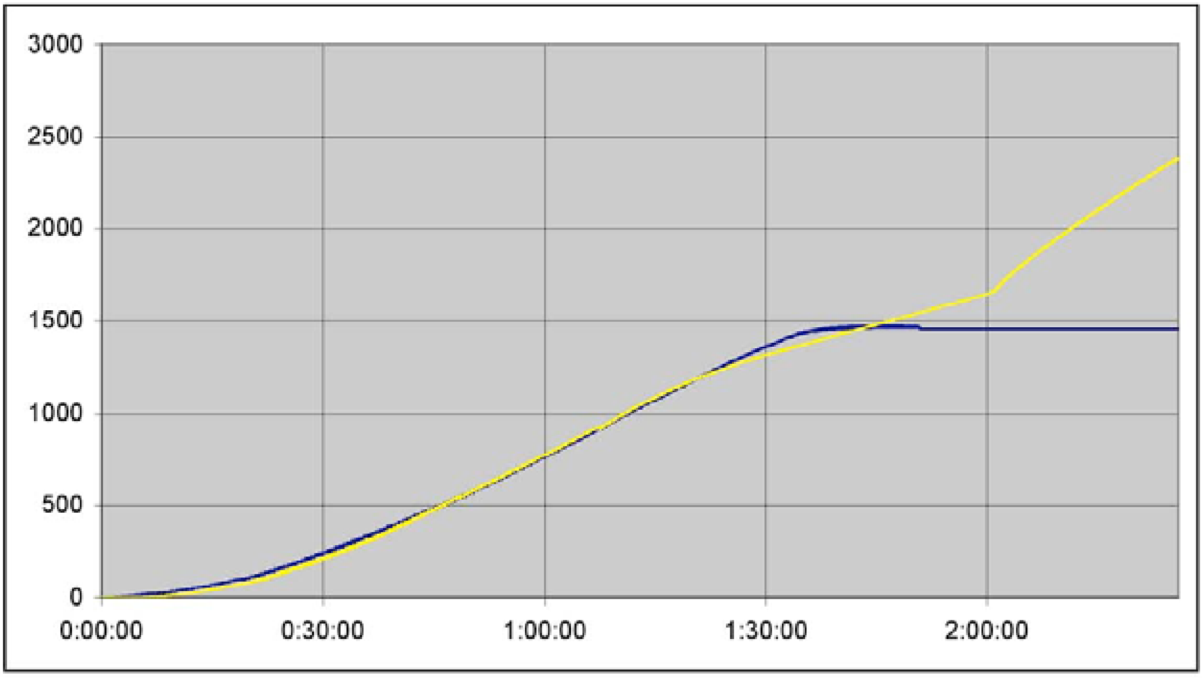
The kiln was then run empty, with the same profile, to determine the energy loss through the kiln walls. The empty kiln, run at the same profiles as the glass/clay and grog/clay bricks, looked like this:

[14] "Low-Thermal-Mass Kiln Installation At Pacific Clay Products, Inc.," California Energy Commission Contract Number: 400-96-019.



Blue line is empty kiln with glass/clay profile, yellow line is empty kiln with grog/clay profile. Left scale is btu's per brick.

Subtracting the empty kiln from the full kiln results in the energy used to actually fire the brick:



Blue line is actual heat into the glass/clay brick, yellow line is actual heat into the grog/clay brick. Left scale is btu's per brick.

One interesting observation is that the two types of brick absorbed almost exactly the same amount of energy until the glass/clay brick reached its fusing range. Then, as the glass softened and the brick mass became more conductive, the glass/clay brick actually used more energy then the grog/clay brick. However, the grog/clay brick had to be fired to a higher temperature and for a longer time to reach full density.

Summarizing:

Energy to make glass/clay brick:	
Including kiln	**7,717 btu's**
Without kiln losses	**1,456 btu's**
Energy to make a grog/clay brick:	
Including kiln	**11,085 btu's**
Without kiln losses	**2,382 btu's**
The percentage of energy saved:	
Including kiln	**30.4%**
Brick only	**38.9%**

Confirming scale of results

To verify that the results make sense, comparisons are made with other published data.

The grog/clay bricks weighed about 3.3 pounds, so for the grog/clay bricks, the energy to fire the bricks per pound was:

Including kiln	3369 btu's per pound
Without kiln losses	721 btu's per pound

The energy used per pound of manufactured brick by the NICE3 Pacific Clay report was

2180 btu's per pound

This would imply about a 33 percent furnace efficiency for firing standard bricks. It was difficult to find a reliable industry value for this efficiency, but this comparison makes sense in scale.

Further, the specific heat of brick clay is approximately .24 btu/pound-°F[15]. So the energy expected to heat brick clay from 350 to 2125°F is

$.24 * (2125\text{-}350) = 426$ btu's per pound

plus any endothermic losses due to the phase changes in the heated clay. Facincani (reference 13) estimated the endothermic loss at

Endothermic loss	400 btu's per pound

[15] Technical Notes 43D - Brick Passive Solar Heating Systems - Part 4 - Material Properties, Reissued September 1988, Brick industry Association.

But that figure is for clay containing a significant amount of calcium carbonate. Redart Fireclay appears to contain negligible calcium carbonate[16], and thus should require less endothermic energy for firing to maturity.

The 721 btu's per pound therefore looks like a very good number.

Another issue to keep in mind is the difference in weight between the grog and glass bricks. For bricks meeting absorption and strength specifications, the weights were as follows:

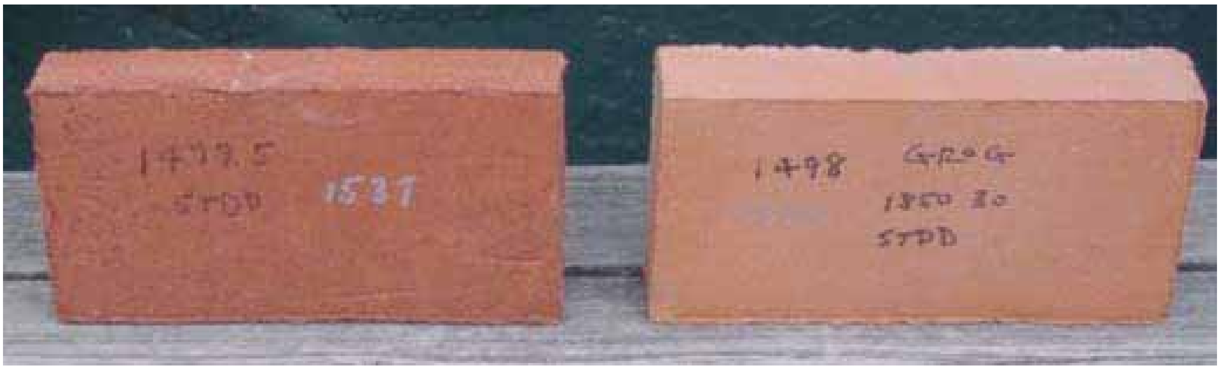
Glass/clay brick average weight	**1310 grams**
Grog/clay brick average weight	**1473 grams**

For a weight savings of 11 percent. This weight savings would apply to ergonomic operations at the factory, storage space, and transportation of raw materials and finished bricks to construction sites.

Color development

Aside from strength and absorption standards, any product expected to be successful in the marketplace will need to be aesthetically pleasing. One of the appealing aspects of brick is the rich red color of red clay fired to maturity.

One of the surprising things noticed while firing the samples is how the glass content lowered the temperature at which the rich red developed. Here is a picture of a grog brick and a glass/clay brick, both fired to 1850°F:



The brick on the left contains 50 percent glass, the brick on the right 50 percent grog. Both were fired to 1850°F.

Process issues

Some things are different about firing glass/clay bricks:

1. Tests were run by one California brick manufacturer in a conventional brick tunnel kiln. It was apparent that glass bricks get softer during firing than bricks made using grog. The bottom bricks in a stack were misshapen by the pressure from the bricks above.

[16] Obstler, Mimi. Out of the Earth, into the Fire, American Ceramic Society, 1996, page 99.

2. Glass is also more sensitive to variations in time and temperature. The glass bricks need to fired quickly with good temperature control. It is not possible to take the time to get heat to penetrate a stack and end up with a uniform product, so glass/clay bricks need to be fired in single layers.
3. The glass fires within a narrow temperature range. In this project that range appears to be between 1825 and 1850°F. Cooler temperatures produce incomplete fusing and higher temperatures result in glass particles oozing out of the brick.
4. Fines need to be included in the glass mix. If there are no fines, or inadequate fines, then the larger particles will ooze out, because there is not enough of a mixture of sizes to establish a complete glassy matrix. Given two or three grades of glass, particle optimization is possible, as long as at least one component includes fines down into the micron range. In this project we used a source that supplied a consistent grade from 12 mesh to dust. Consistency is critical.

From the two observations above, it is apparent that glass bricks cannot be fired in traditional brick furnaces. It may even be impractical to fire glass/clay bricks in low-profile furnaces from the 1990's with bricks stacked three high. It is possible that only single or multiple layer roller hearth furnaces are compatible with the manufacture of glass/clay bricks.

So the bad news is the brick plant needs new technology. But the good news is that bricks can be made using one-third less energy, and within 12 hours from dry clay to finished brick.

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