Remains of an ondol found in North Okjeo (now Russia's Maritime Province).[12]

Part 1

History of Radiant Heating & Cooling Systems

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Radiant floor heating began thousands of years ago. Often, credit is given to the ancient Romans for giving life to these systems, but archeology and research into ancient texts show Asia to be the earliest known developer of these systems, preceding the Romans by thousands of years. Beginning with the excavated floor flues of ancient Korea and moving on to the Greek and Roman hypocausts and similar systems used in the Middle East[1] and then to the subsequent disappearance of European systems post-Roman Empire and to the continual evolution in Asia and radiant floor heating's rebirth by the French and British at the turn of the 19th century, the history of radiant systems is a parallel study within anthropology, archaeology and architecture.

This two-part article describes the main historical milestones in the global evolution leading up to modern embedded radiant heating and cooling systems.

Asia

Looking into the northern areas of ancient China, including the northeast Manchuria region and northern Korea archeologists find early forms of radiant

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heating known as *kang*, *dikang* and *ondol*. The word *kang*, can be traced back to the 11th century B.C. and originally meant, "to dry" before it became known as a heated bed.[2] *Dikang*, literally "heated floor," can be regarded as an extended *kang* that has more heated surface. The Korean traditional floor heating system *ondol*, which means "warmed stone," is somewhat different from *kang* or *dikang* in that it occupies the entire floor of a room.[3]

The *kang* was used predominately in ancient northern China and was a raised heated living and sleeping surface (see first photo on timeline below) found in either a U-shape (such as benches in a locker room) or the shape of a traditional bed. *Kangs* typically could occupy as much as 50% of the room, which during the day was converted to a working and living surface. The *dikang* was the preferred choice in the northeast Manchuria region. Each was constructed with a fireplace and, depending on source of fuel, built without chimneys (for charcoal) or with chimneys for wood and other combustibles. Hot gases followed flues formed or constructed into the masonry or earth, through which heat was conducted to the surface (adobe, brick, or stone). Then, this heat radiated to the occupants and room. The by-products of the combustion called "dragon's breath" were, in some cases, efficiently used for space heating and cooking.

Photo credit: Kyu Nam Rhee

Figure 1: An ondol-floored room in modern Korea.

The choice between *kang* and *dikang* indicates a cultural preference for sitting on the floor or furniture and is a clue to ancestral migration patterns. Inhabitants of northern Chinese areas preferred the raised surface while the Manchurians used the *kang* and *dikang* or, as it is known in parts of Manchuria, *gudeul* (meaning heated stone). Other forms evolved including *huoqiang*, heated wall; *dilong*, floor dragon, that were heated (long) blocks placed under wooden beds; and *huochuang*, oven beds. As hypothesized by Guo,[2] the *kang* may have originated from the artistic/architectural beliefs and lifestyle of the era. The ancient Chinese were masters of clay and pottery and developed heating techniques for roofing tiles, porcelain and glazing. It is thought that through artistic expression and cultural preferences of eating, sitting, and sleeping on the floor that the *kang* and *dikang* evolved.

The Koreans chose and developed the heated floor known to them as *ondol*. From Knapp:

"…in a traditional Korean house, rooms typically have two kinds of floors: gudeul and maru. Underfloor heating systems, called gudeul (also ondol), are installed within closed rooms that are used for sleeping. Gudeul differ in important ways from the heated brick beds or kang, which are found in northern China, although they share certain common elements. Consisting of two principal components, a fire source and a series of flues, gudeul draws heat from a fire hole in the kitchen stove along an outside wall, then leads it through flues before being exhausted through a chimney. As the warm air passes through the flues, it warms flat stones that are placed above the flues, which then radiate heat into the room above, whose surface is finished with a layer of thick yellowish oiled paper or other material. The warmth of gudeul-heated rooms has given rise to a lifestyle in which Koreans remove their shoes before entering, and then use the comfortable heated floor for sitting or sleeping."[4] (*Figure 1* and second photo on timeline.)

Photo credit: Harry A. Franck

Photo credit: Kwang Woo Kim

Photo credit: H. Pringle [6]

c. 10,000 B.C., China, the word "kang," can be traced back to the 11th century B.C. and originally meant, "to dry" before it became known as a heated bed.

c. 5,000 B.C., evidence of baked floors are found foreshadowing early forms of "kang" and "dikang" (heated floor) later "ondol" (warm stone) in China and Korea, respectively.

c. 3,000 B.C., fire hearth, which was used both as kitchen range and heating stove, was used in Korea.

c. 1,000 B.C., ondol type system used in the Aleutian islands, Alaska.

These choices from ancient times influenced modern day Korea. During the 15th century, widespread adoption of the *ondol* occurred, conserving traditional floor lifestyles.

Ancient Asia – Kang, Dikang, Ondol

Archeological sites in Shenyang, China, show humans resided there as early as 7,200 years ago. There is evidence of "baked earth" floors in this region dating between 5300 to 4800 B.C., as well as in Xi'an, China, with "raised surfaces treated by fire," dating to 4800 to 4300 B.C. This process of baking the earth is called *zhi* or *zhidi* and may be the process which gave birth to the *dikang*.[5] Of anthropological interest from Alaska's Aleutian Islands, is an archeological dig at Unalaska revealing remains of a heated floor system characterized by the Korean *ondol* with radiocarbon dating showing remains to be around 3,000 years old (see third photo on timeline). Pringle states:

> *To stay warm, some families built subterranean stone-walled homes with energy-efficient heating systems consisting of a hearth, a stone chimney, and two subfloor channels…the subfloor channels funneled heat or possibly steam to warm the house floors…Such subfloor heating technology was previously unknown in the North American Arctic. But it resembles heated floors known as ondols that appeared in the Korean peninsula and in the Russian Far East during the same Neoglacier period.…*[6]

It is also known from early Chinese writings, excavated at Ningxia Hui (some dating back to 6000 B.C.), with references to heated floors or heated beds recorded over the centuries starting between 2852 and 2205 B.C. Literature from the Xia Dynasty (2070 to 1600 B.C.), Shang Dynasty (1600 to 1046 B.C.) and Zhou Dynasty (1122 to 256 B.C.) all refer to similar heated surfaces.[5] It is during the time of the Zhou dynasty when Europe records its history of the hypocaust (see Part 2 in the next issue).

Imperial China

All through the Qin Dynasty (221 to 206 B.C.) when the Great Wall of China began; through the *Han* Dynasty (205 B.C. to 220 A.D.) in the communities of Xinjiang and Heilongiang, excavations have found remains of *kang*; into the Wu Shu and Wei periods (220 to 280 A.D.), Jin Dynasty (265 to 420 A.D.) where Ji'an excavations find remains of double-flue kangs during the; era of the 16 Kingdoms (304 to 439 A.D.); Southern and Northern Dynasties (420 to 589 A.D.); Sui Dynasty (581 to 619 A.D.); and Tang Dynasty (618 to 907 A.D.).

It is the latter period when a large hall in the Guanji Temple was constructed for 1,000 monks with "heated floors affording students to study in cold winters." As pointed out by Guo, "Monks were learned men, many from aristocratic classes" and it is likely they continued to innovate and improve on this type of heating.[5] Certainly, through their travels they would influence others to use this type of system (see Part 2 with reference to America's Civil War). It was also during the time that poet Meng Jiao writes, "No fuel to heat the floor to sleep, standing and crying in cold at midnight."[7]

Literature and remains of surface heating are found from the Song Dynasty (960 to 1126 A.D.) where Yaozhou excavations of a Tang-Song pottery factory reveal remains of parallel-flue kangs; from the Yuan Dynasty (1271 to 1368 A.D.), Ming Dynasty (1368 to 1644 A.D.) into the Qing Dynasty (1644 to 1911 A.D.) where *kang* was enlarged to become a heated floor for the Manchu.

L-type gudeul.[9]

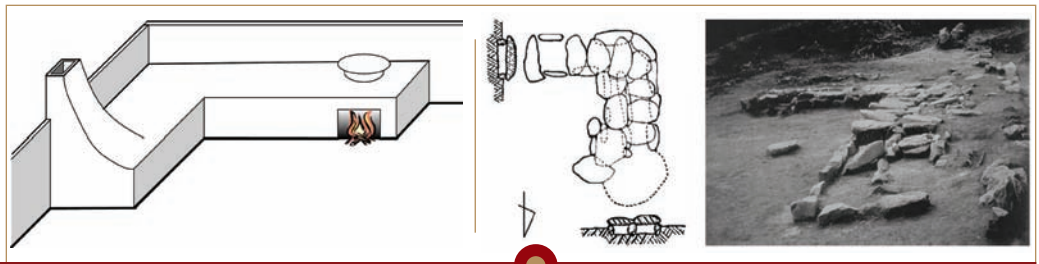

Image credit: Kwang Woo Kim (left image)

c. 1000 B.C., More than two hearths were used in one dwelling. One hearth located at the center was used for heating, the other, at the perimeter, was used for cooking throughout the year. This perimeter hearth is the initial form of the Budumak (meaning kitchen range), which composes combustion section of the traditional ondol in Korea.

c. 500 B.C. Greeks and later Romans scale up the use of conditioned surfaces (floors and walls) with the hypocausts.

c. 200 B.C., The central hearth was developed into the gudeul (meaning heat releasing section of ondol), and a perimeter hearth for cooking became more developed. Budumak was almost established in Korea.

c. 50 B.C., China, Korea and Roman Empire use kang, dikang/ondol and hypocaust, respectively.

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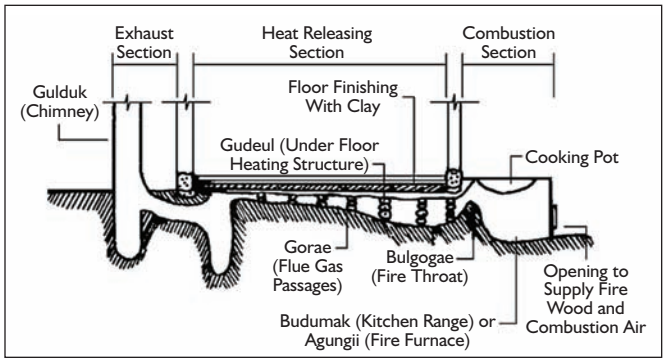

Figure 2: Structure of entirely ondol floored room.[9]

Photo credit: Kwang Woo Kim (left and right photos); Kyu Nam Rhee (center photo)

Figure 3: Entirely ondol floored room dating from the Chosun Dynasty. Left–agungii (furnace); center–bang (room); right–gulduk (chimney).

Development of Ondol in Korea

During the time of the Roman Empire, the Goguryeo Kingdom (37 B.C.), an ancient Korean kingdom located in the northern and central parts of the Korean peninsula, maintained its use of *kang*, *dikang* and *ondol* as referenced in ancient literature and supported by recent excavations in North Okjeo (what is now known as Russia's Maritime Province). Remains found at Sanggyeong Yongcheonbu Palace also show the evidence of floor heating used in Balhae Kingdom (698 to 926 A.D.), which occupied the southern part of Manchuria and the northern part of the Korean peninsula.[8]

In the early stage of development of *ondol* (4th century B.C. to 11th century A.D.), the L- or I-type *gudeul* was used for cooking and heating. This L- or I-type *gudeul*, with an indoor furnace, was lined along the wall in the room, and was covered by partial flooring so that the people using the living space could wear their shoes. The L-type *gudeul* was first developed by the lower class in the cold northern region and was then adopted in the mild central and warm southern regions of the Korean peninsula (see timeline). As its use spread to the southern region, the shorter I-type *gudeul* started to appear in the mild region. In the latter half of this period (700 to 1100 A.D.), more sophisticated L-type *gudeul* were found in several places, and their use indicated that some members of the upper class and other people of prominence had used the L-type *gudeul* in their living quarters.[9]

During the development of *ondol* on the Korean peninsula, the fire furnace was located inside the house and used for cooking and heating. However, it was inefficient because cooking would result in overheating during the summer and the smell of cooked food would linger. For this reason, around 1000 to 1200 A.D., the fire furnace was moved outside and the room was entirely floored with *ondol*, and thereby, established the future of true ondol. However, in the northern region of Korea, where the winter is long and severe, the fire furnace was kept inside the house and there was no partition wall between the fire furnace and the room. This form, of an entirely *ondol* floored room, is still being used in North Korea and the Yanbian Korean Autonomous Prefecture, located on the border of China and North Korea.

Entirely ondol floored room, which is traditional floor heating in Korea with agungii (outdoor furnace), gorae (flue gas passages) and a gulduk (chimney).[9]

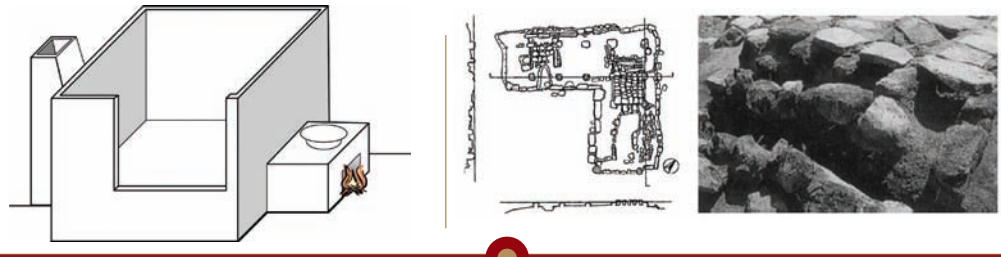

Image credit: Kwang Woo Kim (left image)

c. 500 A.D., Asia continues to use conditioned surfaces, but the application is lost in Europe where it is replaced by the open fire or rudimentary forms of the modern fireplace. Anecdotal literary reference to radiant cooling system in the Middle East that uses snow-packed wall cavities.

c. 700, A more sophisticated and developed gudeul was found in some palaces and living quarters of upper class people in Korea.

c. 1000, The ondol continues to evolve in Asia. The most advanced true ondol system was established. The fire furnace was moved outside and the room was entirely floored with ondol in Korea. Europe uses various forms of the fireplace with the evolution of drafting combustion products with chimneys.

c. 1500, Attention to comfort and architecture in Europe evolves. China and Korea continue to apply floor heating with wide-scale adoption.

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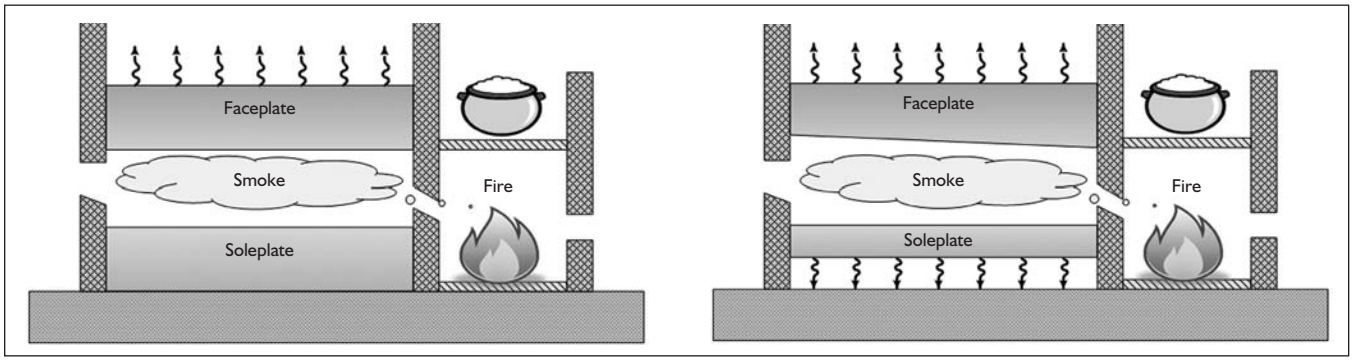

Figure 4: Reducing the heat loss to the ground in a raised kang. (Left) much heat loss via conduction to the ground. (Right) reduced heat loss via conduction to the ground.[13]

The entirely *ondol* floored room comprises an *agungii* (outdoor furnace), a *gorae* (flue gas passages), and a *gulduk* (chimney) as shown in the timeline. Unlike the *ondol* of the former period, the occupant needed to remove his/her shoes to enter the room, and people would sit or lie on the floor. During the Chosun dynasty (1392 to 1910), there was a wide spread adoption of the *ondol* (*Figures 2* and *3*, Page 44).

Modern Asia

China

Since 2000, hot water floor heating gradually has disseminated throughout modern China. Although China has adopted a central heating system that uses radiators, problems have arisen related to heating cost allocation and air pollution. Many residential and/or commercial buildings are being equipped with hot water floor heating systems in many regions of the country. Among the five climate zones of China (severe cold; cold; hot summer and cold winter; temperate; and hot summer and warm winter), three zones to the south of the Yangtze River (hot summer and cold winter; temperate; and hot summer and warm winter zone) have been regarded as regions that do not need heating during the winter.[10] However, the use of floor heating has recently spread rapidly through the southern regions, as well as in other zones (severe cold and cold zone) to the north of the Yangtze River.

Beijing is the largest market of floor heating in China, and since 2006 property developers have begun to consider floor heating at the first stage of building construction. In some cities (Qinhuangdao, Langfang) of the Hubei province, it has been reported that floor heating is being applied in 70% to 80% of newly constructed buildings. The Dongbei region (northeastern China) is renowned for its tradition of floor heating, where approximately 30% of the residential and commercial buildings are serviced by hot water radiant floor heating. The area along the Yangtze River has such cold and damp winters that the application of floor heating is expected to increase in this area to improve thermal comfort during winter. In the southern provinces, which usually have a relatively temperate winter, it has become necessary to adopt heating systems as a response to the heavy snow and severe winter of 2008.[11]

In China millions of traditional *kangs* are mainly heated by biomass with a low energy efficiency. It would be too costly to renovate and install modern water-based floor heating systems. Instead, studies have been looking at how to increase the energy efficiency of the traditional *kang*. One way is to decrease the heat loss to the ground by raising the kang as shown in *Figures 4* and *5*.

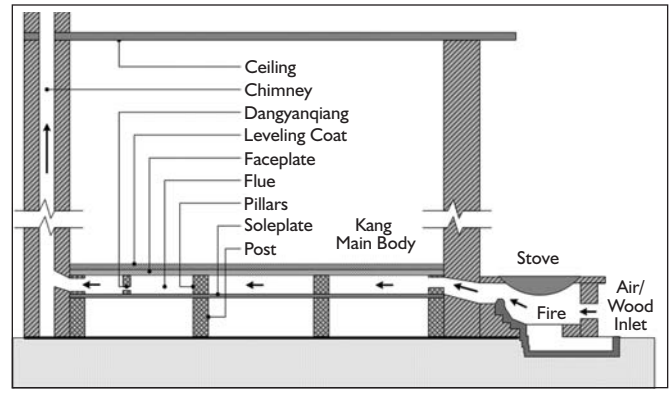

Figure 5: Reducing the heat loss to the ground by ducting the flue under the heated surface.[13]

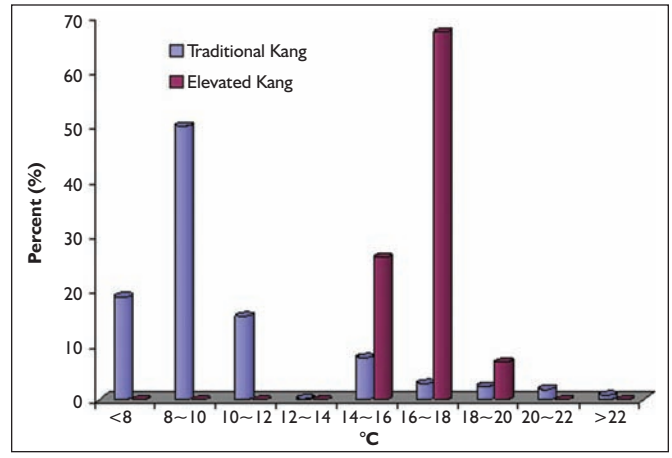

Figure 6: Measured increase in room temperature with an elevated kang compared to a traditional kang.

This type of renovation has a significant influence on the room temperature obtained as shown from the data in *Figure 6*, where the room temperature by a traditional kang is lower than 10°C (50°F) for more than 70% of the time, while for a raised kang the room temperature for 70% of the time is higher than 16°C (61°F).

Japan

In Japan, the application of the hot water floor heating system (*yukadanbou* in Japanese) has increased steadily since the late 1980s. Statistics from the Japan Floor Heating Association show that the average annual growth in the use of *yukadanbou* is approximately 10%.

Korea

Following the Korean War (1953), the traditional *ondol* was replaced in Korea by a modified *ondol*, where the *agungii* was adapted for the use of anthracite coal because the Korean government wanted to reduce deforestation. This modified structure was re-engineered with a prefabricated cast concrete block and mortar floor finishing. Less heat was lost from the combustion section and heat releasing section in this modified *ondol* than in that of the traditional *ondol*, because the *agungii* and the ground of the *gorae* were insulated more tightly (*Figure 7*). Despite this improvement, the occupants would sometimes inhale toxic gas leaking through cracks in and around the finished floor.

Since approximately 1975, the hot water radiant floor heating system has been used to improve thermal comfort, maintenance, energy efficiency and to prevent toxic gas hazards. Due to rapid modernization and economic development, the supply of apartments has been radically increasing, and the hot water floor heating system has become the only main heating system for residential buildings.

During the early 1970s, several construction companies provided radiators in new apartments to encourage the movement towards a more western lifestyle, which was regarded as modernized and convenient at that time. However, radiators were rapidly replaced by floor heating because most occupants were accustomed to a warm floor surface, which could not be attained by using radiators. Subsequently, hot water radiant floor heating has been used in almost every residential building, even in Tower Palace, a high-rise residential building in Seoul, Korea. The floor area of approximately 60 million m^2 (65 million ft^2) is being equipped with floor heating system annually in Korea.

Part 2 covers Europe, the Middle East and North America.

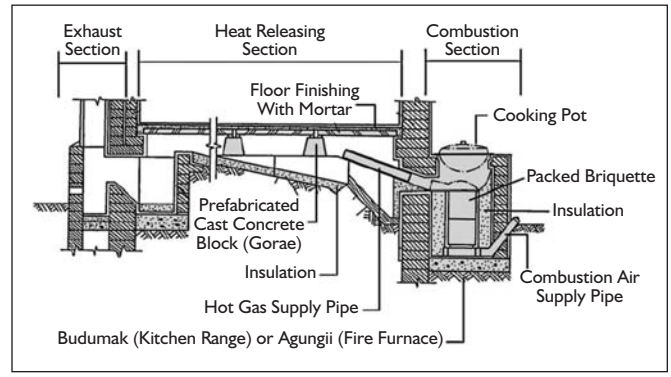

Figure 7: Structure of modified anthracite coal ondol.[9]

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