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Early Iron Domed Roofs in Russian Church Architecture: 1800–1840

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Large-span church domes rank among the most highly representative expressions of architectural and engineering design of their time, making them extremely interesting subjects for historico-architectural analysis. Almost without changing their quasi-spherical form, these structures have passed through many stylistic periods in the development of architecture and many stages in the development of building technology, remaining a distinctive feature in the evolution of construction. The new possibilities brought by the Industrial Revolution at the end of the 18th and beginning of the 19th centuries fundamentally altered the construction of large-span domes, often transforming them into complex experiments in engineering, particularly with regard to iron structures. The aim of this paper is to analyse the most important examples of early ("empirical") iron and timber domes from building practice in St. Petersburg between 1800-1840. Contemporaries of the now demolished Halle au Blé in Paris, together with a number of other innovative structures of the early 19th century, they remain an important and little studied part of our European architectural heritage, without knowledge of which the history of the development of early iron architecture is incomplete [1].

It should be noted that the analysis in this paper of orthodox church domes as complex works of engineering is as one-sided as their more usual treatment as intricate architectural forms. Rooted deeply in Byzantium, domed roofs were the symbolic embodiment of the basic Christian canons [2]. Originally designed to complete the interior vertical space of the church, domes were to become the main spatial element in the embodiment of the orthodox model of the universe, determining the spiritual property and significance of the building itself. Large-scale church buildings traditionally occupied an important position in both the town planning of medieval and post-medieval Russian towns and in the typological hierarchy of public buildings of their day. The special social and town planning status accorded orthodox cathedrals transformed domed structures into distinctive symbols of particular historical periods.

The Kazan Cathedral Dome, 1806-1810

The wrought-iron outer dome of the Kazan Cathedral in St. Petersburg is generally considered the first iron 'spatial roof' of significant size in Russia[3]. Erected in 1801-1811 from a design by the architect A. N. Voronikhin[4], this building is a gifted attempt at interpreting the compositional plan of St Peter's in Rome in the monumental style of St. Petersburg high classicism (Fig. 1).

Fig. 1 The Kazan Cathedral, St. Petersburg (1801-11), a view from Nevsky Prospect.

Begun during a period of rising patriotism in the face of anti-monarchist currents emanating from France, the Kazan Cathedral was conceived by Tsar Paul I as a national monument – a systematic work by Russian

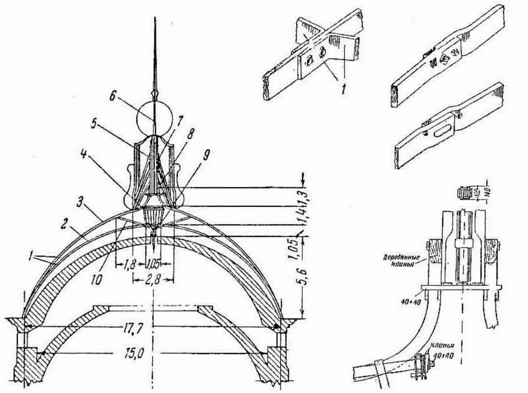

Fig. 2 The dome of Kazan Cathedral, 1806-10 (from V.F. Ivanov, *Istoriya stroitel'noi tekhniki* (History of Building Technology), p.321). Details show the bolt and wedge joints of the ribs and the structure supporting the upper assemblage.

masters, entirely constructed from native materials[5]. As one of Russia's largest-scale structures of the early 19th century, today it provides a wealth of material for analysing the state of building technology at the time, primarily in the field of masonry construction[6].

The main vertical accent of the building became the slender dome erected on a high drum above the semi-circular colonnade which opened on to Nevsky Prospect (height of the cathedral with dome: 71.6 m). Its profile was to play an important role in forming the appearance of the central part of the city's main axis (Fig. 2). As with the majority of large-scale European churches of the 18th to 19th centuries, the Kazan Cathedral dome was composed of three levels of enclosing structures: a decorative inner dome (15 m in diameter with an light opening of 6.2 m in diameter); a second brick dome (outer diameter – 17.7 m) positioned above the light openings of the drum; and an outer iron enclosure of the same diameter (17.7 m). Completing the architectural appearance of the cathedral, this dome also had other functions: its ribs provided a frame for the iron roof and bore the weight of the chandelier dropped through the circular openings of the two lower brick domes.

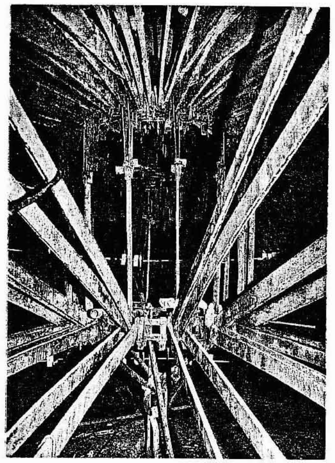

Fig. 3 Kazan Cathedral: the inner supporting drum of the dome, elements of the lower belt and cross stays.

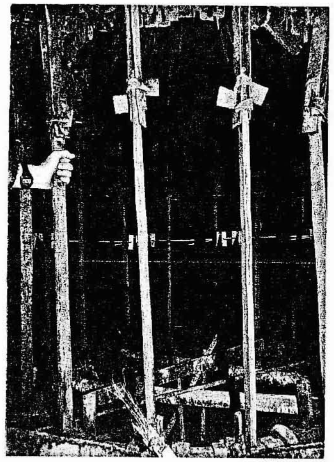

Fig. 4 Kazan Cathedral: the vertical ribs of the dome's inner drum.

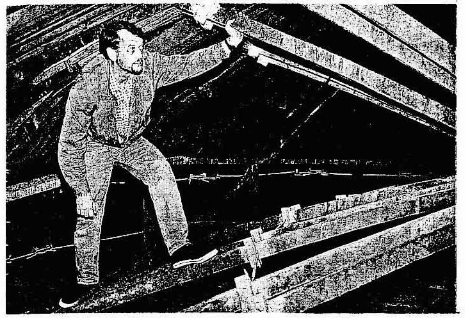

Fig. 5 Kazan Cathedral: the braces between the outer and inner ribs of the dome (showing also reinforcement introduced in 1993).

The outer dome of the Kazan Cathedral is executed as a radial-concentric structure without diagonal braces and consists of two layers of supporting ribs [7]. Joined by a common outer supporting ring of 17.7 m in diameter, they divide in the centre of the span at a height of 1.4 m. The outer ribs (128 pieces) form a frame for the dome's iron roof covering and are of two types of section: 120 x 15 mm (32 pieces) and 70 x 15 mm (96 pieces). The stability of the structure's "outer layer" increases that of the 'inner layer' consisting of 32 ribs in 70 x 15 mm section, attached to the outer ribs by 32 braces. These braces facilitate the equal distribution between the ribs of two levels of vertical loads – the dome's decorative lantern (2.8 m in diameter) and the chandelier. Therefore, the 32 twin-layered segmental arches become the main supporting element of the dome structure and are built with only a partial lattice frame, leaving a considerable unsupported length of arch ribs (Figs. 2, 5). It is clear that stress diagrams for similar arch structures were too flexible and insufficiently stable. However, the large number of twin-layered and ordinary ribs (128), set close together, reduced the effect of torsion due to wind loads, as a whole contributing to the structure's exceptional state of preservation today [8].

All elements of the dome and its drum are constructed from wrought iron of flat section. The bars from which the radial ribs are made are positioned in vertical planes and attached by sections of the same bars, forming circular elements in plan (Fig. 3-5). The radial and circular elements are fastened by bolts 1.5 inches in diameter; the iron bars along the ribs by bolts or wedges inserted into holes in the bars in a heated state and hammered down (Fig. 2). In effect, this type of joint was the prototype for rivets, which were to appear in Russia in the 1830s, and is an interesting example of a transitional form of riveted joint. The central vertical strut, which supports the cathedral's cross, is formed from a cluster of iron bars fastened together by clamps. Timber wedges have been introduced into the structure where the upper drum joins the dome.

Sources on the history of the construction of the Kazan Cathedral[9] indicate that the time of its final design and the erection of the dome's iron structures was 1806-1810. The first granite monoliths for the inner columns were supplied in 1804. In the following year, the brickwork proceeded apace and by autumn the building had been raised up to the cornice. In 1806 preparatory work began on the cathedral

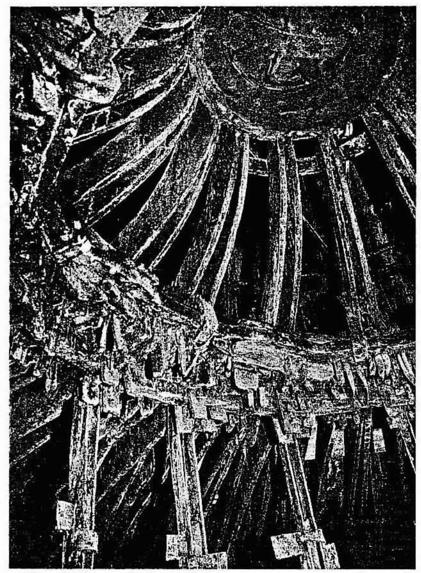

Fig. 6 Kazan Cathedral: the upper supporting ring and radial ribs of the dome.

roof. In 1807, after completion of the vaults, scaffolding was erected to raise the main dome[10]. The following year, having unexpectedly acquired a considerably greater freedom of action[11], Voronikhin planned to finish the dome, balustrade and front facade, and remove the scaffolding in the autumn of 1808. As archival material shows, the dome's ribs, semi-circular braces and clamps – manufactured from templates at state-owned iron foundries – were already prepared in 1806[12]. Documents from the next building season note the following: "*...To be recorded in the inventory – items received from the state factory store, under Mr Gascoigne's control, for the construction of the Kazan Church and witnessed by Mr Beketov, the supervisor: 16 cast-iron bases for the dome, each weighing 26 poods... Throughout this year of 1807 for various uses in the construction of the Kazan Church: various grades of iron with details of individual forged items produced and any waste. From quality iron... two circular braces manufactured from template for the dome – 3/4 inch wide, 3/8 inch thick, 140 poods in weight, 30 foot long... braces manufactured from template for the dome – 3 inches wide, 3/4 inch thick, 546 poods in weight, 37 foot long... removable clamps manufactured from template for the dome – 1 inch wide, 3/8 inch thick, 264 poods in weight, 11 foot long* [13]."

The initial plan had been to assemble the sections for the dome on the ground and then raise them into position in one piece[14]. However, due to lack of experience of similar projects, the workmen were unable to cope with the assembly technology which was new for those years. Subsequently, a new method for raising the dome was proposed – the assembly of the dome's elements in situ from a special wooden model. The erection of the ironwork above the masonry dome was carried out in parallel with the building's interior decoration from March to August 1809[15]. The following year the iron frame was covered with white tinplate[16]. The cathedral's interior was completed in 1810-1811 and the building officially consecrated on 27 September 1811.

The detailed archival materials of the 'Commission on the Construction of the Kazan Cathedral' do not contain any graphic or textual information regarding the design of the iron dome. However, they do confirm Voronikhin as the author of the structural solution for the building, including the dome's completion in iron[17]. The absence of detailed technical documentation on the Kazan Cathedral dome was most probably due to the structural solution changing in the course of the ten years of building work, while stress factors were tested in the process of preparing 'detailed practical models'. Indirect confirmation that work on the dome's design was completed at almost the same time as the building work itself, is provided by Voronikhin's sections of the cathedral made in 1810. These already show the construction of the outer dome in the form of a thin shell, supported by two crossed, curvilinear braces[18]. Archival materials prove that it was Voronikhin who prepared the technical calculations for the design, in particular determining the force of the thrust from the brick domes. The calculations themselves, in their traditional form for those years (combined loads, stress calculations, etc.) are absent from the comments, replaced by an enumeration of the weights of individual elements of the masonry structures[19].

The iron dome of the Kazan Cathedral has been compared in many Russian-language publications to the cast-iron dome of the Halle au Blé in Paris (1807-1813, architect – F. J. Bélanger, engineer – F. Brunet), one of the first and most important examples of early iron domed roofs[20]. Indeed Voronikhin had studied architecture and building practice in Western Europe and, evidently, this found its reflection in the design for the Kazan Cathedral. The building design as a whole included a series of technical innovations which bear witness to the author's originality of thought in engineering[21]. However, the comparison with the Halle au Blé is not entirely correct. In contrast to its Parisian contemporary, which bore a cast-iron dome of almost 40 m diameter[22], the only role played by the Kazan Cathedral's light 17 m domed enclosure was that of a structure with a limited range of supporting functions. If the dome of the

Halle au Blé was to become one of the first fruits of activity by the young French engineering school, already familiar with the use of stress calculations, the roof of the Kazan Cathedral may be considered an 'empirical' example of a new iron structure integrating the considerable achievements of the Urals metal industry in 18th century Russia with the country's wide experience of timber construction (obvious from a study of the joints in the roof). It is fair to consider this domed structure one of the last examples of the virtually forgotten technique of Russian iron roofs of the second half of the 18th century – a little studied period which may rightly be considered the first stage in the development of Russian iron structures [23].

The Domes of Trinity Cathedral, 1827-1835

The next important stage in the development of early Russian iron domes may be considered the design and construction of the Trinity Cathedral in St. Petersburg (1827-1835, architect – V. P. Stasov)[24]. One of the last buildings in the city to be built in the traditions of high classicism, the cathedral is a symmetrical cross in plan with four small domes and one central dome (height of the building with dome 74.5 m) (Fig. 7). In contrast to the Kazan Cathedral, the domes of Trinity Cathedral consisted of two layers of enclosing structures: a spherical, brick inner dome and a light metal crown raised high above the former. An important feature of the building history of Trinity Cathedral is the existence of three versions of the design for the domed roof. The alternative designs were occasioned by an unexpected building accident when, at the end of February 1834, a gale-force wind swept away the primary roof of the main dome – a light iron structure – from the almost completed building. The task of developing a design for the new roof was given to P.-D. Bazaine, one if the leading representatives of the French engineering school in St. Petersburg[25]. Between February and June 1835 he developed two fundamentally different versions of the design. The first proposal, which courageously developed the structural principles of iron radial domes, was rejected[26]; the second proposal, which implemented new statical principles for composite structures using traditional timber, was executed in the same year. The professional discussions surrounding the design of the domes of Trinity Cathedral, in which more than ten leading engineers and architects of the St. Petersburg of those years took part, did much to determine the principles for the later development of iron metal "spatial" structures in the city.

Fig. 7 Trinity Cathedral: St. Petersburg, 1827-1835 (from a postcard view of c.1900).

Drawings of the destroyed metal roof of Trinity Cathedral's large dome have not survived in the archives[27]. The only known description of this structure, developed in 1827-1831, can be found in written materials belonging to the commission which investigated the building accident:

> *"a) The ribs of the dome's structure are made of bar iron of flat section. The use of this flexible material in structures subject to perceptible movements and changes does not contribute to the system's stability... If it is decided to use this material again in cases similar to the existing, then square-section bar iron has indisputable advantages over either flat-section bar iron or band iron.*

> *b) The ribs were almost entirely independent of each other since, apart from the upper section which was fastened by horizontal braces to support the lantern and cross, over the remaining surface of the dome the ribs were joined only by thin strips of copper intended for securing the copper roofing sheets.*
>
> *c) The upper section, where the lantern and cross were fastened, was too heavy in comparison with the light structure of the dome itself... at the slightest movement of the system, the centre of gravity – which was set too high – upset the balance and contributed to the dome's collapse.*
>
> *d) Finally, the main reason for the incident lies in the dome having been placed on a main wall without being solidly tied to the latter. In the opinion of the Commission, a sold tie is essential, if not for all the ribs, then at least for a number of main ones which should be larger and reinforced to allow the attachment of the less resistant ribs."*[28]

This roof consisted of a radial-circular structure of 25.6 m in diameter (probably two-layered) with elements made of flat-section bar iron. The ribs of the upper section of the dome were joined by horizontal iron braces, those of the lower section only by thin strips of copper. It is obvious that the structure as a whole was not fixed securely to the supporting wall and that the upper section with the lantern and cross was too heavy, while the considerable elevation of the structure's centre of gravity reduced its stability in wind conditions. These characteristics – discovered only once the roof had already collapsed – led to the rare catastrophe: of all the dome's elements, only the iron supporting ring remained in place, while the framework of the dome was thrown by the wind on to the small eastern dome and the brick vault of the church's eastern side-chapel. All the ribs were bent and a portion of them broken; the circular braces between the ribs were torn and the copper sheeting torn off[29].

The identical structures of the small domes, which were completed at the same time as the main dome and survived until the beginning of the 1950s, add to our picture of the structural solution for Trinity Cathedral's great central dome (Fig. 8)[30]. 11.5 m in diameter and 8 m high, each dome consists of a radial-circular structure of 64 curvilinear iron ribs (70 x 15 mm in section) – identical to the rib sections in the Kazan Cathedral dome – fastened by 18 horizontal rings (50 x 5 mm in section). The lower supporting ring is 50 x 50 mm in section. Each dome is topped by a small lantern,

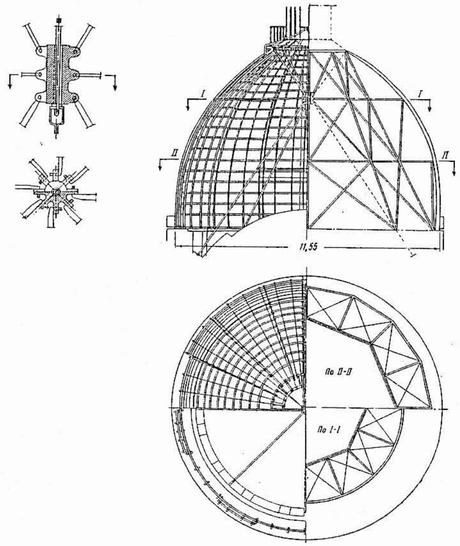

Fig. 8 The small iron domes of Trinity cathedral, 1827-34: section, plans and details of the stabilising structure (from V.F. Ivanov, *Istoriya stroitel'noi tekhniki* (History of uilding Technology), pp.324-25). The right-hand side of the section and plan show the design for the reconstruction of 1952.

comprising 24 ribs, placed upon the upper supporting ring (60 x 60 mm in section), to which all the ribs are connected by means of "forked" joints. The light ribs of the structure were stabilised using a principle new to Russian practice: a cast-iron component with eight vertical ribs was suspended within the dome at a point around 2/3 of its height. Braces were then attached to these ribs in eight radial planes (three braces per plane), strengthening the frame in a radial direction. However, notwithstanding the smaller spans of the small domes, the rigidity provided by their copper roofs in a tangential direction proved inadequate: during the Second World War two of the domes were seriously damaged by the effect of an explosion, the ribs coming loose from the dome's vertical planes and twisting around the vertical axis[31].

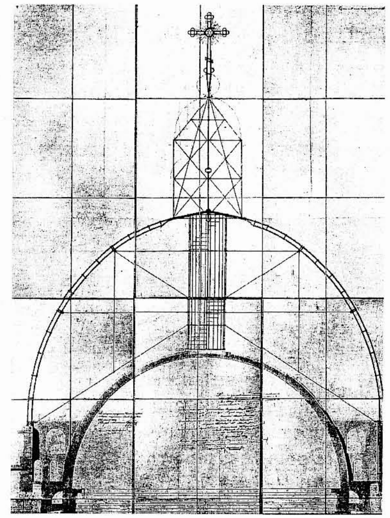

Fig. 9 Design for the great iron dome of Trinity Cathedral by P.-D.Bazaine, 1834: section (from the Russian State Historical Archive, St. Petersburg).

The original iron domes of Trinity Cathedral were the combined work of the architect V. P. Stasov and his constant partner on iron structures, the engineer and metallurgist Matthew Clark. Whilst recognising the obvious breadth of Stasov's professional interests[32], as a man who constantly used innovative engineering solutions in his buildings, the frequent assertion in Russian language publications that he was the sole author of the complex domed structure – in terms of its structural design and details – remains untrue. In fact, this dome was to be the first work in the field of iron spatial roofs by Matthew Clark, one of the leading exponents of the British experimental engineering school in St. Petersburg[33]. Lack of experience in the erection of roofs with wide spans[34] clearly prompted an attempt at further development of the structural concept of the Kazan Cathedral dome, an illustration of the practical application of the postulate "similar structures are equally stable" so typical of empirical engineering of the 18th to early 19th centuries. However, the increase in diameter from 17.7 to 25.6 m proved fateful for this construction and led to its collapse.

At the end of April 1834, P.-D. Bazaine, a member of the commission set up to investigate the cause of the accident, presented a 6-sheet design for the new dome of Trinity Cathedral (estimated cost 120,000 roubles). The documentation for this design, which has survived intact in the archives, remains to this day insufficiently studied by historians of architecture and building technology[35]. In fact, Bazaine's structure (the second version of the domed enclosure) is an interesting attempt at improving the deficiencies of the original "empirical" iron roof of Trinity Cathedral, whilst preserving the original structural principle. Outlining the reasons for this approach to the project, Bazaine wrote: *"Changer aujourd'hui de systéme, pour construire avec d'autres matériaux, ce serait avouer, il me semble, que l'on a reconnu à la première opération, un caractère d'impossibilité, qui dans l'opinion publique ne manquerait pas de décharger l'architecte de tout le blâme qu'il a justement encourie, pour le déverser sur une authorité parfaitement innocente des fautes qui ont été commises. Cette considération... ne m'a pas plus permis de penser au bois, qu'à la fonte; dans la rédaction du projet dont j'étais chargé"* [36].

Bazaine designed the 26.7m radial-circular dome from 104 radial ribs of two different types, joined by three circular rings (Fig. 9, 10). It was intended to execute the 32 'main' ribs of the structure as light arches with parallel rings of iron strips (30 x 25 mm in diameter; circa 40 cm distance between the axes) joined together by 13 vertical cross stays. In line with the architectural solution for the dome[37], the 'main' arches were positioned on a variable module; the standard arch ribs between the two rings on a regular module (Fig. 9, 11). All the ribs met at the flat central supporting ring, almost forming a parabola in section. The lantern structure (height 9.6 m; diameter 5.4 m) rested on the outer periphery of the supporting ring and itself supported the cross. Lower down, a cylindrical lattice structure (length 10.6 m; diameter 2.9 m) was suspended from the inner periphery of the same supporting ring to hold the spiral staircase. At the same time, this structure strengthened the radial braces, these being the main elements stabilising the roof (Fig. 9, 12). In Bazaine's design, the structure of the inner circular staircase played the same role as the cast-iron component for fastening the braces in Clark's original design Fig. 13). In Bazaine's design, three groups of radial braces were attached to the dome's three rows of circular rings, commencing from the supporting ring. The introduction of a system of flexible braces into the spacial radial structure ensured stability along the working surfaces of the twin-layered arches. However, maintaining rigidity as the dome pivoted remained problematic.

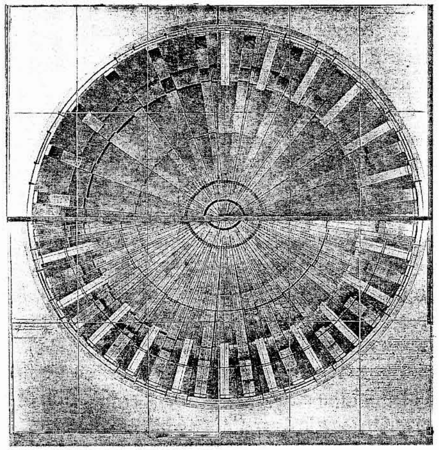

Fig. 10 Design for the great iron dome of Trinity Cathedral by P.-D.Bazaine, 1834: composite plans for various levels of the structure (from the Russian State Historical Archive, St. Petersburg).

At the beginning of May 1834 Bazaine's design and the opinions of commission members[38] were reviewed by the Council of the Department of the Way of Communications and Public Works. The majority of those present, terrified by the

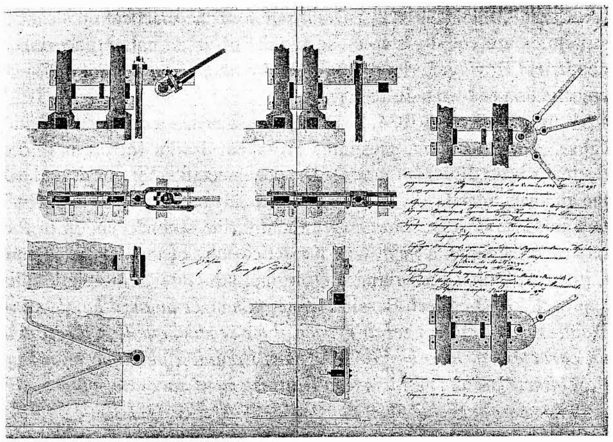

Fig. 11 Design for the great iron dome of Trinity Cathedral by P.-D.Bazaine, 1834: supporting assemblages and details of the twin-layered arches (from the Russian State Historical Archive, St. Petersburg).

collapse of the first iron dome, considered wrought iron an entirely inappropriate material for the construction of a large-diameter dome, irrespective of the structural solution. Of all the members of the commission, only the architect K. A. Thon acknowledged as feasible the use of wrought iron for the supporting ribs of the wide-span dome, while refusing to endorse the proposed structural scheme. At the same time, he expressed the opinion that the dome of Trinity Cathedral might be implemented in brick[39]. A.-R. Montferrand, who also did not support Bazaine's structural solution, proposed that the feasibility of designing the dome in timber be investigated[40]. By far the most decisive voice raised against the use of iron in domed structures was C. Potier: "... *Or dans une coupole toutes les parties sont pressées de le sens de leur longueur, ou poussées par le vent pendiculairement à le longueur et cela ne peu être autrement; et s'ensuite, que de touts les materiaux le fer forgé est celui, que est le plus impropre à la construction d'une coupole. Ce principe une fois démontré, l'examen de diverses parties de la coupole proposée devient inutile et dès lors superflu*".[41]

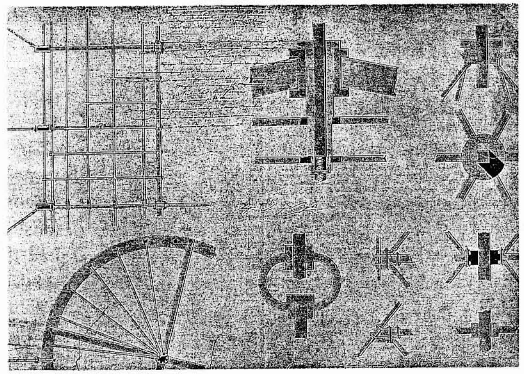

Fig. 12 Design for the great iron dome of Trinity Cathedral by P.-D.Bazaine, 1834: structural details of the lantern and staircase (from the Russian State Historical Archive, St. Petersburg).

In the opinion of most experts, cast iron – rather than wrought iron – was an excellent material for withstanding compression forces, making it ideal for building domes without the requirement for an arrangement of internal stabilising braces. The commission members agreed unanimously that cast iron had clear advantages over other building materials. In particular, C. Potier remarked in his extensive review of the design that "... *I cannot agree with Lieutenant-General Bazaine's decision to design the dome once again in wrought iron, notwithstanding all his proposed important improvements to the first system, and I believe that cast iron would far better answer the given purpose, that is by ensuring the stability of the dome even in the most unfavourable circumstances.*" Although the reviewers correctly pinpointed the potential areas of use of these new building materials (wrought and cast iron) in consideration of the structure's optimal stresses (compression-tension), they failed to appreciate the essential engineering innovation of Bazaine's design. He had attempted to develop a light enclosing structure in which "... *(wrought) iron may replace cast iron in*

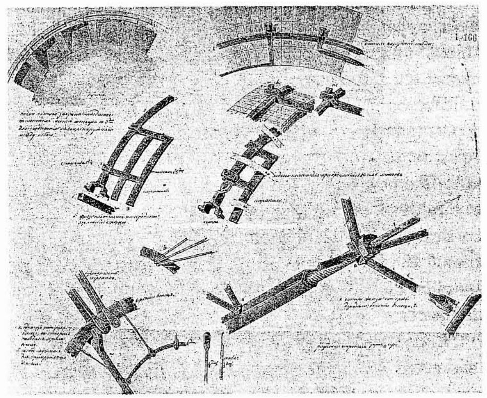

Fig. 13 First design for the iron dome of Trinity Cathedral by Matthew Clark, 1831?: structural details of the concentric circular elements and supporting frame (from the Scientific Library of St. Petersburg University of Structural Engineering).

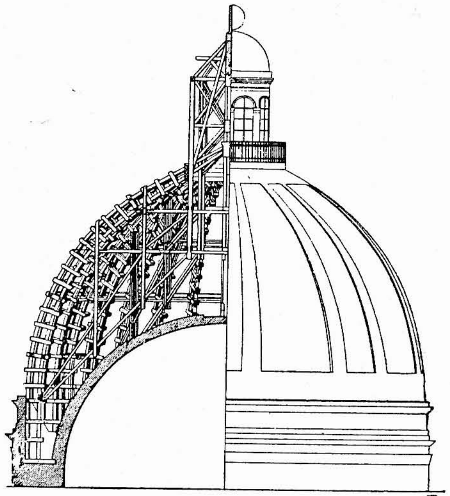

Fig. 14 Design for the wooden dome of Trinity Cathedral by P.-D.Bazaine, 1834-5: (from *Ocherki istorii stroitel'noi tekhniki Rossii* (Sketches of the History of Building Technology in Russia), p.51).

all instances where, by means of internal ties, it can achieve an equal degree of inflexibility...". Indeed, to increase the supporting capabilities of his structure, Bazaine chose the untraditional approach of increasing the sections and creating a composite system built on the combination of compressed-curved arch elements and tensile-flexible elements (Fig. 9). These had the function of contemporary back stays and considerably increased the rigidity and stability of roofs in complex spatial forms[43]. In effect, Bazaine's design for the iron dome was neither understood nor fully appreciated by his colleagues, a fact he noted with bitterness: "*Toutes les qualités que j'ai tâche de rendre inhérentes à mon systême, n'ont été ni analysées, ni même bien comprises par les membres de la Commission... Ce que Telford eût fait sans doute pour son pont de chaînes, je crois pouvoir le faire aujourd'hui pour ma coupole, en demandant que les membres de la Commission veuillent bien se donner la peine de résoudre la question suivante, qui, ce me semble, a toujours été la seule qui eût dû faire l'objet de leurs investigations; déterminer par des calculs exacts basés sur les principes de l'art et les données de l'expérience, quelle est la relation qui existe entre les plus grands efforts qui doivent agir sur la coupole en fer forgé, et le maximum de résistance dont elle est susceptible, et faire connaître, d'après cette relation degré de confiance qu'on peut avoir dans la stabilité de cet ouvrage.*"[44]

Archival documents indicate Bazaine's readiness to provide calculations on the roof and "*... prove that my design satisfies without the slightest doubt all conditions necessary to ensure stability.*" At the same time he proposed that his opponents prove the error of his technical solution for the new dome using their own calculations[45]. The absence of any theoretical foundation or example from the practice of those years increased the doubts of the commission members. To settle once and for all whether the roof could be built from Bazaine's design, it was decided to conduct practical trials on two full-scale opposing arch ribs from the dome[46]. However, both the trials and the early design work for Russia's first cast-iron dome were halted by an order from Tzar Nicholas I calling for a timber design for the new dome to be drawn up immediately, using the scaffolding left over from the erection of the Alexander Column on Palace Square[47].

In mid-June 1834 Bazaine drew up a new design for the large dome of Trinity Cathedral to be implemented in timber at an estimated cost of 138,500 roubles (Fig. 14). Clearly unwilling to continue the engineering discussions begun when the earlier design was under consideration, he presented his new design as a traditional structure containing no technical innovations and, therefore, no items for fresh discussion. "*The system I have adopted for the dome structure combines all the conditions necessary to ensure its stability since no change to the form of the structure as a whole nor to the arrangement of the constituent parts is permitted. Therefore, I consider any additional strengthening of the system to be superfluous*"[48].

The main feature of this dome, which has survived intact to the present day, is the clear transfer of new structural principles, developed for iron domes, to a traditional building material

– timber (Fig. 9, 14). The timber dome of 24.8 m in diameter and 21.3 m in height consisted of 32 identical radial ribs spaced at regular intervals. Each rib was conceived as a twin-arch with parallel ribs (total height approx. 1.1 m) joined by 21 paired vertical struts (Fig. 15). The arch ribs are constructed from two squared timbers of 30 x 30 cm in section, set 20 inches (50.8 cm) apart. Twenty-four ribs rest against the upper timber supporting ring (crown) of (5.33 m) in diameter. The remaining eight ribs pass through the ring and meet at an octagonal oak shaft positioned on the dome's axis. In a circular direction the ribs are fastened by four tiers of twin braces, which join the arches and form a two-layered spatial system. To increase the stability of the supporting section of the timber dome, its ribs reach down to the base of the inner brick dome and are strengthened by a third, horizontal tier of struts. Resting on the attic section of the brick drum and on the brick dome, these struts prevent any horizontal displacement of the rib supports (Fig. 17).

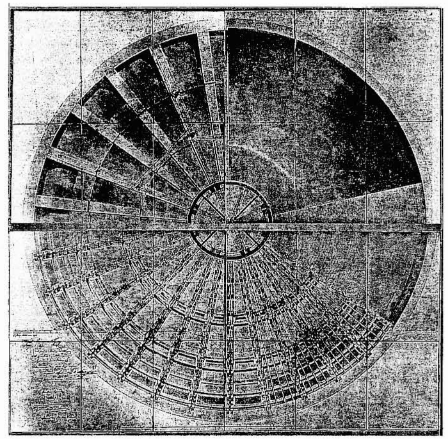

Fig. 15 Design for the wooden dome of Trinity Cathedral by P.-D.Bazaine, 1834-5: composite plans of various levels of the structure (from the Russian State Historical Archive, St. Petersburg).

Torsion and bending loads from the lantern frame (weight inclusive of cross – 25,716 kilos) were distributed across the structure's eight main ribs through a system of vertical "suspended" uprights and sloping tie-beams (Fig. 16). In many ways this system of internal struts and tie-beams repeated in timber the principles contained in Bazaine's design for the iron dome and provided additional spatial rigidity to the roof. On the exterior, the dome is clad in timber boards (3 inches thick) laid down along the ribs. The cladding is completed by a lining of one-inch boards covered in sheets of copper. All squared beams in the structure are fastened by pins and bolts (Figs. 16 – 17)[49].

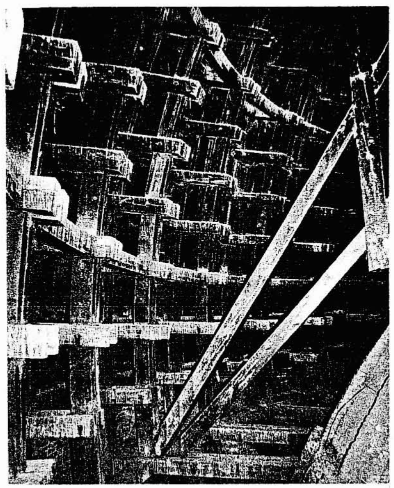

Fig. 16 The wooden dome of Trinity Cathedral (1834-5), showig the twin-layered ribs and radial braces.

The design for the timber dome was approved unanimously and by July 1834 construction work had already commenced. Building work was carried out by the structural engineer P. P. Mel'nikov, later to become famous as the builder of the St. Petersburg-Moscow railway. For the first time in Russian practice the cantilever assembly method – familiar from the Halle au Blé – was used to erect the dome[50]. The preliminary assembly of the 4.27 m high sections was carried out from templates laid out in a special area. Next the sections assembled below were raised along an

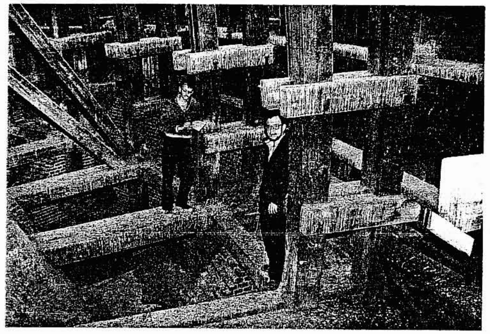

Fig. 17 The wooden dome of Trinity Cathedral (1834-5), showing the junction of the ribs and brick drum.

inclined surface and fixed into position as stipulated in the design. Three months later, in October of the same year, work was complete. The co-operation of the two engineers Bazaine and Mel'nikov – the two leading Russian specialists of their day – created a dome that is unique both in structure and building technology. The publication of descriptions of the construction of the timber dome (1835) made its timber structure widely known in specialist circles[51]. At the same time, the previous design for an iron dome with flexible braces was entirely forgotten.

The debate on the use of new or traditional building materials in architecture (wrought iron, cast iron, timber) that unfolded during the design of the Trinity Cathedral dome was the most important debate of its kind in Russia and ranks alongside the debates on principles seen among European schools of engineering in the early 19th century. The design of the Halle au Blé in Paris in 1806-1807 had been met with opposition from the adherents of masonry and cast-iron structures[52]. The fame of this project, as well as the very close ties existing between specialists of the St. Petersburg Corps of Engineers of the way of communications of those years and the French engineering school, ensured that the dome of the Halle au Blé was constantly held up as a standard during all stages of discussions on Bazaine's design. Even after the construction of the timber version of the Trinity Cathedral dome, contemporaries continued to compare it structurally with the original timber dome of the Halle au Blé. *"Before the construction of the cast-iron dome, the hall was surmounted by a timber dome built to Philibert Delorme's design and was the largest timber structure of its kind, although sadly it fell victim to fire. Second place after the Halle au Blé, in terms of size, should go to the Trinity Cathedral dome which replaced the original iron dome carried off by a gale..."*[53].

The final structure of the Trinity Cathedral dome is interesting not only as an example of the new type of timber roof – the "spatial" two-layered system – but also as an example of the successful translation of a well-known cast-iron prototype (the Halle au Blé) into timber, together with the introduction of elements from Bazaine's design for the reinforced light iron dome. This unrealised design (Fig. 9-12) may justly be considered one of the most interesting engineering proposals in St. Petersburg practice of the 1820s-1830s. In contrast to the "empirical" method of designing new structures used in the construction of the Kazan Cathedral dome, Bazaine's design method was based on the optimisation of static characteristics, rather than fixed geometric parameters (the traditional, almost spherical form). His design for the new metal dome with its "flexible stays" represented the optimisation of existing prototypes to an approximately "ideal static model".

The Dome of St Isaac's Cathedral, 1836-1839

St Isaac's Cathedral was built between 1818-1858 in the centre of St. Petersburg's complex of ceremonial squares as the Russian Empire's foremost religious building[54]. Designed by the architect A.-R. Montferrand[55] in the last decades of the development of classical architecture, this monumental, cruciform structure almost spanned two epochs – late classicism and early

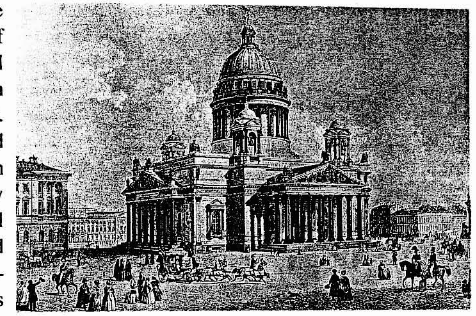

Fig. 18 St. Isaac's Cathedral, 1818-58.

historicism (Fig. 18) . The unique position – from a town planning point of view – of St Isaac's Cathedral predestined its dome to become the main vertical accent in the historic centre of St. Petersburg. This uniqueness was sensed by Montferrand and found expression in the building's composition: from many angles, its vast volume appears a pedestal for the granite colonnade of the drum and its crowning dome. The traditional five-domed composition of orthodox churches was provided by the small domed crowns of the open bell towers, whose fine profiles underlined the might and importance of the central dome's size (height of the cathedral with cross – 101.5 m).

The original versions of the design (1818, 1825) presupposed the construction of a three-layered brick enclosure for the cathedral's central dome[56]. At the same time, all the supporting structures of the building itself were also designed in masonry and brick[57]. However, building delays and the long-standing experience of using iron in St. Petersburg building practice at the beginning of the 1830s, rendered the majority of Montferrand's masonry structures archaic and technically complex. The necessity for essential compositional and structural changes led to the development of a new (third) design which was approved in 1835. The first, rather dilettante proposals for a metal dome for the cathedral under construction appeared as early as 1826 [58]. Pronouncements on the advantages of cast iron in the construction of wide-span domes, which had been made so convincingly during discussions on the designs for the Trinity Cathedral domes (1834), as well as Montferrand's participation in these same discussions, evidently influenced the choice of structure for the central dome of St Isaac's Cathedral. In the final version of the design, it assumed the form of an entirely iron (cast-iron and wrought-iron) composite roof. In unanimously supporting the experiment to create an innovative iron roof for Russia's foremost religious building, the members of the commission for the cathedral's construction were clearly motivated by both technical considerations and the desire to set an example: *"saisirent cette occasion de prouver au monde savant qu'à Saint-Péterbourg on était loin de se traîner sur les vielles routines. Au contraire, mettant à profit les progrès de l'epoque, on y prenait l'initiative dans l'application des grandes constructions en métal..."* [59].

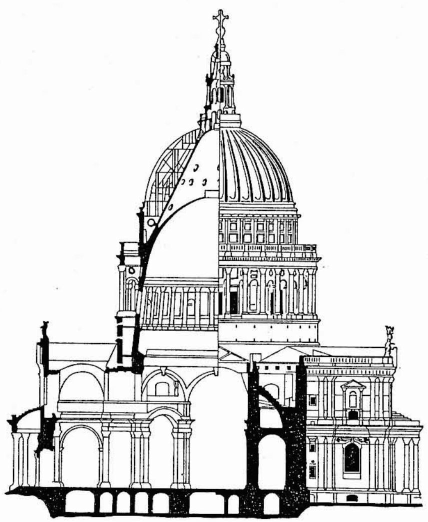

Fig. 19 St. Paul's Cathedral (1675-1710), the prototype for the dome of St. Isaac's Cathedral.

During design work on the dome of St Isaac's Cathedral, Montferrand studied the dome structures of other famous cathedrals –

Florence Cathedral, St Peter's in Rome, Sainte-Genevieve (Panthéon) in Paris, St Paul's in London, but also the Kazan Cathedral in St. Petersburg[60]. Among books used by Montferrand in his work, we find monographs by Philibert Delorme, Mathurin Jousse, Girard Désorge, François Dérand, Mézange Desfourneaux, Rondelet and Grafft. Analysis of existing buildings led Montferrand to the conclusion that "*..A l'exception de l'église Saint-Paul à Londres, nous ne connaissons aucun grand monument à dôme qui offre une solidité irréprochable...*"[61]. As a result, it was the dome of St Paul's Cathedral in London that was taken as the prototype for the new roof of St Isaac's (Fig. 19). At the same time, the "three-casing" structural plan of St Paul's masonry and timber roof was translated into new materials – cast wrought and wrought iron. As Montferrand subsequently wrote: "*... Quant à nous, nous avions à nous décider pour un mode de construction qui, en remplissant, comme le dôme de Londres, les conditions d'une solidité à toute épreuve, offrît en autre l'avantage d'une plus grand légèrité. Ce résultat nous l'avons obtenu en adoptant un système combiné de fonte, de fer forgé et de poteries, pour les voûtes du dôme de la cathédral de Saint-Isaac*" [62].

Details of the erection of the dome's iron structurre have not been found in the archives. A general structural history of the building may help establish the broad chronological framework of its erection [63]. The construction of the main bulk of the cathedral, including the entablature and the greater part of the attic, was completed in 1836-1838 (Fig. 22). Work on raising and installing the 24 granite columns of the dome's drum (each weighing 66 tons) – begun in November 1837 – was particularly labour-intensive. Once the drum was in place, assembly of the pre-fabricated cast-iron elements of the dome, together with the covering, took place in 1838-1839 and was complete by August 1839 [64]. The total weight of the metal used to construct the dome amounted to 106,463 poods, 7 pounds (1743.87 tons). All general building work on St Isaac's Cathedral was finished in 1841, but interior finishing and painting continued until 1858.

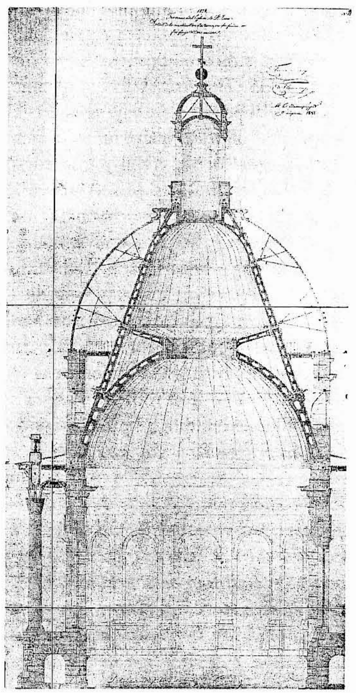

Fig. 20 St. Isaac's Cathedral: cross-section of the dome, 1838 (from the Scientific Library of the Railway Engineers University, St. Petersburg).

Just like its masonry prototype in London, the dome of St Isaac's Cathedral is composed of three sections: two inner domes with common supports and an external enclosure of semi-spherical form (Fig. 20)[65]. The inner domes are set on a cast-iron ring of 22 cm in thickness, itself placed on the brickwork of the drum at the level of the entablature of the external colonnade. The main supporting structure of the roof is a ribbed, circular dome built in cast iron and almost conical in form, which was described in subsequent publications as "a catenary form" (diameter at the base – 24 m, upper diameter – 2.4 m) [66]. The height of the conical section of the structure (21 m) was determined by that of the dome's summit, itself dictated by compositional considerations. Its supporting frame is composed of 24 ribs made from separate I-sections with oval holes in their webs. These are fastened together by bolts and strengthened by three horizontal circular braces made from separate cast-iron plates (Fig. 21). The lantern structure is also

executed from pre -fabricated cast-iron elements and is installed on top of the supporting conical section of the roof. A semi-spherical inner dome of the same diameter (24 m) is positioned in its lower section and shares common supports with the conical part of the roof. The perforated cast-iron ribs of this dome meet at a wide inner ring of 5.9 m in diameter "suspended" from the conical section of the roof. The gaps between the cast-iron ribs of the dome are filled with hollow ceramic pots. New to Russia, but already widespread in European architecture of the 1830s, ceramic pots made a good insulator, improved the acoustics and facilitated the roof-laying.[67]

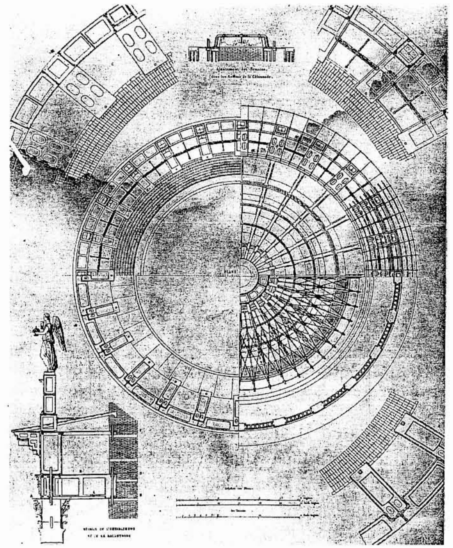

Fig. 21 St. Isaac's Cathedral: composite plans of the iron dome, 1836-9 (from A.-R. Montferrand, Eglise Cathedral De Saint Isaac).

The light semi-spherical dome enclosure (27.0 m in diameter; height from attic to balcony – 14.2 m) is made from 48 wrought-iron arched ribs 13.3 in height and 4.5 cm in thickness. The lower ends of these are fastened to the cast-iron cushion positioned above the drum's attic, their upper ends to the upper ring of the conical section (Figs. 23, 24). In a circular direction, the ribs are riveted together by 36 rows of iron strips. The technique for stabilising the flexible arched elements – by means of two groups of struts attached to the circular braces of the inner conical frame – is of considerable interest. The ribs of the outer dome serve as a frame for the cladding of gilded copper sheets (Fig. 25).

In contrast to its prototype, the dome structure of St Isaac's Cathedral used a design new to engineering practice of the day – a metal "thrustless" dome. The forces of outward thrust were taken by the supporting ring and circular tie-beam, suspended in the inner space, and "dispersed" within the structure (Figs. 20-21). This feature of the dome was highly regarded by Montferrand, who asserted that : "*Notre nouveau système offre un ensemble stable qui ne saurai laisser advenir aucune désunion, qui n'a pas de poussée, et dont le poids se trouve réduit au dixième de celui qu'il aurait fallu si le dôme eût été construit d'après l'ancienne méthode*" [68].

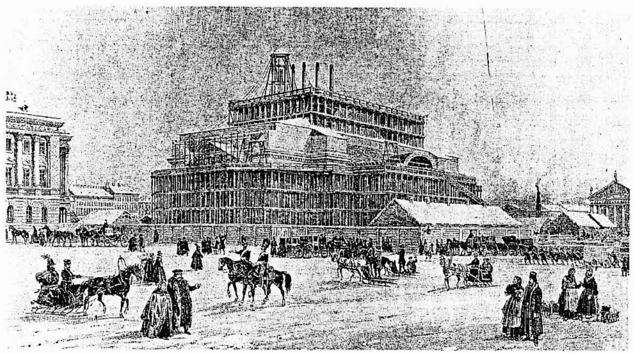

Fig. 22 St. Isaac's Cathedral: building works in progress (from A.-R. Montferrand, *Eglise Cathédral de Saint A.-R. Isaac*).

These cast-iron supporting structures are used not only in the dome, but also in many other roof elements of St Isaac's. Thus, the

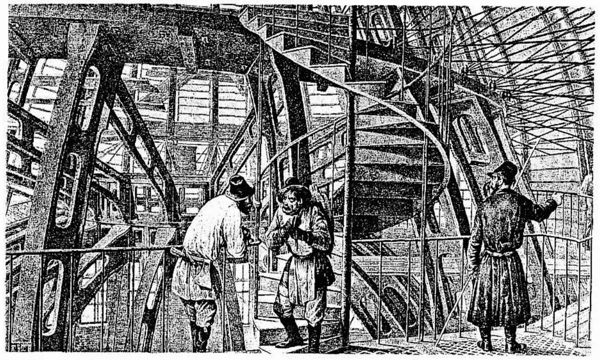

Fig. 23 St. Isaac's Cathedral: view of the dome during the completion of the building works, 1839 (from A.R. Montferrand, *Eglise Cathédral de Saint-Isaac*).

colonnade entablature, which forms a continuous ring around the drum of the central dome, is made from cast-iron caissons. As Montferrand subsequently remarked: "*Dans notre plan, l'entablement en fer et en bronze de la colonnade n'est un simple ornement architectural; il devient une ceinture solide qui étreint la tour du dôme de manière à lui donner une trés grande stabilité...*"[69]. Prefabricated U-shaped cast-iron frames and analogous semi-circular arches have been introduced into the ceiling structures of the southern and northern porticos. The system of cast-iron supports and iron girders, mounted on to the brick roof vaults of the main naves, forms the base for the cathedral's attic roofs (Figs 26-28).

The design and manufacture of elements of the dome proved a complex task for its time and involved specialists from many backgrounds who remain unknown to this day. As many authors affirm, structural calculations were produced by the engineer P. K. Lomonovsky[70]. All the components for the iron structures of the dome and cathedral were manufactured at St. Petersburg's largest private iron foundry, owned by Charles Baird[71]. Baird was evidently Montferrand's chief consultant on all questions concerning the design of the metal structures for the cathedral. As Montferrand noted in his monograph, it was at Baird's insistence that the number of the dome's supporting ribs was reduced from 32 (the original 1835 design proposal) to 24. W. Handyside, the chief engineer at Baird's factory in those years, also played an important role in the manufacture of the metal structures. The involvement of two leading representatives of the British engineering school in the construction work contributed to the creation of a iron dome that was optimal in terms both of static and technological parameters: all supporting and enclosing elements of the dome's cast-iron structure are built using components made from light-weight small prefabricated parts of uniform section, simplifying manufacture, supply and assembly. As a whole, the dome of St Isaac's may justly be considered one of the greatest example in Russia of an "industrial" design method, typical of British building practice in the first half of the 19th century. Because of that, St. Isaac's Dome was subsequently chosen as the prototype for the

Fig. 24 St. Isaac's Cathdral: interior view of the dome, between the conical dome and the outer spherical dome (photograph courtesy of Professor Rainer Graefe).

United States capitol dome in Washington (1856-67).[75]

The iron dome of St Isaac's is the most important piece of engineering work by A.-R. Montferrand, a man who is known chiefly in Russian architectural history as an architect, artist and draughtsman[73]. His interest in building construction was influenced by the traditions of the French school of the late 18th and early 19th centuries in which he had been educated. Developing the ideas of the Enlightenment, it set architects and engineers alike the task of creating a new, ideal environment, in which such typologically new projects as canals, sluices and bridges, among others, were equally important constituent parts. At the same time, engineering structures were built using a system of aesthetic criteria developed by post-Renaissance architectural practice. The emotional enthusiasm for technical progress typical of the Age of Enlightenment is frequently encountered in statements made by Montferrand himself. Referring to the works of his contemporary Navier, the leading French engineer of the day, he wrote: "*Une construction en fer, si l'on y trouve la grandeur et la simplicité de forme, dit l'ingénieuer Navier, peut aussi bien qu'un édifice en pierre mériter le titre de monument. Peu importe, sur ce point, la nature de la matière; et d'ailleure le fer fondu ou forgé n'est-il pas assurément une substance plus durable que la plupart des marbre ou des pierres quel'on emploie, dans tous les pays, pour les édifices les plus magnifiques? Tout dépend du caractère que l'architecte aura imprimé à sa construction, par la manière dont il l'aura disposé*" [76].

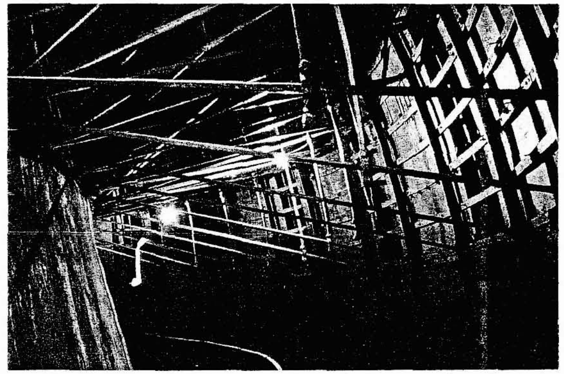

Fig. 25 St. Isaac's Cathedral: interior view of the dome (photograph courtesy of Professor Rainer Graefe).

Montferrand was entirely successful in realising this thesis and in creating a dome that may rightly be considered a monument of building art of the early age of cast-iron structures. While it remains a fundamental part of the supporting structure of the building, the dome of St Isaac's is also a work of enormous aesthetic merit itself and blends in harmoniously with the overall system of architectural proportions (Figs. 20, 23). However, summing up the completed work on the construction of the cathedral, which had become his life's

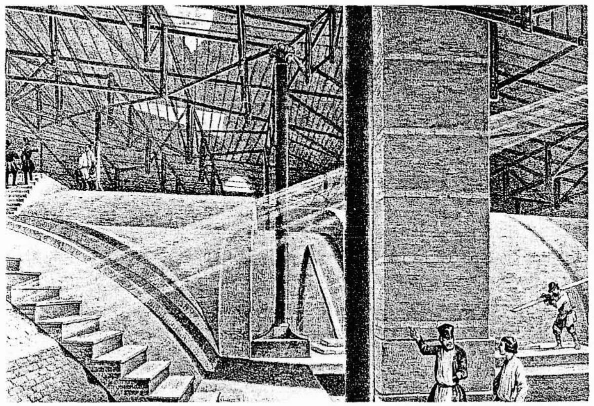

Fig. 26 St. Isaac's Cathedral: perspective of the area above the brick vaults (from A.-R. Montferrand, *Eglise Cathédral de Saint-Isaac*).

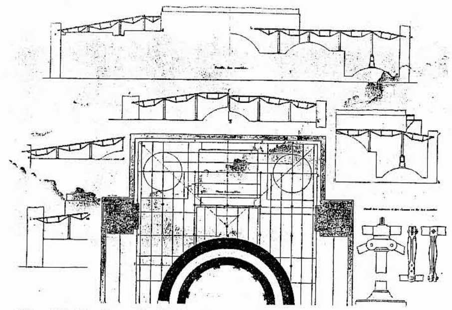

Fig. 27 St. Isaac's Cathedral: plan and section of the beam structures above the brick vaults (from A.R. Montferrand, *Eglise Cathédral de Saint-Isaac).*

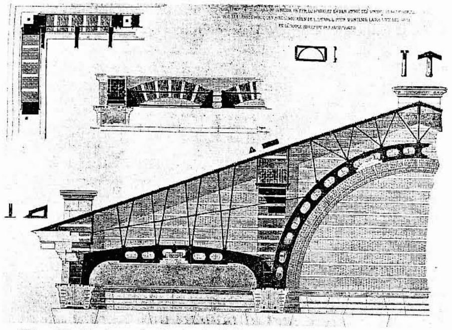

Fig. 28 St. Isaac's Cathedral: ironwork in the side chapel porticos (from A R Montferrand, *Eglise Cathédral de Saint-Isaac).*

work, Montferrand concluded somewhat surprisingly at first glance that *"this building belongs to the past and not the present age"*[77]. His assessment, which referred primarily to the building's architectural merits, is in many ways true also of its structure. In effect, the design of St Isaac's dome summed up in its own distinctive way the early stage of development of iron architecture in St. Petersburg. By the 1840s structural design in iron had become a separate subject in engineering and was attracting the active interest of graduates of the first Russian structural engineering schools. The rapid development of new methods of design and calculation confirmed what Bazaine had said in 1829 about the necessity of moving on *"from empirical copying of prototypes to the design of new types of structures on the basis of calculations"*[78].

Conclusion

The examples given here illustrate separate stages in the evolution of Russian (St. Petersburg) domed structures of the first half of the 19th century but do not claim to provide a complete picture of the development of these structures. All three domes considered above were designed during the early stages of development of new methods of calculating resistance and stability and at a time when the new engineering profession was being actively formed in Russia. These factors allow us to attribute these domed buildings to the "empirical" stage of development of building structures in Russian practice, i.e. the end of the 1800s to the beginning of the 1840s.

Familiarity with Russian domed structures reveals that by the beginning of the 19th century local Russian traditions of design and construction of iron roofs were already in existence, rooted in the iron foundries that had developed in the Urals throughout the 18th century. This base of broad, practical experience led to the development of a variety of roof structure systems (including domes) which imitated in large part the construction of timber beam structures [79].

A feature of professional practice in St. Petersburg in 1810-1830 was the successful collaboration of two leading European schools of engineering – the "experimental" British and the "engineering" French school. The best examples of structural engineering of those years in St. Petersburg, including domed roofs, were built with their direct involvement and under conditions of continuous contact with West European practice. These structures often realised the best of national professional traditions on Russian soil. Thus, the design for the light arched dome of Trinity Cathedral (1834) may be considered typical of the French engineering school, while the "composite" cast-iron dome of St Isaac's Cathedral (1836-1839) is characteristic of the British school. As a whole, the success of a number of brilliant West European specialists in Russia at

the beginning of the 19th century contributed to the development of an indigenous engineering school which, by the second half of the century, was capable of solving the widest possible range of problems concerning the design and construction of new types of wide-spanned spatial systems (including domes)[80].

The examples presented here show that domed roofs were the most complex and interesting types of structure – from a technical point of view – built during the "empirical" period of the development of iron structures. The St. Petersburg experience of their design broadens our understanding of the extent and structural range of early European iron architecture. The exceptional state of preservation of a whole range of important domed roofs in St. Petersburg dating from the first half of the last century makes them not only a worthy subject for historico-architectural analysis, but also important monuments of European building technology deserving careful protection and professional restoration.

Translated by Diana Turner.

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1 This publication is a revised and expanded version including new archival sources of the following article: S. G. Fedorov, "Frühe Eisenkuppeln in der russischen Sakralarchitectur vor 1840. Zur Entwicklung der eisernen räumlichen Dachtragwerke in Europa", *Erhalten historisch bedautsamer Bauwerke. Jahrbuch 1993. Sonderforschungsbereich 315 Universität Karlsruhe* (Berlin, 1996), pp. 163-193.

2 The following monograph is an example of a study of the relationship between a large-scale domed building and its liturgical purpose: R. J. Mainstone, *Hagia Sophia. Architecture, Structure and Liturgy of Justinian's Great Church* (1988).

3 The Cathedral of the Kazan Icon of our Lady (the Kazan Cathedral) lies on the southern side of Nevsky Prospect between the Griboedov Canal and Kazan Street (address: 2, Kazan Square). From 1932 to 1991 the cathedral housed the Museum of the History of Religion and Atheism, part of the Academy of Sciences of the USSR.

4 Andrei Nikiforovich Voronikhin (born 17.10.1759, Novoe Usol'e, Urals; died 21.2.1814, St. Petersburg). Until 1786, was a serf on the Count Stroganov's estates and remained closely associated with the family all his life. Received his initial art education in the Urals. From 1777 lived and studied in Moscow, from 1779 in St. Petersburg at the home of Count A. S. Stroganov, president of the St. Petersburg Academy of Arts. From 1786-1790 travelled to Berlin, Switzerland and Paris to complete his education. Author of a number of palace interiors and residences belonging to the Stroganov family in St. Petersburg and its environs. Most important works: the Kazan Cathedral (1801-1811) and the College of Mines building (1806-1811) in St. Petersburg, some of the finest works of Russian high classicism ("Empire") – the last stage in the development of classicism in architecture in St. Petersburg.

5 It was for this reason that the design was commissioned from A. Voronikhin, despite his lack of experience of such large-scale works, rather than the Scot Charles Cameron, the main court architect of those years.

6 I. A. Bartenev, "Stroitel'naya nauka v Rossii (XVIII v. – pervaya polovina XIX v.)" [Building Science in Russia (XVIII to First Half XIX Century)], *Trudy Vserossiiskoi Akademii Khudozhestv. Vypusk I*, (Leningrad-Moscow, 1947), pp. 151-155.

7 The first publication containing information on the structural solution for the Kazan

Cathedral dome is a small article in the journal *Stroitel'naya promyshlennost'* [Construction Industry]: "Pervyi metallicheskii kupol (*Iz istorii stroitel'nogo iskusstva*)" [The First Metal Dome (From the History of Building Art)], *Stroitel'naya promyshlennost'*. (1941, No. 6), pp. 28-29.

The article is based on the first inspections and measurements made of the dome during the replacement of the spire's cross. These works formed part of the "ideological reconstruction" of the cathedral after its hand-over to the new Museum of Atheism.

The measurements taken by Yu. Ivanov in 1939 are used in: N. N. Aistov, "Razvitie metallicheskikh konstruktsii s XVIII do XIX veka" [The Development of Metal Structures from 18th to 19th Century] in *V. F. Ivanov* (Editor), *Istoriya stroitel'noi tekhniki* [The History of Building Technology], (Leningrad-Moscow 1962), pp. 320-321.

8 The dome's state of preservation was also helped by difficulty of access. Entry to the inner attic space of the dome is via an open external iron staircase and a manhole in the upper part of the drum. Archival sources do not indicate either rebuilding or restoration of the dome in the 19th century. The first restoration work, when additional concentric braces were installed, took place in 1993.

9 The 'Commission on the Construction of the Kazan Cathedral' archive is held in the Russian State Historical Archive (Rossiiskii gosudarstvennyi istoricheskii archiv – RGIA) in St. Petersburg: RGIA, 817. The RGIA also holds files on the construction of the cathedral in 796, 797, etc. A brief description of the construction history of the cathedral is given in the following books: A. Aplaksin (compiler), *Kazanskii sobor. Istoricheskoe issledovanie o sobore i ego opisanie* [Kazan Cathedral. Historical Research on the Cathedral and its Description], (St. Petersburg 1911), pp. 32, 34, 66; G. G. Grimm, *Arkhitektor Voronikhin* [The Architect Voronikhin], (Leningrad-Moscow 1963), p. 48; V. G. Lisovskii, *Andrei Voronikhin*, (Leningrad 1971), p. 70.

10 This is evidenced by Voronikhin's report of 13 December 1807: "The dome can be said to be almost completed, that is to say the walls and vaults have already been completed, except for the attic which has not yet been faced with Pudozh stone ... Materials used ... rectangular-section, square-section, quadrangular and other iron for the construction of the church's walls and vaults – 8657 poods, 26 pounds [141,812 kilos – S. F.]". (RGIA, 817-1-625, "Ob iskhodataistvovanii otpuska sredstv na okonchanie sooruzheniya Kazanskoi tserkvi. 1807-1810" [On Obtaining Resources for Completion of the Kazan Church Building. 1807-1810], pp. 28-33].

11 After the death in April 1808 of the architect I. E. Stasov, a member of the commission on the construction of the Kazan Cathedral who consistently queried all Voronikhin's new technical proposals, Voronikhin himself was appointed to his place on the commission by imperial decree from September 1808.

12 Evidence that a number of iron elements for the main dome were ready in 1806 is contained in the following file: RGIA, 817-1-531: "O prikhode i raskhode zheleza, svintsa, instrumentov. 1806" [On Income and Expenditure of Iron, Lead and Instruments. 1806], sheet 28, verso 29.

13 RGIA, 817-1-582: "Pis'mennye dokumenty o zapiske v prikhod po stroeniyu Kazanskoi tserkvi ... . 1807" [Written Documents on Records in the Receipts Book Concerning the Construction of the Kazan Church], p. 92 verso.

Concise details of the activity in Russia of Charles Gascoigne, the former director of Carron, are given in the typescript of John James's lecture at the Newcomen Society (12 January 1983): *The Application of Iron to Bridges and Other Works in Russia to About 1850*, pp. 3, 28.

14 This is indicated in a report made by Beketov, the building supervisor, on 30 April 1807:

"Voronikhin instructed me to add a further 6 men to the 10 carpenters already employed since the 16th of this month on various works in order that we may prepare the necessary scaffolding for the iron rafters to be mounted on the ground." (RGIA, 817-1-606): "Ob ustroistve dlya kupola lesov. 1807-1817" [On the Erection of Scaffolding for the Dome. 1807-1817], p. 41).

15 G. G. Grimm, *Arkhitektor Voronikhin...*[The Architect Voronikhin], p. 48; A. Aplaksin (compiler), *Kazanskii sobor ...* [Kazan Cathedral], p. 34.

16 Voronikhin's design envisaged the use of tin-plate (galvanized) iron as a roofing material. During restoration work in the 1950s, the dome was covered in sheets of copper.

17 Indirect confirmation of this fact is provided by other works of Voronikhin's in this new area of metal architecture. For example, at the end of the 1800s, Voronikhin designed one of the first cast-iron bridges in Russia (Scientific Museum of the Academy of Arts, Inv. No. 901, 902, undated). In 1812 a "fireproof beam" design was drawn up by him for a rectangular plan building of 19.22 (bay) x 25.56 mm in size (State Museum on the History of St. Petersburg, archives, inv. No. 236).

18 The original drawings for the final design of the Kazan Cathedral of 1810, including the sections, are held in the graphic collection of the State Hermitage. Preliminary drafts are held in the library of the St. Petersburg Engineering & Building Institute and in the architectural graphics archives in the State Museum on the History of St. Petersburg (G. G. Grimm, *A. N. Voronikhin. Chertezhi i risunki* [A. N. Voronikhin. Drawings and Sketches], Leningrad-Moscow, 1952, pp. 145-147, ill. 36, 37).

19 Examples of such calculations are found, in particular, in a note by Voronikhin: "O kupole Tserkvi Kazanskoi Bogoroditsty s podnozhiem onago" [Concerning the Dome of the Church of Our Lady of Kazan and its Pedestal] (RGIA, 817-1-236, "Delo ob issledovanii ukrepleniya stroeniya Kazanskoi tserkvi. Iyul' 1803-avgust 1805" [File on Investigations into Strengthening the Kazan Church Structure. July 1803 – August 1805], sheets 7-8).

20 The first publication on the dome of the Kazan Cathedral includes a not entirely substantiated claim that it is the first metal domed structure of its kind in the world: "Until now, the dome over the Granary in Paris with its span of around 39 metres was considered the first metal pivoted dome... The Kazan Cathedral was built by the Russian architect A. N. Voronikhin in 1801-1811 and is, consequently, not only the first such building in the USSR, but also the most famous of all those remaining in the world at the present time." (Yu. S. Ivanov, *Pervyi metallicheskii kupol...*[The First Metal Dome], p. 28). Today this claim is considered typical of the attempt by "ideologized" research publications in the Stalin era to establish new national priorities in the development of science and technology.

21 As archival documents show, during the erection of the Kazan Cathedral, Voronikhin's attention – as an engineer – was attracted primarily by the masonry structures, in particular by the horizontal ceilings of the colonnade's side corridors (span – 14.9 m) and the inner pylons of the dome space. A special commission was set up in August 1805 to resolve questions on the stability of the side corridors' ceiling structures and included the leading specialists of the day: N. N. Novosil'tsev, president of the Russian Academy of Science; L. I. Kraft, an academic in the Mathematics and Physics Department; the academic N. I. Fuss; the architect A. N. Zakharov; General-Engineer Sukhtelen, director of the Engineering Department. The commission recognised the necessity of carrying out practical trials in which the structure would be reduced to collapse (RGIA, 817-1-236, sheets 24-25; 817-1-250, "Mnenie chlena komissii statskogo sovetnika Starova o raznikh chastyakh stroeniya Kazanskogo sobora. 1803-1805" [The Opinion of Commission Member and Councillor of State Starov on Various Parts of the Kazan Cathedral Structure. 1803-1805], sheets 15, 22, 38).

22 M. K. Deming, *La Halle au Blé de Paris 1762-1813*, (Brussels, 1984); F. Brunet,

Dimensions de fers qui doivent former la coupole de la Halle aux Grains, calculées pour l'exécution du projet de M. Béranger (Paris, 1809).

23 Information on the early stage of development of the Russian metallurgical industry and its contribution to early iron architecture can be found in the following books: V. V. Danilevskii, *Russkaya tekhika* [Russian Technology], (Leningrad, 1948), pp. 37-47, 68-84; R. Portal, *L'Oural au XVIII siècle* (Paris, 1950); N. S. Alferov, *Zodchie starogo Urala: pervaya polovina 19 veka* [Architects of the Old Urals: First Half of 19th Century], (Sverdlovsk, 1960); I. G. Vasil'ev, Osnovnye predposylki obrazovaniya metallicheskikh konstrukstii [Basic Premises on the Formation of Metal Structures]; G. M. Lyudvig (Editor-in-Chief), Ocherki istorii stroitel'noi tekhniki Rossii XIX – nachala XX vekov [Sketches on the History of Building Technology in Russia in the 19th – Early 20th Centuries], (Moscow, 1964), pp. 77-80.

24 Cathedral of the Holy Trinity of the Izmailovo Regiment Life-Guards (address: 7a, Izmailovsky Prospect). From 1932-1990 the cathedral was used as a store by the Ministry of Communications of the USSR.

25 Pierre-Dominique (Petr Petrovich) Bazaine (born 13.1.1786, Sées, France; died 16.9.1838, Paris). French engineer, mechanic and mathematician. Graduate of the Ecole Polytechnique (1805) and the Ecole des Ponts et Chaussées in Paris. In Russian civil service from 1810 to 1838, Lieutenant-General (1830). Teacher and director of the Institute of the Corps of The Way of Communications Engineers. Chairman of the Committee for Building and Hydraulic Works (1824-1834) – the main body in charge of building in St. Petersburg in those years. Author of theoretical works on mechanics and of numerous designs for bridges and hydraulic works (D. Yu. Guzevich, I. D. Guzevich, *Petr Petrovich Bazen*. 1786-1838 [Petr Petrovich Bazaine, 1786-1830], (St. Petersburg, 1995).

26 S. G. Fedorov, D. Yu. Guzevich, "Proekt pervogo v Rossii kupol'nogo pokrytiya s vantovym podkrepleniem" [The Design for the First Domed Roof with Lattice Girders in Russia], *Issledovaniya novykh tipov prostranstvennykh konstruktsii. Sbornik Trudov LenZNIIEP* [Research on New Types of Spacial Structures. Anthology of Works from LenZNIIEP] (Leningrad. 1985), pp. 105-110.

27 Immediately after the collapse, Stasov was instructed to deliver detailed plans of all the iron domes to Bazaine's flat (RGIA, 206-1-46, p. 4). It is possible that odd drawings of fragments of the metal radial structure in the Bazaine archive in the Scientific Library of the St. Petersburg University of Communications (No. 18560, 1-163/165, see Fig. 13) form part of the original dome design. The iron dome enclosure is not shown on the design drawings (sections) held in the archives of the State Museum of the History of St. Petersburg.
The original design for Trinity Cathedral dates from 1827, the final design from 1831, enabling us to date the reworked structure to this period.

28 RGIA, 208-1-78, "Zhurnal Komissii proektov i smet Vedomstva putei soobshchenii. 1834" [Journal of the Commission on Designs and Estimates of the Department of Communications. 1834], sheets 3-7.

29 RGIA, 468-35-155: "Po rabotam postroeniya bol'shogo kupola i kolokol'ni tserkvi sv. Troitsty leib-gvardii v Izmailovskom polky. 28 fevralya 1834-16 yanvarya 1835" [On the Construction of the Great Dome and the Bell Tower of the Church of the Holy Trinity of the Izmailovo Regiment Life-Guards. February 1834 – January 1835], sheets 7-8.

30 A description of the structure of the small domes and the measurement drawings from the early 1950s are given in the following books: N. N. Aistov, "Razvitie metallicheskikh konstruktsii s XVIII do XIX veka" [The Development of Metal Structures from the 18th to 19th Centuries]; V. F. Ivanov (Editor), *Istoriya stroitel'noi tekhniki* [The History of Building Technology], (Leningrad-Moscow, 1962), pp. 323-325; I. G. Vasil'ev, "Osnovnye predposylki obrazovaniya metallicheskikh konstruktsii..."[Basic Premises on the Formation of Metal Structures], *Ocherki istorii stroitel'noi tekhniki Rossii XIX-nachala XX vekov* [Sketches on the History of Building Technology in Russia from the 19th – Beginning of 20th Centuries], (Moscow, 1964), pp. 90-91.

31 During restoration of the small domes of Trinity Cathedral in 1952, an octagonal three-tiered supporting pyramid of angled sections was introduced inside three of the domes. The curvilinear ribs of the original domes were attached to the pyramids by means of small, horizontal girders positioned in two places vertically, as well as level with the pyramid rings. The same pyramid system was introduced into the fourth small dome in which the original radial-circular casing had survived (N. N. Aistov, "Razvitie metallicheskikh konstruktsii s XVIII do XIX veka" [The Development of Metal Structures from the 18th to 19th Centuries], pp. 323-325; Fig. 8).

32 Vasily Petrovich Stasov (born 1769, Moscow; died 1848, St. Petersburg). Russian architect, one of the last masters of the classical school in St. Petersburg. Worked in Moscow (1783-1794), completed his education in Italy (1802-1808). Professor and member of the Academy of St. Luke in Rome. From 1809 lived and worked in St. Petersburg. Author of a series of albums of "standard designs", a number of which were implemented in the Russian provinces; also of designs for residences, monumental, public and religious buildings in St. Petersburg and its environs, Moscow, Vilnius and Potsdam, etc.

33 S. G. Fedorov, "Matthew Clark and the Origins of Russian Structural Engineering 1810s-40s: An Introductory Biography", *Construction History*, 8, 1992, pp. 69-88.

34 In M. Clark's important earlier works, iron was used for decorative finishing in public buildings or in cast-iron gates and pavilions for landscaped parks. The iron hall of the general staff archive on Palace Square (1819-1823, architect – K. I. Rossi; engineer – M. Clark) was the only example in his work of a building in which iron was used in its new supporting role (a three-tiered cast-iron frame with an arched roof).

35 RGIA, 485-2-1078, "Troitskii sobor. Plan, razrez i detali konstruktsii" [Trinity Cathedral. Plan, Section and Details of the Structures], sheets 1-8 (original drawings – S.F.); archive 1488-3-391, "Troitskii sobor. Plany ustroistva kupola" [Trinity Cathedral. Plans of the Dome's Structure], sheets 1-8 (copies – S. F.). Scientific Library of the St. Petersburg University of Communications, No. 18560, 1-161/173 (Sketches and supplementary drawings from Bazaine's design for Trinity Cathedral – S. F.).

36 RGIA, 486-35-155, sheet 27. Minutes of the commission meetings and contributions by its members have been preserved in the archives in Russian and, partly, in French. In the latter case, they are cited in this work in the original language.

37 Stasov's architectural solution envisaged the division of the domes' surface into decorative radial strips laid out at variable module and span. This decorative motif, enlivening the strict classical facade of the cathedral, significantly increased the complexity of the iron structures, particularly those of the supporting and circular belts.

38 The commission investigating the reasons for the collapse of the Trinity Cathedral dome included the engineers P.-D. Bazaine, M. G. Destrem, M. S. Volkov, F. L. Zerge-von-Laurenberg. P. P. Mel'nikov, V. V. Trofimovich and the architects P. I. Visconti, A. I. Mel'nikov, A. A. Mikhailov, A.-R. Montferrand, K. A. Thon, N. I. Charlemagne. After completion of the investigation and work on the preliminary designs for the new dome, the same commission examined Bazaine's new drafts of the design.

39 RGIA, 486-35-155, sheet 24; 206-1-46, sheet 36. Thon's involvement in the work of the commission probably influenced the choice of structure for the great dome of the Church of Christ the Saviour in Moscow (1832-1858, architect K. A. Thon), in which the stability of the iron ribs was provided by two tiers of inner ties (E. I. Kirichenko, *Khram Khrista*

Spacitelya v Moskve [The Church of Christ the Saviour in Moscow], (Moscow, 1992), pp. 88, 129. 244-245).

40 RGIA, 206-1-46, sheets 20-21; 208-1-78, sheets 12-13. Montferrand suggested the wooden dome of the Dome des Invalides in Paris as a possible model for the wooden dome of the latter, it being equal in size to Trinity Cathedral.

41 RGIA, 208-1-78, sheets 14 verso, 15.

42 RGIA, 206-1-46, "Ob osvidetel'stvovanii i ustroistve sorvannogo kupola sobora sv. Troitsy, chto v Izamailovom polku" [Concerning the Inspection and Construction of the Dome of Trinity Cathedral of the Izmailovo Regiment], sheets 30 verso, 31.

43 "Wiegmann-Polonceau" girders, which appeared in European practice after 1836, are examples of plane structures similar in static principle.

44 RGIA, 468-35-155, sheet 28 verso

45 Calculating the stability of Bazaine's dome was already a real possibility in those years. In 1827-1828 the French engineers G. Lamé and B. Clayperon, who worked in Russia in those years under Bazaine's direct management, were the first to apply general calculations on the stability of flexible structures to concrete engineering problems. See S. P. Timoshenko, *History of Strength of Materials*, (1953), pp. 114-119; G. K. Mikhailov, "Mekhanika sploshnoi sredy. XIX vek" [Mechanics of Solid Media], *Istoriya mekhaniki s kontsa XVIII veka do serediny XX-veka* [The History of Mechanics from the End of the 18th Century to the Middle of the 20th Century], (Moscow, 1972), pp. 46-66.

46 RGIA, 206-1-46, sheets 29, 30-31, 34.

47 RGIA, 206-1-46, sheet 41. The Alexander Column was erected in the centre of Palace Square in 1832-1834 from a design (1829) by the architect A.-R. Montferrand. The erection of the monument (total height – 47.5 m) required the construction of special multi-tiered wooden scaffolding and forms an interesting chapter of its own in the history of building technology. See A.-R. Montferrand, *Plans et détails du monument consacré à la mémoire de l'Empereur Alexandre*, (Paris, 1836).

48 RGIA, 206-1-46, sheets 48 verso, 49.

49 I. Sokolov (compiler), *Opisanie modelei muzeuma instituta Korpusa inzhenerov putei soobshcheniya* [Description of Models for the Museum of the Institute of the Corps of THe Way of Communication], (St. Petersburg, 1862), pp. 173-178.

50 M. K. Deming, *La Halle au Blé*, p. 193

51 I. Buttats, Zapiska k chertezham kupola tserkvi Sv. Troitsy, nakhozhyazheisya v Sankt Peterburge. V knige: *Sobranie chertezhei po chasti stroitel'nogo iskusstva, isdavaemoe Korpusa Inzhenerov Putei Soobshcheniya poruchikami, Evreinovym, Kerbedzom, Demidovym, Yastrzhembskim i Dantsenshternom* [Note on the Drawings of the Dome of Trinity Cathedral in St. Petersburg. In the Book: Collection of Drawings on Building Art, Published by the Lieutenants of the Corps of the Way of Communications Engineers Evreinov, Kerbedz, Demidov, Yastrzhembskii and Dantsenshtern], (St. Petersburg, 1835), Vol. 1, pp. 21-34; Vol. 2 (drawings), sheet IV.

52 M. K. Deming, *La Halle au Blé*, pp. 188-190.

53 I. Buttats, *Zapiska k chertezham kupola tserkvi Sv. Troitsy*... [Note on the Drawings of the Dome of Trinity Cathedral], p. 21.

54 Cathedral of St. Isaac the Dalmatian (1, Isaac Square). Closed for religious services after 1928 and subsequently turned into the St. Isaac's Cathedral State Museum.

55 Auguste Ricard de Montferrand (born 1786, Paris; died 1856, St. Petersburg). Architect of the late classical, early historical period. Studied at the Royal School of Architecture in Paris (from 1806). From 1816 served in Russia as court architect. Author of many architectural designs and of a range of palaces, private residences and ceremonial interiors in St. Petersburg. Main buildings: St. Isaac's Cathedral (1818-1858) and the Alexander Column (1829; 1832-1834).

56 The original design for the cathedral (1818) was fundamentally reworked in 1825. The masonry structure of the dome remained in the design until the early 1830s. It is a masonry structure that is shown in the model of the cathedral executed in 1818-1821 and 1827-1831 from Montferrand's drawings and under his direction. (NIMAKh, inv. No. AM-12). Subsequent changes were fixed in the design of 1835 held in the Scientific Library of the St. Petersburg University of Communications (No. 15296, etc).

57 In 1825-1826 the French engineers G. Lamé and B.-E. Clayperon, who were working in St. Petersburg at the time, devised a new calculation theory based on the "theory of rope polygons" to facilitate calculation of the brick vaults of the naves of St Isaac's (Lamé, Clayperon, "Ob ustoichivosti svodov" [On the Stability of Vaults], *Zhurnal Putei Soobshchenii*, [Journal of Means of Communication] 1826, No. 1-3).
In a number of Russian-language publications it is erroneously claimed that Lamé and Clayperon – who left Russia in 1831 – were involved in the calculations for the final version of the metal dome of St. Isaac's.

58 See the proposal to use an iron dome of around 80 m in diameter, designed by the amateur inventor Logunov, for St. Isaac's Cathedral in St. Petersburg and the Church of Christ the Saviour in Moscow, which were both under construction in those years (RGIA, 206-1-716, "O proekte Logunova postroeniyu visyachego mosta cherez Nevu. Yanvar' 1827-mart 1829" [Concerning Logunov's Design for a Suspension Bridge Across the Neva. January 1827-March 1829], sheets 3-4, description without drawings).

59 A.-R. Montferrand, *Eglise cathédral de Saint-Isaac. Description architecturale, pittoresque et historique de ce monument*...(St.Petersburg-Paris, 1845), p. 56.

60 In 1826-1836 Montferrand was involved in inspection and rebuilding work on the masonry structures of the Kazan Cathedral and was probably familiar with the structure of the cathedral's iron dome (materials on these inspections are held in the Scientific Library of the St. Petersburg University of Communication).

61 A.-R. Montferrand, *Eglise cathédral de Saint-Isaac*... p. 56.

62 A.-R. Montferrand, *Eglise cathédral de Saint-Isaac*... p. 56.

63 N. P. Nikitin, *Ogyust Monferran. Proektirovanie i stroitel'stvo Isaakievskogo sobora i Aleksandrovskoi kolonny* [Auguste Montferrand. Design and Construction of St. Isaac's Cathedral and the Alexander Column], (Leningrad, 1939); O. Chekanova, A. Rotach, *Ogyust Monferran* [Auguste Montferrand], (Leningrad 1990), pp. 17-114.

64 The completion date for the dome also enables us to date the official unveiling of the cross: "Sur une platforme élevée à trois cent cinquante-quarante pieds de hauteur, le 14 septembre 1839, vers le milieu du jour, les habitants de Saint-Pétersbourg...pouvaient voir un autel que dominait une croix resplendissante d'or et de lumière..." (A.-R. Montferrand, *Eglise cathédral de Saint-Isaac*... p. 60.)

65 The original design drawings for St. Isaac's Cathedral are held in the Scientific Library of the St. Petersburg University of Communications and the Science Museum of the Russian Academy of Arts (both in St Petersburg). Unfortunately, the original drawings illustrating the main stages in the construction of the metal dome are not dated, making it difficult to compile a detailed chronology of the erection of the cathedral. See V. K. Shuiskii, *Ogyust Monferran. 1786-1858. Katalog yubileinoi vystavki proizvedenii* [Auguste Montferrand. 1786-1858. Catalogue of the Anniversary Exhibition of His Works]. (Leningrad, 1986).

66 I. Sokolov (compiler), *Opisanie modelei muzeuma instituta Korpusa inzhenerov putei soobshcheniya*...[Description of the Models in the Museum of the Institute of the Corps of Structural Engineers] , pp. 178-181.

67 For example: Ch. Eck, *Traité de construction en poteries et fer, à l'usage des batiments civils, industriels et militaires* (Paris, 1836).

68 A.-R. Montferrand, *Eglise cathédral de Saint-Isaac*... p. 56.

69 A.-R. Montferrand, *Eglise cathédral de Saint-Isaac*... p. 56.

70 A. L. Punin, *Arkhitektura Peterburga serediny XIX veka* [Architecture of St Petersburg in the Mid-19th Century], (Leningrad, 1990), p. 103.

71 Charles Baird (born 1766; died 1843, St. Petersburg). Scottish engineer-metallurgist, mechanic and entrepreneur. From 1786 worked in St. Petersburg. From 1802 – owner of a factory which he transformed into the most successful private iron foundry and mechanics factory in St. Petersburg. Together with steam engines and the first steamships, many of the city's arched and all its suspension bridges were manufactured here, as well as a whole range of unique architectural structures for large-scale public buildings. Unfortunately, the professional biography of Baird – one of the most important engineers working alongside the leading Russian architects of the first three decades of the 19th century – remains wholly unresearched.

72 William Handyside (1793-1850). Scottish engineer and mechanic, author of a number of major inventions in the field of building technology. Chief engineer at Baird's factory (Obituary of W. Handyside, *Minutes of Proceedings of the Institution of Civil Engineers*, Vol. X, 1850-1851, pp. 85-87).

73 Montferrand describes in his own book how the structure was executed according to his design: "... la construction de la coupole qui, du reste, a été exécutée sur notre plan et d'après un dessin..." (A.-R. Montferrand, *Eglise cathédral de Saint-Isaac*...p. 60).

74 A. Picon, *French Architects and Engineers in the Age of Enlightenment*, (Cambridge 1988); A. Picon, M. Yvon, *L'ingénieur artiste. Dessins anciens de l'Ecole des Ponts et Chaussées. Presses de l'Ecole nationale des ponts et chaussées*, (Paris. 1989).

75 T. Bannister, "The Geneaology of the Dome of the United States Capitol", *Journ. of the Society of Architectural Historians* 7 (1948), pp. 6-7.

76 A.-R. Montferrand, *Eglise cathédral de Saint-Isaac*... p. 56.

77 O. Chekanova, A Potach, *Ogyust Monferran* [Auguste Montferrand], p. 171.

78 This remark was made in 1829 during the engineering discussions on the choice of roof for the Alexandrinsky Theatre in St. Petersburg, built between 1828-1832 (RGIA, 486-35-7, p. 295).

79 I. G. Vasil'ev, *Osnovnye predposylki obrazovaniya metallicheskikh konstruktsii*...[Basic Premises on the Formation of Metal Structures], pp. 77-80.

80 This is seen, in particular, in the work of the Russian engineer V.G. Suchov: R. Graefe, M. Gappoev, O. Pertshi, *V. G. Suchov 1853-1939. Kunst der Konstruktion* (Stuttgart, 1990).