10兆瓦高温气冷实验堆

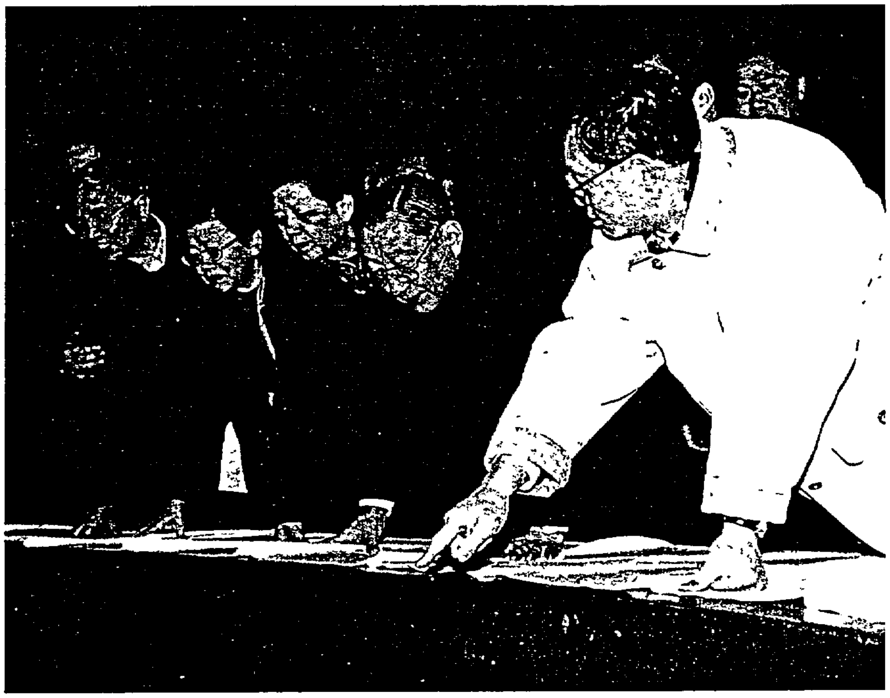
10MW High Temperature Gas-cooled Reactor Test Module

HTR-10

清华大学核能技术设计研究院
Institute of Nuclear Energy Technology, Tsinghua University

国家领导人关心支持HTR—1

Governmental Support for HTR-1



李岚清副总理等视察堆芯安装
Vice Premier Li Lanqing inspecting the installation of reactor core

国务委员吴仪和科技部部长朱丽兰等观看蒸发器吊装
State Councillor Wu Yi and Minister of Ministry of Science and Technology Zhu Lilan inspecting the installation of steam generator

国家领导人关心支持HTR-10

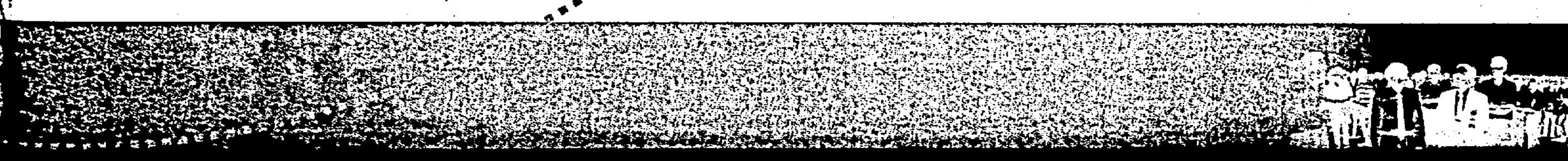
原国务委员宋健等参加HTR-10工程开工仪式
Former State Councillor Song Jian taking part in the ceremony of pouring the first concrete

国外核能专家关注HTR—10

International Cooperation for HTR-10

国际原子能机构总干事布利克斯到HTR-10工程现场指导工作
Mr. Hans Blix, Director General Emeritus of IAEA, visiting HTR-10 and giving instruction

德国核能专家苏尔登教授受聘于清华大学并亲临HTR-10指导工作
Prof. Schulten, Germany nuclear expert, was awarded as a guest professor of Tsinghua University, visiting HTR-10 and giving instruction



高温气冷堆

高温气冷堆是一种安全性好、经济性好、有着广泛用途的先进反应堆。它采用全陶瓷燃料元件，用氦气作冷却剂，具有很高的热稳定性和自动停堆、非能动排出余热的能力，并具有阻止放射性释放的多重屏障，因此它在任何运行和事故情况下都是安全的，绝不会发生像美国三哩岛和前苏联切尔诺贝利核电站那样的严重事故。高温气冷堆冷却剂的出口温度可达950°C，是现有各类反应堆中温度最高的堆型，使用氦气透平直接发电，效率可达43-47%，比普通核电站高20-40%；除发电之外，它产生的热量还可用于开采稠油和炼制石油，生产各类化工产品，使煤气化、液化，制造洁净的燃料氢气、甲醇等等，这对降低使用化石燃料造成的严重环境污染和温室效应，具有重要意义，因此高温气冷堆在能源系统中具有大规模发展应用的良好的产业化前景。

英国从1965年起就开始研究发展高温气冷堆技术，1962年与西欧共同体合作开始建造热工率为20MW的高温气冷实验堆-龙堆（Dragon），1964年8月首次临界，1966年4月达到满功率运行。至1976年完成了原先制定的运行和试验计划。与此同时，美国和德国开始积极发展高温气冷堆技术。美国于1967年建成并运行了电功率为40MW的桃花谷（Peach Bottom）实验高温气冷堆核电厂，1974年10月按计划完成了试验任务后停堆退役。德国也于1967年建成了电功率为15MW的球床实验高温气冷堆核电厂（AVR），1974年将该堆的一回路氦气温度提高到950°C，成为世界上运行温度最高的核反应堆，1988年按计划停堆退役。1967年后高温气冷堆进入原型堆电厂建造运行阶段，美国电功率315MW的圣·符伦堡（FORT.ST.VRAIN）高温气冷堆核电厂于1967年达到临界，1979年并网运行。德国于1971年开始建造电功率为300MW的钍高温气冷堆球床堆（THTR-300）.1985年9月建成达到临界。1986年9月达到满功率运行。

1981年德国电站联盟（KWU）/国际原子公司（INTERATOM）提出模块式球床高温气冷堆方案。 1984年美国通用原子公司（GA）也提出了模块式柱状高温气冷堆的民用核电厂设计方案，以其小型化、标准化和具有非能动安全性为目标，把高温气冷堆核电厂的发展推向一个新的阶段，随后由于受世界上核能发展的影响，高温气冷堆一直处于缓慢发展状况。近几年来，人们对核能的安全性和经济性更为重视。高温堆的发展在国际上又引起了关注。尤其引人注目的是南非ESKOM电力公司在八十年代曾建造和运行了压水堆型的核电站，但是到了九十年代，经过综合研究决定选择模块式高温气冷堆作为今后发展的堆型。ESKOM公司选择的高温气冷堆采用氦气循环发电技术，效率达44%；用模块化方式建造，建造周期可大大缩短。其发电成本有可能和煤发电成本相比拟。美国和俄罗斯已合作进行利用模块高温气冷堆烧毁军用钚的研究，二回路采用氦气透平循环方案，其最终目标是用于商业化发电。法国Framatome和日本富士电机公司也已加入此合作研究行列。

HTR—10 简介

我国自70年代开始研制高温气冷堆。以热功率100MW钍-铀热增殖堆为目标进行了单项关键技术研究以及工程实验。80年代初和德国研究单位和公司合作进行了模块式高温气冷堆在我国应用技术与经济可行性研究。1986年以后高温气冷堆作为能源领域的一个专题列入我国“863”高技术发展计划。进行了以热功率200MW模块式高温气冷堆为目标的单项关键技术研究。1995年经国务院批准开始在清华大学核能技术设计研究院建造10MW高温气冷实验堆（HTR-10）。

HTR-10的建造目的是：1.掌握高温气冷堆在设计建造和运行方面的技术；2.提供一个燃料元件和材料的辐照实验基地；3.进行发电和区域供热实验；4.验证模块式高温气冷堆的发展的非能动安全性；5.开展高温堆工艺热的应用。

10兆瓦高温气冷堆是一座高温氦冷球床堆。反应堆和蒸汽发生器、氦风机分别布置在反应堆压力壳和蒸汽发生器压力壳内，中间由热气导管和热气导管压力壳联接在一起，形成“肩并肩”的布置方式。图1 表示了HTR-10反应堆堆体与一回路的剖面。

温度为250°C的氦气经主循环风机加压后，经热气导管外的环管进入堆芯石墨侧反射层下部，通过侧反射层块内的孔道自下而上进入堆芯顶部空腔，再自上而下流过堆芯球床被加热后进入堆底部的热气联箱。由堆芯球床出来的不同温度的热氦气流在热气联箱中充分混合后，平均温度为700°C的热氦气流出反应堆压力壳，并通过热气导管进入蒸汽发生器，氦气载热质把热量传给蒸汽发生器二次侧的水并产生额定参数的蒸汽，同时使氦气温度降到250°C再回到循环风机的入口，构成一回路的氦气闭合循环。

反应堆堆芯区是一个由石墨反射层围成、内装燃料元件约27000个，其活性区体积约5m^3，直径为180cm，等效高度为197cm。

在反应堆底部由气动脉冲式单列器将燃料元件逐一卸出，经碎球分离器后筛选出尺寸不符合要求的燃料元件，通过燃耗测量装置将未达到设计燃耗值的燃料元件重新装入堆芯再循环，对已达到设计燃耗值的燃料元件则排到乏燃料储罐。

HTR-10反应堆设置有控制棒系统和吸收小球系统，对反应堆实施功率调节和停堆。控制棒系统由设置在侧反射层孔道内的10根吸收棒组成。控制棒系统的反应性当量能满足功率的调节，热停堆和长期冷停堆的要求。吸收小球装置是第二停堆系统，在控制棒系统发生全部失效事故时，依靠吸收球系统可以使反应堆由热态最终达到冷态次临界状态。

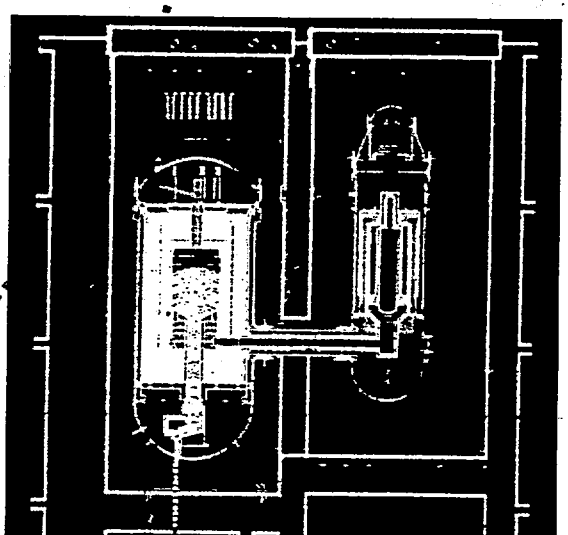
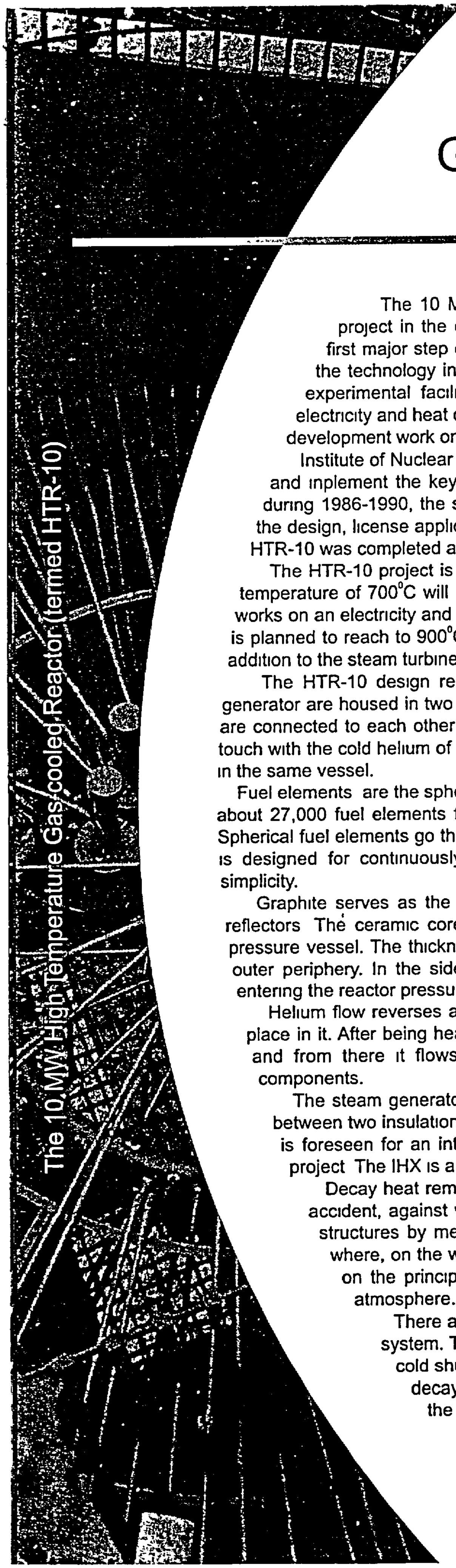


图1



The 10 MW High Temperat… Gas-cooled Reactor Test Mo…
(termed HTR-10)

The 10 MW High Temperature Gas-cooled Reactor Test Module(termed HTR-10) is a major project in the energy sector of the Chinese National High Technology Programme, serving as the first major step of the development of modular HTGR in China. Its main objectives are: 1. to explore the technology in the design, construction and operation of HTGRs, 2. to establish an irradiation and experimental facility, 3. to demonstrate the inherent safety features of modular HTGR, 4. to test electricity and heat co-generation and closed cycle gas turbine technology and 5. to perform research and development work on nuclear process heat application

Institute of Nuclear Energy Technology (INET) of Tsinghua University is the leading institution to organize and inplement the key technology development, the conceptual design and the feasibility study of HTGR during 1986-1990, the so called Seventh Five-Year Plan Period, and then it continues to be responsible for the design, license application, construction and operation of the HTR-10 test reactor. Now the construction of HTR-10 was completed at the site of INET, which is located in the northwest suburb of Beijing city.

The HTR-10 project is to be carried out in two phases In the first phase, the reactor with an coolant outlet temperature of 700°C will be coupled with a steam generator providing steam for a steam turbine cycle which works on an electricity and heat co-generation basis. In the second phase, the reactor coolant outlet temperature is planned to reach to 900°C. A gas turbine cycle and later on a steam reformer will be coupled to the reactor in addition to the steam turbine cycle.

The HTR-10 design represents the features of modular HTGR design The reactor core and the steam generator are housed in two steel pressure vessels, which are arranged in a side-by-side way These two vessels are connected to each other by a connecting throeugh the hot gas duct . All these steel pressure vessels are in touch with the cold helium of about 250°C coming out from the circulator which sits over the steam generator tubes in the same vessel.

Fuel elements are the spherical fuel elements (6 cm in diameter) with coated particles The reactor core contains about 27,000 fuel elements forming a pebble bed which is 180 cm in diameter and 197 cm in average height Spherical fuel elements go through the reactor core in a"multi-pass" pattern. Pulse pneumatic fuel handling system is designed for continuously charging and discharging fuel elements.It has the advantage of reliability and simplicity.

Graphite serves as the main material of core structures which mainly consist of the top, bottom and side reflectors The ceramic core structures are housed in a metallic core vessel which is supported on the steel pressure vessel. The thickness of side reflector is 100 cm, including a 25 cm thick layer of carbon bricks at the outer periphery. In the side reflector, cold helium channels are designed in which helium flows upward after entering the reactor pressure vessel from between the connecting vessel and the hot gas duct.

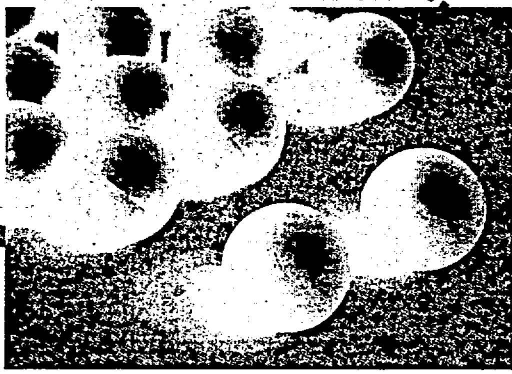
Helium flow reverses at the top of reactor core into the pebble bed, so that a downward flow pattern takes place in it. After being heated in the pebble bed, helium enters into a hot gas chamber in the bottom reflector, and from there it flows with reactor outlet temperature through hot gas duct to the heat exchanging components.

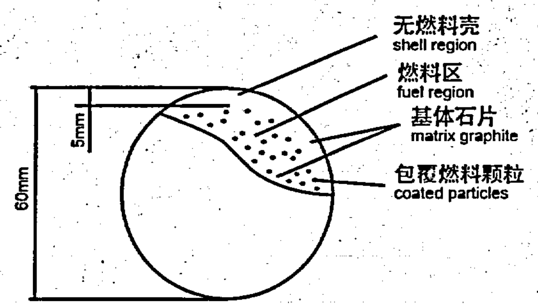
The steam generator is composed of a number of modular helical tubes, which are arranged in a circle between two insulation barrels inside the steam generator pressure vessel The place inside the inner barrel is foreseen for an intermediate heat exchanger (IHX) which will be installed in the second phase of the project The IHX is a helical tube type Nitrogen flows inside the tube while helium flows outside the tube.

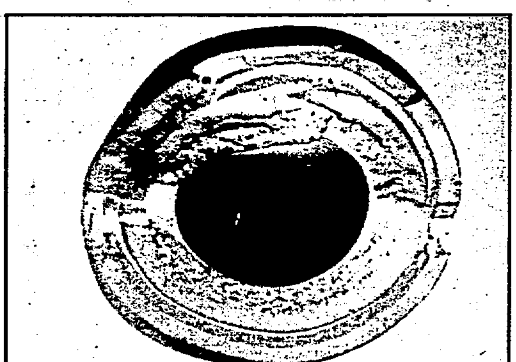
Decay heat removal of the HTR-10 is designed on a completely passive basis. At a loss of pressure accident, against which no core cooling is foreseen at all, decay power will dissipate through the core structures by means of heat conduction and radiation to the outside of the reactor pressure vessel, where, on the wall of the concrete housing, a surface cooling system is designed. This system works on the principle of natural circulation of water and it takes the decay heat via air coolers to the atmosphere.

There are two reactor shutdown systems, one control rod system and one small absorber ball system. They are all installed in the side reflector. Both systems are able to bring the reactor to cold shutdown conditions. Since the reactor has strong negative temperature coefficients and decay heat removal does not require any circulation of the helium coolant, so the turn-off of the helium circulator can also shut down the reactor from power operating conditions.

HTR-10燃料元件
HTR-10 Fuel Elements


核燃料元件球
Spherical fuel elements




包覆小球剖面图
Cross section of coated particle


四层包覆层图
Coating layers

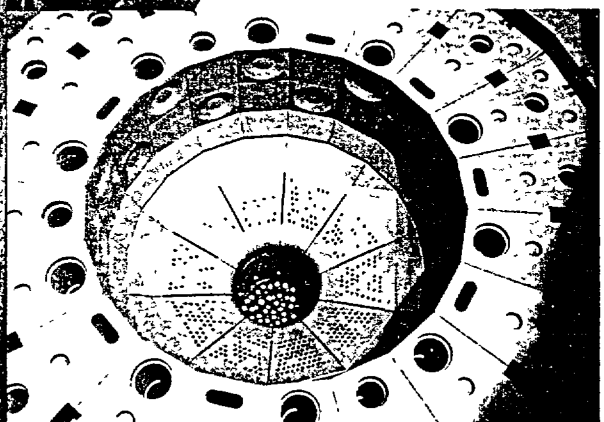
HTR-10采用全陶瓷型包覆颗粒球形燃料元件，直径为60mm，其中直径为50mm的球芯是均匀的弥散了燃料包覆颗粒的石墨基体，每个燃料元件球中包含有约8300个燃料包覆颗粒。包覆颗粒采用TRISO颗粒，即采用三层包覆层，在热解碳的疏松层外的两个致密层之间加一层碳化硅（SiC）层，用以防止金属裂片铯、锶、钡等的扩散迁移。

The HTR-10 fuel elements are spherical ones with coated particles. Fuel element diameter is 60mm. About 8300 coated particles are homogeneously dispersed in a graphite matrix region in every fuel element. The matrix region has a diameter of 50mm. The coated particles are TRISO type, i.e., there is one SiC coating layer between two pyrocarbon layers which is very effective in retaining fission products within the particles.

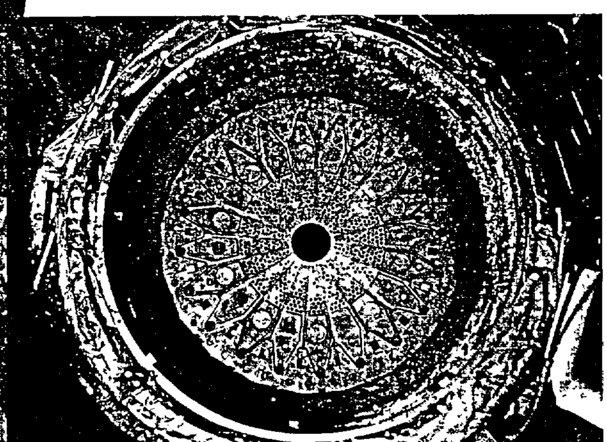
外径: Outer diameter	60mm
装铀量: Uranium loading	5g
U^{235}加浓度: U^{235}-enrichment	17%
核芯直径: Kernel diameter	0.5mm
燃料元件正常运行温度: Normal operation temperature of Fuel Elements	920°C
燃料元件最高允许温度: Maximum limiting temperature of Fuel Elements	1600°C

10兆瓦高温气冷堆技术参

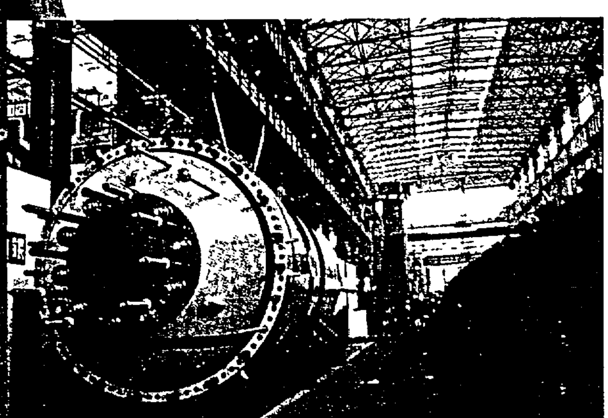
Specification of HTR-



石墨构件组成的堆芯底部
Bottom of reactor core with graphite construction



石墨构件组成的冷氦气腔室
Cooling helium chambers in graphite reflector blocks



反应堆压力壳
Reactor Pressure Vessel

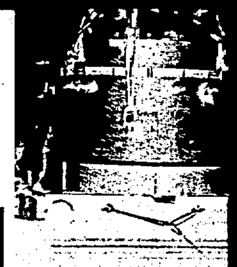
10兆瓦高温气冷堆技术参数

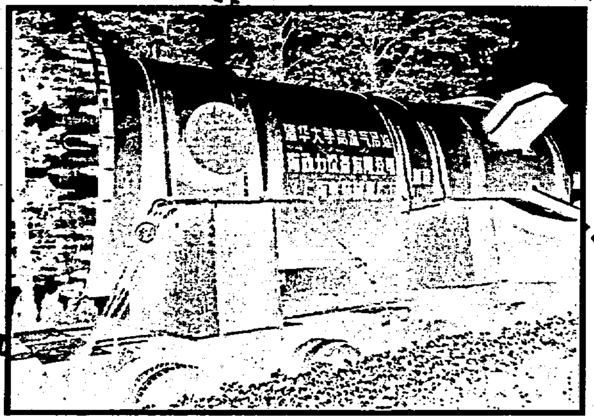
反应堆堆芯:
Reactor core

热功率: Thermal power	10MW
平均功率密度: Averaged power density	2MW/m³
堆芯直径: Core diameter	1800mm
堆芯等效高度: Equivalent core height	1790mm
燃料元件球个数: Number of fuel elements	27000
堆芯氦气压力: Helium pressure in core	3.0MPa
堆芯入口氦气温度: Core inlet temperature of helium	250°C
堆芯出口氦气温度: Core outlet temperature of helium	700°C
反射层内冷却氦气通道: Number of helium cooling channel in the reflector	20
反射层内控制棒数: Number of control rods in reflector	10
反射层内吸收小球孔道数: Number of absorb ball channels in the reflector	7
结构材料: Construction material graphite, carbon	石墨、碳

反应堆压力壳
Reactor pressure vessel

壳体内径: Inner diameter	4200mm
简体壁厚: Thickness	80mm
总高度: Total height	11344mm
工作压力: Working pressure	3.0MPa





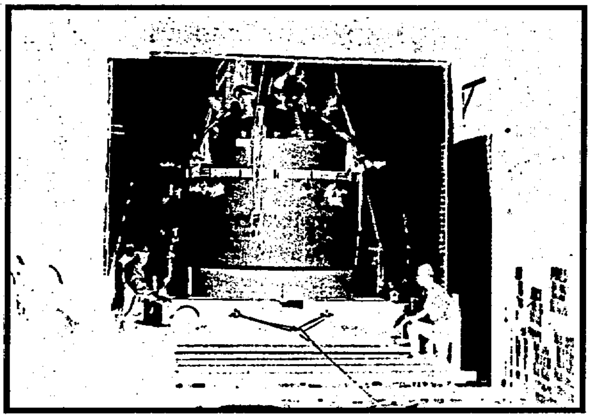
蒸汽发生器压力壳
Steam generator pressure vessel

蒸汽发生器:
Steam generator

传热管根数 Number of heat transfer tubes	30
总传热面积 Total heat transfer area	$52m^2$
二次侧入口温度（水） Inlet temperature of water	104^0C
二次侧出口温度（蒸汽） Outlet temperature of steam	440^0C
水一蒸汽流量 Mass flow rate	3 49Kg/S

蒸汽发生器压力壳:
Pressure vessel of steam generator

壳体内径: Inner diameter	2500 mm
筒体壁厚: Thickness	50 mm
总高度: Total height	12000mm



正在吊装中的氦风机及其压力壳
Installing helium circulator in pressure vessel

氦风机:
Helium circulator

台数: Number	1 台
结构型式: Type	立式 vertical
叶轮型式: Impeller	离心式 centrifugal
升压: Pressure rise	60KPa
流量: Flow rate	4.3Kg/S
额定转数: Rated speed	5300转/分
调速范围: Speed range	30～100%

热气导管压力壳
Pressure vessel of hot gas duct

总长: Total length	3[illegible]5mm
外径: Outer diameter	[illegible]80mm
壁厚: Thickness	40mm

安装工人正将热气导管套入热气导管压力壳内
Inserting hot gas duct into its pressure vessel

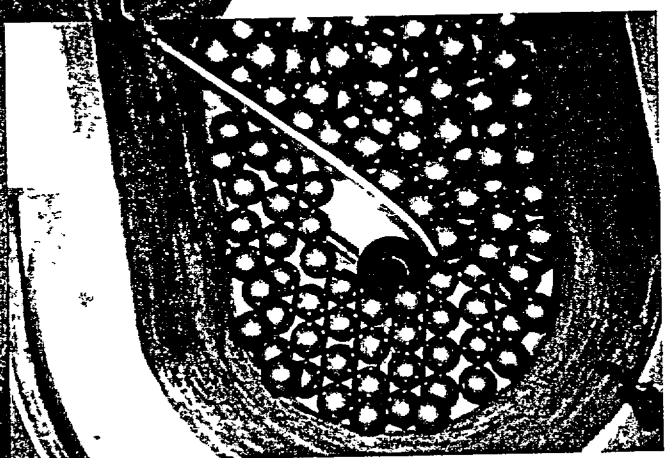
热气导管
Hot gas duct

外管壁外径: Outer diameter of outer duct	570mm
外管壁厚: Thickness of outer duct	10mm
内管壁内径: Inner diameter of inner duct	300mm
内管壁厚: Thickness of inner duct	5mm
绝热层厚度: Thickness of insulation	120mm

10兆瓦高温气冷堆技

Features of H

10兆瓦高温气冷堆技术特点



球形燃料元件单列器
Singlor of fuel elements

10兆瓦高温气冷堆的燃料元件装卸系统采用吸送方法输送球形燃料元件，并利用脉冲气流实现燃料元件球从卸料管中单列化，取代了机械运动式的单列器，克服了设备难以维修的技术难题，提高了反应堆的可利用率。

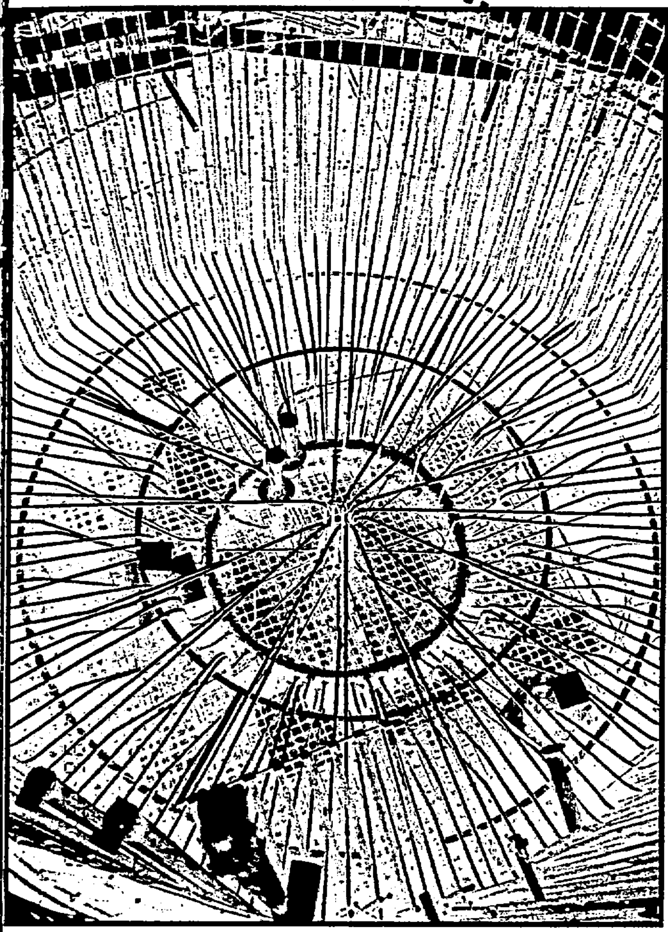
HTR-10 Fuel handling system works on pneumatic principle. Fuel elements are removed from the reactor core in a singularized way by means of pneumatic pulses.

燃料元件球提升器
Fuel element elevator

10兆瓦高温气冷堆的控制与保护系统实施了重大创新。各系统的仪器仪表实现全数字化，并将平板显示器，触摸屏、局域网等当今先进的设备和技术用到了控制保护系统上，提供了一个更高的可靠性和一个好的人机界面。

Ddigital reactor protection system is applied at the HTR-10 with friendly and reliable man machine interface is provided.

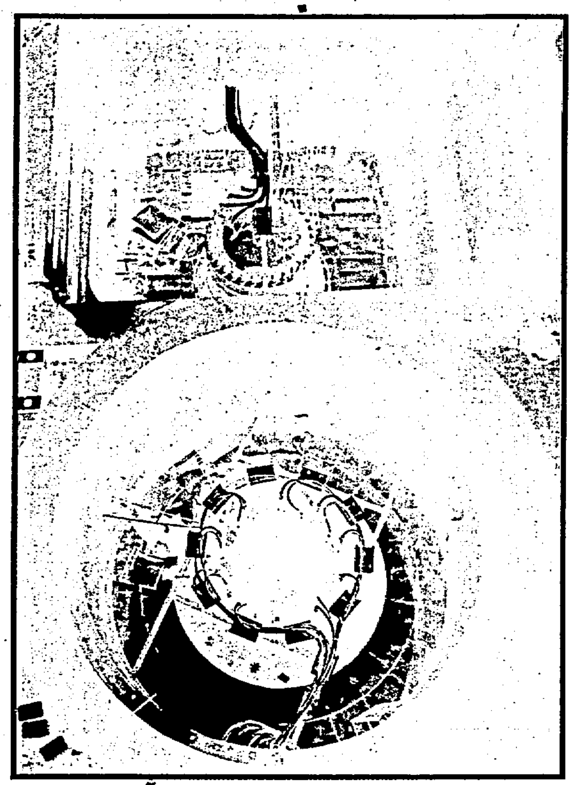
主控制室
Main control room



堆舱砼内冷却水管施工现场
Cavity cooling system

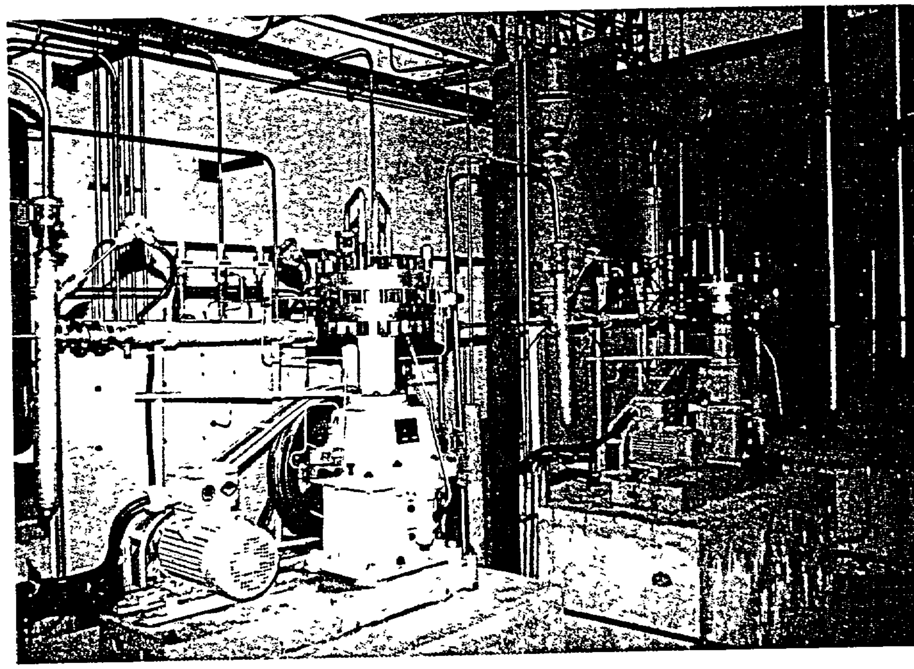
10兆瓦高温气冷堆的堆内结构材料采用导热性能良好的石墨、碳砖，反应堆停堆后裂变所产生的热量以及堆内放射性衰变产生的等余热，借助于对流、辐射及传导，传给反应堆压力壳周边的水冷壁上的垂直列管里的水。被加热的水自然循环到高位的空气冷却器，将热量散发到空气，并由百页窗排到大气。如此非能动的排出余热，大大避免了燃料元件因高温熔化的可能，极大地提高了反应堆的安全性。

The HTR-10 reactor internal material is primarily graphite and carbon bricks. Residual heat removal from the reactor core can take place through mechanisms of heat conduction, radiation and nature convection.. Cavity cooling system takes the residual heat away to air coolers. Both cavity cooling and air coolers work on natural circulation principle. These passive/inherent features of the residual heat removal enhance reactor safety .



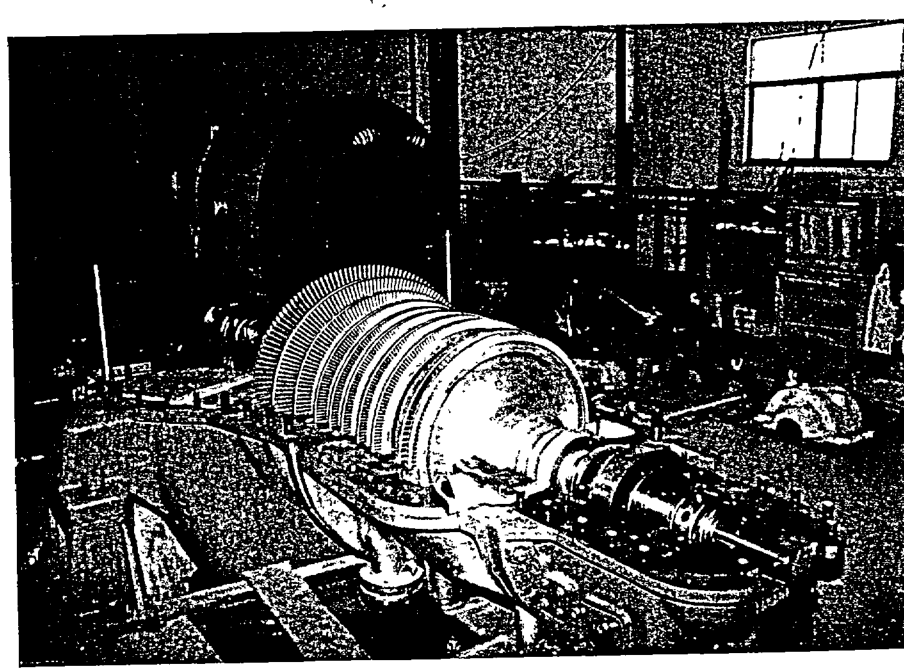
反应堆舱室和蒸汽发生器舱室俯视
Bird's-eye-view of the confinement of reactor and steam generator of HTR-10

10兆瓦高温气冷堆由于采用全陶瓷包覆燃料元件球，其破损外溢放射性的可能性极低。由于设置有氦气净化和再生系统，不断对一回路中的冷却气体氦气抽出部分进行净化，去除杂质和放射性，因此冷却氦气的放射性水平是很低的。

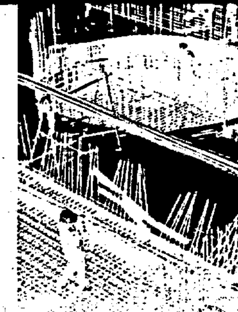


氦气净化系统
Helium purification system

Even though radioactivity released into primary coolant is minimized, helium purification system which continuously removes radioactivity and other impurities from primary coolant is designed, so that radioactivity level of primary coolant is very low.

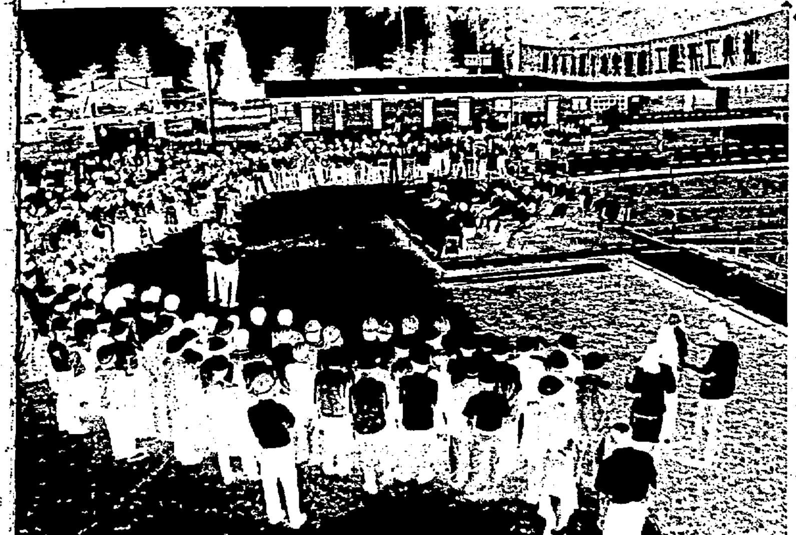


发电机组水蒸汽透平
Steam turbine generator



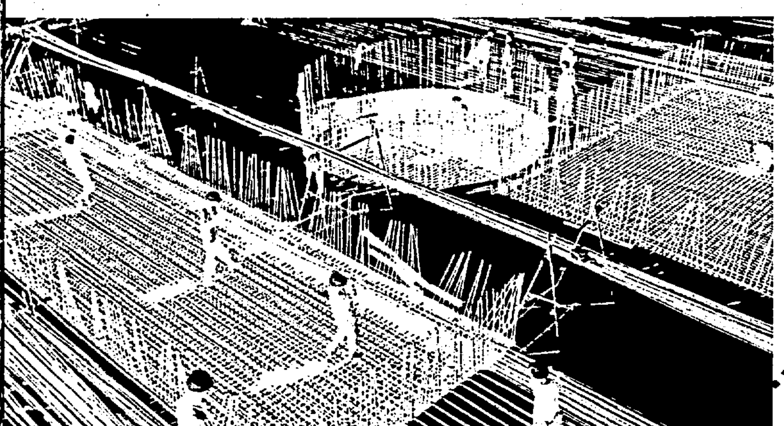
10兆瓦高温气冷堆建造历程

Milestone of constructing HTR-10



HTR-10开工仪式
Construction ceremony of HTR-10

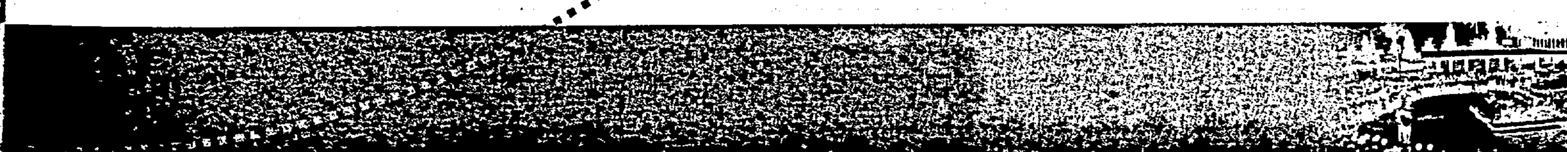
建造许可证
Construction Permit



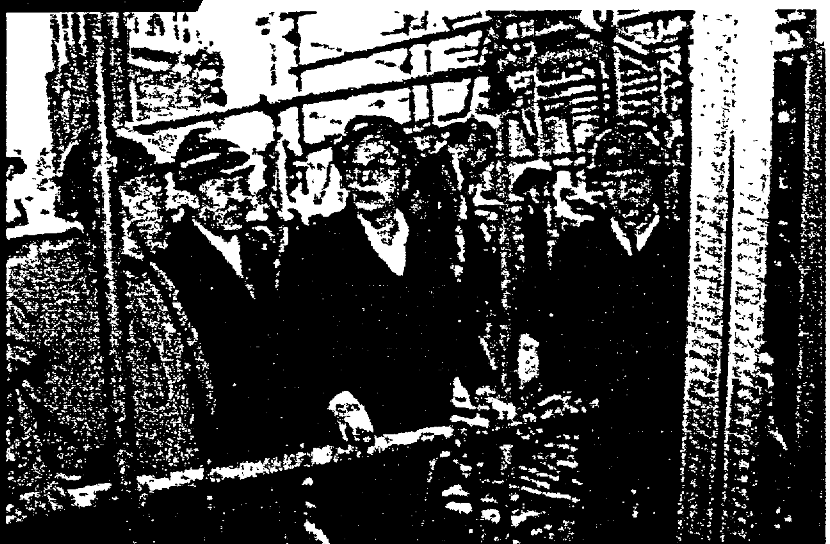
HTR-10基坑
Basement Construction of HTR-10

1992.3.14	国家批准10兆瓦高温气冷堆作为国家"863"发展计划立项
1994.12	国家核安全局给10兆瓦高温气冷堆发放建造许可证
1995.6.14	HTR-10土建工程浇灌第一罐砼
1997.10.28	反应堆主厂房土建工程结构封顶
1998.11.27	反应堆压力壳和蒸汽发生器压力壳吊装就位
2000.12	陶瓷堆内构件安装完毕
2000.4.29	反应堆压力壳封盖
2000.9	设备与系统安装结束
2000.11.17	国家核安全局发放装料许可证
2000.11.20	开始往堆芯装入核燃料元件球
2000.12	10兆瓦高温气冷堆实现临界

1992.3.14	HTR-10 project was approved by government as one of the national "863" project
1994.12	Construction Permit of HTR-10 was issued by National Nuclear Safety Administration
1995.6.14	First concrete was poured
1997.10.28	Main building of HTR-10 was completed
1998.11.27	The Reactor Presure Vessel and Steam Gernerator Pressure Vessel was installed into the cavity
1999.12	Installation of ceramic internals was completed
2000.4.29	The head of pressure vessels were covered
2000.9	Components and systems installation were completed
2000.11.17	Fuel loading Commissioning license was issued by National Nuclear Safety Administration
2000.11.20	Starting fuel loading
2000.12	First criticality of the HTR-10

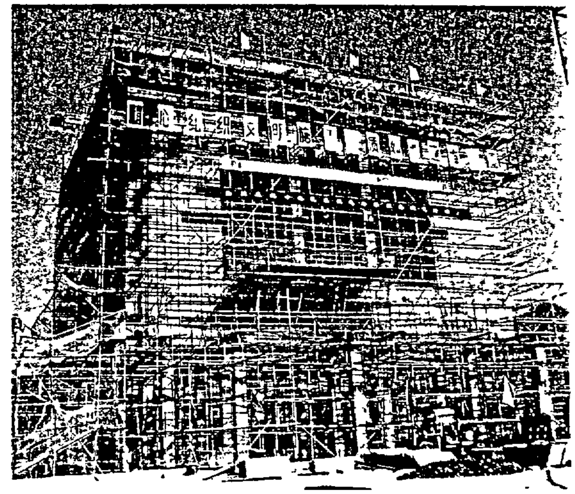


Milestone of constructing HTR-10

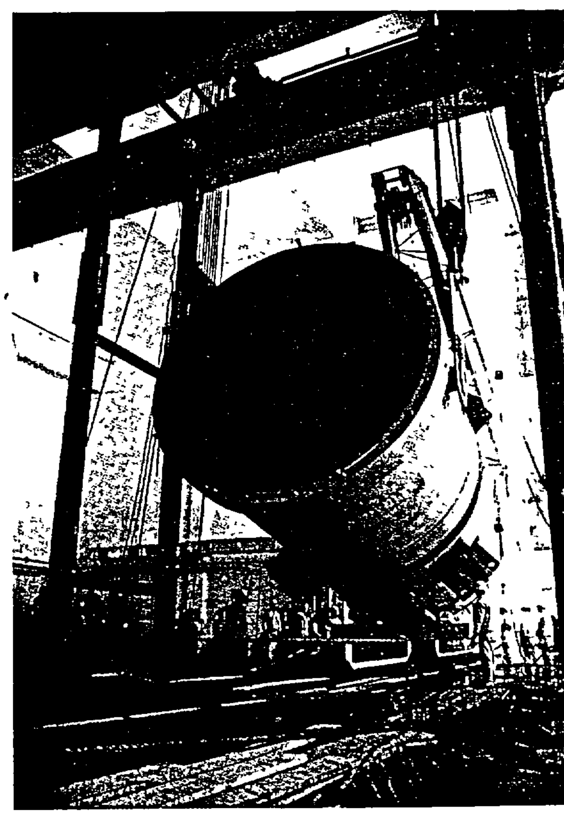


原国家核安全局长黄齐陶在现场检查
Former Director of National Nuclear Safety Administration Huang Qitao checking up on work

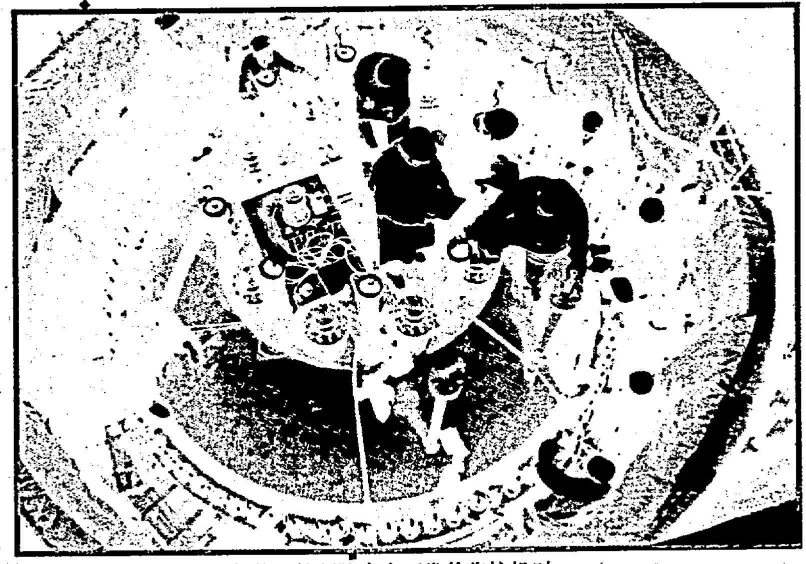
能源领域专家委员会赵仁凯、阮可强院士在现场检查
Academician Zhao Renkai and Ruan Keqiang, members of energy expert committee, checking up on work.



反应堆主厂房封顶
Construction of HTR-10 main building



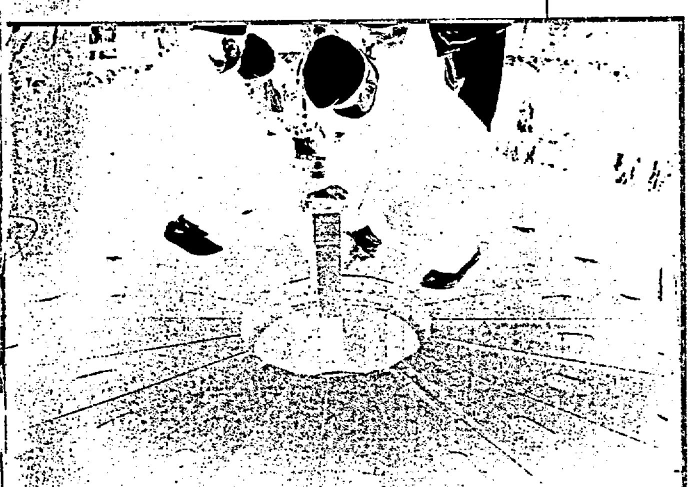
反应堆压力壳正在吊装就位
Installing Reactor Pressure Vessel



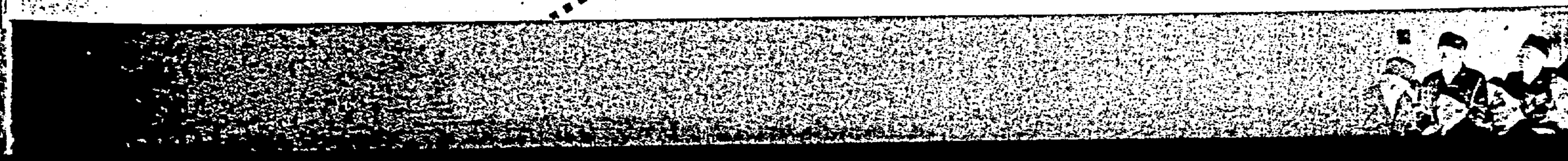
安装工人和设计人员一起使用核研院自主开发的张拉机对反应堆压力壳法兰上的M80螺栓进行张拉紧固
Fastening the flanges of reactor pressure vessel by stretching M80 bolts using stretch machines developed by INET

堆芯壳正在安装中
Installing core internals

国家核安全局监督人员与工程人员正在关注物理起动
Officers and staffs of National Nuclear Safety Administration monitoring physical startup



工人们正在安装最后一块碳砖构件
Installing the last carbon component



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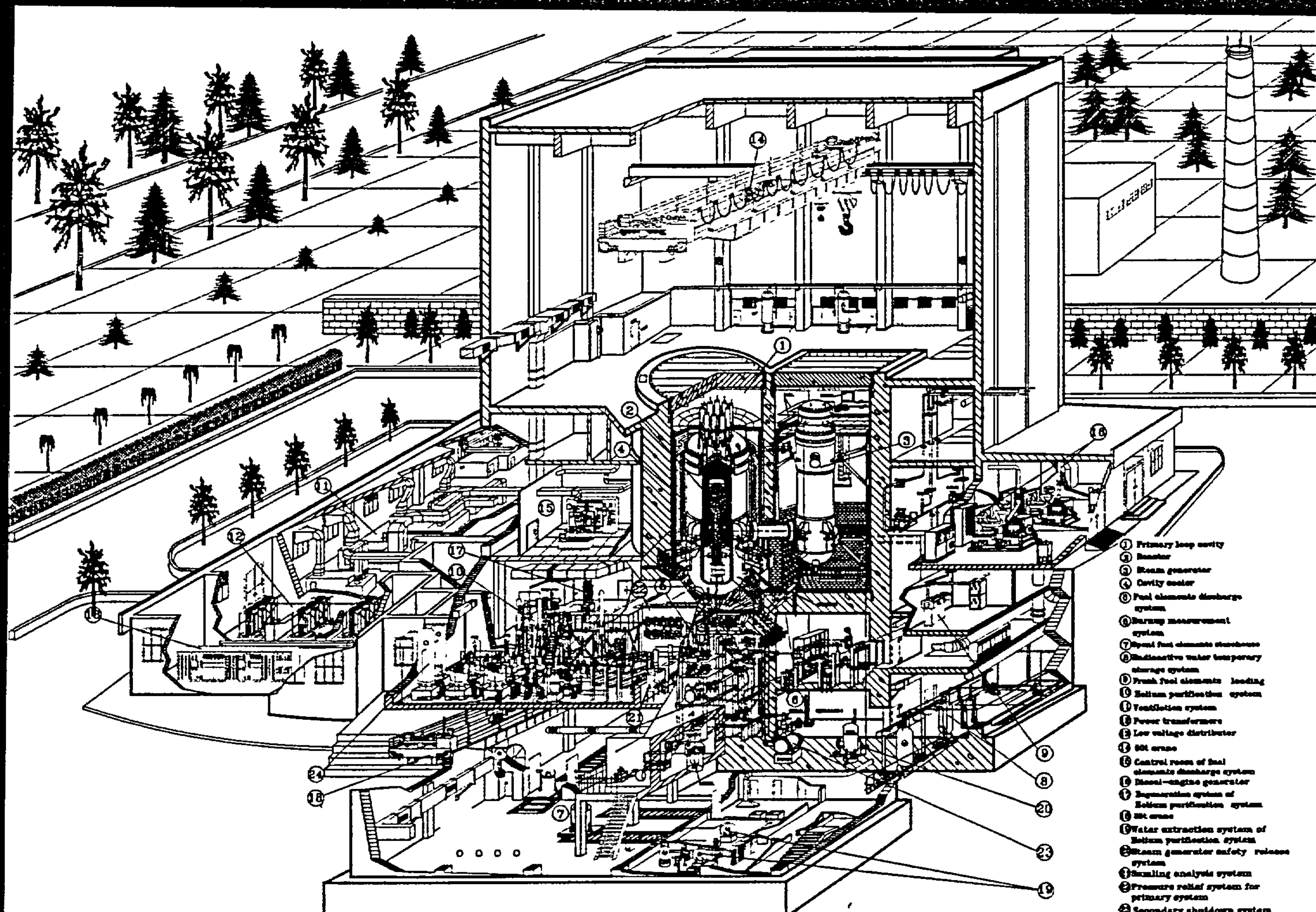

清华 10MW 高温气冷实验堆

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