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Technical analysis for preferring more efficient and green technology for thermal power generation: "Advanced-Ultra Supercritical 760°C"

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***Abstract* –** This paper deals with the technical analysis for preferring more "Efficient and Green" of "Advanced-Ultra Supercritical 760°C" technology for power generation for achieving more savings on Efficiency, Capital Cost, O&M Cost and with reduced GHG emissions instead of preferring "710°C technology" . There is an urgent need for the shifting of the focus of technology development for proposed A-USC (Advanced Ultra-Super Critical) from A-USC-710°C to A-USC-760°C for availing greener and less costly cost power generation option. It is said that just a 1% gain in efficiency for a typical 700 MW plant reduces 30-year lifetime emissions by 2,000 tonne NOx, 2,000 tonne SO2, 500 tonne particulate matter and 2.5 million tonne CO2. Further to that improvements in the Efficiency will not only decrease operating costs and make better use of fossil fuels, they will also reduce the emissions.

This paper describes how the concept of advanced ultra-super critical technology came in to existence in India and how the Government of India gave thrust to develop this technology. This paper on technology side covers the cycle conditions used and performance and efficiency of the technology. This paper also reviews the comparison of different technologies *vis-à-vis* parameters of steam temperature, pressure of Advanced Ultra Supercritical and sub-critical technologies. The information on work done on Boiler material selection based on strength and stability is also covered. The aspect of saving on the part of material, thickness and size are also discussed. The study indicated that such work has earned ASME Boiler and Pressure Vessel Code that regulates the design and construction of boilers and pressure vessels. The paper also has discussions on the A-USC 760°C technology development including test-runs, performance runs and component test accomplished for 1,00,000 hours (11+ years).

The review of the development of this technology indicated that the study started as early as 1995 outside India and India turned to this technology around 2010. An insight into the development of special steel containing different proportions of Chromium and Nickel indicated that material properties are greatly improved and operations could be done at 760°C leading for cost reduction and improved environmental parameters. In summary and conclusion recommendation emerged after the discussions is also given for the selection of most suitable and appropriate technology. For the purpose of ready understanding the work done by leaders in A-USC their few slides are re-produced here in the paper.

I. INTRODUCTION

In todays' time, the renewable technology route like Solar is the India's top most priority for power generation, but the relevance of Coal route, that too through the development of Advanced-Ultra Super Critical (A-USC) Technology – a more efficient with reduced carbon foot prints, is in no way lesser. It is true that India would depend on coal for energy for at least next 30 years and India's for coming years as solar and wind power would not be able to replace coal in near future. India's requirement for energy through Renewable Energy route would probably need huge lands covered with solar cells panels and even than India may remain still power deficient. Also, the sun shines only half the day and the dust/silt requires constant cleaning to maintain their efficiency. Further to that unless lower cost "storage capability" is developed; Solar power and Wind power availability would be constrained for coming few decades.

As per the India's national Electricity Plan 2016, In the 12th Plan, likely capacity addition from conventional sources as per review carried out as on 31.3.2016, will be 101,645 MW (Coal 86,250 MW, Lignite – 1,290 MW, Gas – 6,080 MW, Hydro – 5,525 MW, Nuclear – 2,500 MW) against a target of 88,537 MW. This is about 115% of the target. The 2. 56 % of total capacity addition during 12th plan is expected to come from private sector. There is likely to be considerable slippage in capacity addition target in respect of Hydro (5,601 MW) and Nuclear (2,800 MW) in the 12th Plan period. During 12th plan, capacity addition from supercritical technology based coal power plants is likely to contribute around 39% of the total capacity addition from coal based plants. The total capacity addition during 2017-22 is likely to be 1,87,821 MW. As per NITI Aayog "Energizing India Report 2017". Business as usual scenario showed that based on projected yearly growth basis, share of Ultra Super-Critical technology (USC) in total generation capacity of 848 GW in 2032 & 1566 GW in 2047 be 35% in 2032 & 60% in 2047. However, share of Integrated Gasification Combined Cycle (IGCC) technology is projected to be lower at 10% in 2032 & 40% in 2047. Clean Coal Technology (CCT) scenario shows that the USC will increase to 45% in 2032 & 40% in 2047 and share of IGCC technology will be 15% in 2032 & 60% in 2047. The share of USC is slowly being replaced by IGCC under CCT scenario. The Sub-Critical technology in coal based power plant is projected to retire by 2032.

The Government of India is also making efforts to develop the technology and set up a first thermal plant and notified by several press releases through the note of Press Information Bureau (PIB) and the story goes as early as the year August 2006, which is as described below.

The planning commission was introduced the concept of super critical technology in 2006 in its Integrated Energy Policy Report, April 2006 release [1] by member Planning Commission and was duly signed by 20 Experts including six Secretaries to the Government of India, TERI, ASCI, FICCI, ASSOCHAM, SERC, IIT Mumbai, IDFC and others. Consequently, India adopted the supercritical and then ultra-supercritical technology to get the benefits of improved efficiency of coal power plants. Moreover, the A-USC project is expected to reduce the carbon dioxide emission by 15-25% at source and the power plant based on A-USC technology would reduce coal consumption about by 20% as compared to the sub-critical plant and by 11% in comparison to the super critical technology plant. Furthermore, the A-USC operating efficiency is expected to be above 50% which is much higher than sub-critical and super critical technology. Hence, the project would lead to operational cost savings.

It has stated that The Integrated Energy Policy of the Government of India envisages an ambitious program for power capacity addition to about 800 GWe by 2031-32 towards meeting the energy demands of the country for ensuring the required economic growth and improved standards of living. For minimizing carbon dioxide emissions, through achieving the highest possible energy efficiency and reducing coal required per unit of power generated, it is planned to adopt clean-coal-based power generation technologies such as supercritical, ultra-supercritical, advanced ultra-supercritical and integrated gasification combined cycle, which are in different stages of development, demonstration and commercialization worldwide. Certain innovative options such as carbon dioxide capturing and sequestration and high-temperature bio-waste and bio-fuel based plants are also being explored. This paper discusses the materials research and opportunities of these power generation technologies.

As referred in the Power Technology 2018 article entitled "Yuhuan 1,000MW Ultra-Supercritical Pressure Boilers" Siemens reports that just a 1% gain in efficiency for a typical 700 MW plant reduces 30-year lifetime emissions by 2,000 tonne NOx, 2,000 tonne SO2, 500 tonne particulates and 2.5 million tonne CO_2. [2]

The CEA (Central Electricity Authority) has projected to reduce the dependence on coal based power plants and has designed framework to adopt new renewable sources, yet the available renewable resources are not viable enough to meet the increasing domestic demand, and therefore, coal based power plants will continue to be a feature of Indian Power Sector at least for 50-60 more years. Furthermore, the advanced ultra-supercritical technology is a pioneering indigenous technology and has potential enough to solve the bottlenecks of coal based power plants. The A-USC project will enable Indian industries to design, manufacture and commission higher-efficiency and low polluting coal-fired power plants. This in turn will also lead to establishment of new industries and generate employment opportunities in the country.

It could be seen that Advanced-Ultra Supercritical Technology operating at very high pressures & temperatures have the needed ability to provide a great scope of improvement in Turbine cycle efficiencies. Learning this advantage, the Government of India took various decisions to promote the use of such technology in our country by advocating a gradual shift to Supercritical Technology to Ultra Super Critical Technology and the plan to Advanced Ultra Super Critical Technology in the 12th Plan period and then in the 13th Plan the Government envisages the total switchover to Supercritical Technology for Utilities, thus contributing a great extent to a drastic reduction in Carbon Footprint & Global Warming. The main advantages of the Supercritical shift would be on the following lines

- Equipment cost per MW cost reduction
- Availability of more efficient & reliable products
- Steam turbine modules to perform on higher efficiencies of scale
- To be more competitive to cater to emerging market

If coal based power plants have to survive and to compete with Solar Power generation plants, and then they have to prepare & choose the most advanced coal based power generation machines such as the regimes of Advanced-Ultra Supercritical Technology (A-USC-760°C) as compared to just Ultra Supercritical Technology. As it is known that the efficiency in prevailing sub-critical power generation technology is about 32%, whereas in Advanced-Ultra Super Critical Technology the efficiency of power generation is in the range of 46-50% and additionally CO_2 abatement capability is increases from 12% and 41%. By 2032, India is planning to convert the present sub-critical fleet of power plants to only Ultra Super Critical (USC) Technology having 42-45% thermal efficiency and 28% CO_2 reduction by staying at say 603°C-605˚C. The internationally Turbines-Boiler materials to function at 603°C-605˚C are developed and they are working well as the Ultra-Supercritical technology units and also have developed 700°C-720°C materials successfully. Additionally western countries have already run and tested their material for 1,00,000 hours. In contrast to that India yet to start such work.

Thinking on the similar lines, the Government of India in its best efforts to be at the front of the latest technology made efforts to develop the Advanced Ultra Super Critical (A-USC) Technology which would perform at 710°C-720°C and decided to go for the development of the technology through R&D work to be conducted by IGCAR-BHEL-NTPC-MIDHANI which is evident from the releases of Press Information Bureau as explained below:

As early as December 2009, Under the National Action Plan on Climate Change Government of India (GOI) emphasized on development of underground coal gasification (UCG) or in-situ coal gasification, a clean coal technology, that allows exploitation of coal reserves conventionally regarded as uneconomic or inaccessible due to depth or mining and safety considerations. UCGs are more beneficial in terms of health and safety and lower capital and operating costs and environmental effects. In India almost 40% of available coal reserves are beyond 300 m in depth, to access these reserves UCG promotion is important. *(PIB – Towards green coal technology, 9 December 2009*) [3].

Further to that in April 2011, the Cabinet Committee of Economic Affairs (CCEA) approved the constitution of a National Clean Energy Fund (NCEF) and the Finance bill 2010-11 provided creation of a corpus called NCEF to invest in entrepreneurial ventures and research in clean energy technologies. Subsequently CBEC issued Clean Energy Cess Rules, 2010. The Inter Ministerial Group (IMG) approved the projects/schemes eligible for financing under NCEF. *(Press Information Bureau, Government of India-PIB:* - Creation of National Clean Energy Fund – NCEF, April 6th 2011 [4].

After a lull of three years in August 2014 *vide* Press Information Bureau (PIB), Government of India announcement, A new scheme for "Development of Advanced Ultra Super-Critical (A-USC) Technology for Thermal Power Plants" was introduced in the Union Budget of 2014-15 as an R&D project to improve power plant efficiency to 45-46%, reduce CO_2 emissions and reduce coal consumption, and establish a demonstration power plant 800 MW capacity. The cost is estimated at Rs 1554 Crore and for financial year 2014-15, government made budgetary provision of Rs. 100 Crore *(Press Information Bureau, Government of India-PIB: Development of ADV-USC Technology for Thermal Power Plant as an R&D, 11 August 2014*).[5]

Then in March 2015, the government of India approved an Advanced Super Critical Technology (A-USC) R&D Project for Rs. 1500 Crore to achieve enhanced efficiency of thermal generation, reduce carbon dioxide emissions, and reduce coal consumption for coal based power plants. *(Press Information Bureau, Government of India-PIB: March 2, 2015*) [6].

Through an another PIB release, it was announcement, that the following initiatives have been taken to reduce carbon footprint of power sector – out of a total of 87,000 MW thermal capacity under construction about 48,000 MW is supercritical that uses less coal; supercritical technology mandatory for Ultra Mega Power Plant (UMPP); in 13th plan all coal fired capacity addition will be through supercritical units; A-USC technology approved by government; renovation, modernization and life extension of old thermal power units and retirement of old and inefficient thermal generation units, in phased manner – 3,000 MW already retired; policy of automatic transfer from old units to new supercritical units; doubling coal cess from Rs 100/tonne to Rs 200/tonne for funding projects under National Clean Energy Fund (budget speech 2015-16); increasing share of renewables; PAT Scheme under National Mission on

Enhanced Energy Efficiency is under implementation by Bureau of Energy Efficiency (BEE) for improving energy efficiency for 144 number of thermal stations. *(Press Information Bureau, Government of India-PIB:* Initiatives to improve the efficiency of Coal Based Power Plants, March 12, 2015) [7]

For bringing A-USC (Advanced Ultra Super Critical Technology) to India the Cabinet Committee on Economic affairs approved the R&D on AUSC with an estimated cost of Rs. 1554 Crore i.e. Rs. 270 Crore from BHEL, Rs. 50 Crore from NTPC, Rs. 234 Crore from ICAR, Rs 100 Crore from DST, and balance Rs. 900 Crore from DHI as a grant spread over three years, commencing from 2017-18, provided to BHEL as a plan Gross Budgetary Support for implementation of R&D. The project will enable Indian industries to design and manufacture higher efficiency coal power plants using advance technologies without any technological collaboration/ licensing agreement with foreign companies. The proposed technology is still in research stage in all countries and not matured and demonstrated however, it is expected to give 20% reduction in CO_2 emission at source, 20% saving of coal consumption compared to sub critical plant and 11% saving compared to supercritical plants thereby ensuring energy security for the country. *(PIB – Cabinet Approves financial support to BHEL for R & D for development of AUSC technology August 10 2016)* [8]

Government of India further took the steps in March 2017 and April 2017 to modernize and improve the efficiency of coal based thermal power plants and reduce pollution levels from these plants include Adoption of supercritical technology with design efficiency 5% higher, lower fuel consumption and CO_2 emissions than that of 500 MW subcritical units. A capacity addition of 39,710 MW power based on supercritical technology already achieved and 48,060 MW of technology is in pipeline. Ultra Mega Power Projects (MPPs) required to use supercritical technology and coal based capacity addition during the 13th plan period shall be through super critical units. Policy of automatic transfer of Letter of Assurance/ coal linkage granted to old plants to adopt new supercritical units by state utilities/IPPs. Under the Performance Achieve and Trade (PAT) Scheme under National Mission on Enhanced Energy Efficiency under Bureau of Energy Efficiency-PAT cycle II – individual target for improving efficiency assigned to 154 thermal power stations. High efficiency electrostatics preceptor and low NO_X burners installed to capture PM (particulate matter-fly ash) and reduce NO_X emission from flue gasses. Flue gasses dispersed through tall stacks (275 meter) to achieve SO_2 emission control and reduce concentration of polluting gasses at ground level. **A capacity of about 7751.94 MW units of old and inefficient unit has already been retired**; Research on A-USC with targeted efficiency of 10% over supercritical units is being pursued. As discussed earlier a MoU was signed in August 2010 between key BHEL, NTPC Ltd., and IGCAR for development of 800 MW A-USC pilot plant (main steam pressure of 310 kg/cm^2 and temperature of 710°C-720°C). *(Press Information Bureau, Government of India-PIB: Steps taken to improve the efficiency of coal based thermal power plants 30 March 2017*) [9]; *and (Press Information Bureau, Government of India-PIB: Plan for reduction of pollution level of coal based thermal power plants, April 6th 2017.* [10]

As per the Department of Heavy Industries and Public Enterprises, Government of India [11], R&D Project for "Development of Advanced Ultra Supercritical Technology for Thermal Power Plants" on a Mission Mode, at an estimated cost or Rs. 1554 Crore was under consideration in the Department and by now it has been cleared. The project is proposed to be executed in two phases. The objective of the first phase of the project is to undertake R&D on all aspects of Advanced-USC technology for thermal power plants in order to improve power plant efficiency, reduce carbon-dioxide emissions and reduce coal consumption per unit of power generated. In the second phase, an 800 MWe Advanced-USC Demonstration power plant based on the developed technology will be established. The project will be carried out jointly by BHEL under DHI, Indira Gandhi Centre for Atomic Research (IGCAR) under Department of Atomic Energy and National Thermal Power Corporation Limited (NTPC) under Ministry of Power, who have entered into a Memorandum of Undertaking (MoU). The duration of the R&D project is estimated to be two and a half years from the date of approval. Though the time limit of two and half year has been set, but it is most unlikely to happen due to the system constraints.

Such technology developed indigenously would enable India to be among the first few countries in the world to demonstrate the technology. It will facilitate manufacture of large power plant equipment with advanced technologies and without Technological Collaboration/ Licensing Agreement from foreign companies. Further, the spin-off from this project will include benefits to other industries dealing with high temperature, high pressure exposure of metal objects. Once developed, use of these technology in future large thermal power plants will ensure energy security for our Country for a longer period, along with reduction in impact on the environment.

In March 2017, the "Consortium of BHEL, NTPC and IGCAR under the aegis of DHI-Ministry of HI& PE Government of India" *vide* Open Advertisement No.: 01/2017 dated March 30, 2017 had announced for the need of Appointment to the post of Mission Director of AUSC project on Contractual basis. A consortium of three government entities, namely BHEL, NTPC and IGCAR is jointly developing Advanced Ultra Super Critical (AUSC) technology for thermal power plants of future, envisaging reduced coal consumption as well as reduced carbon dioxide emission. The project is formulated with a time cycle of two and a half years under the aegis of DHI, Ministry of HI & PE and involves an estimated expenditure of INR 1554 Crore, with major funding of INR 1000 Crore from Govt. of India. The Applications had been invited from the citizens of India for filling up the post of Mission Director for aforementioned R&D project. As "Mission Director–R&D Project" for Development of A-USC technology on CONTRACT basis for a period of 30 months. The position has been filled now and the positional is functional now and is being headed by industry expert.

It is planned to perform the following designing and scheming of activities during the currency of the project of 30 months; Material characterization of special alloy to be used in high temperature high pressure steam cycle component in Boiler, tubing, valves and steam turbine. b) Development of manufacturing technologies including casting, machining, welding etc. for all components made out of special alloys. c) Detailed design of components, sub-assemblies, assemblies etc. for manufacturing, testing for final erection and commissioning. d) Manufacturing and testing of prototypes to validate the design. e) Design of complete systems of power plant and documentation for establishing a 800 MW demonstration power plant using this developed AUSC technology. f) Any other work relating to the project as mandated by Over Arching Committee for AUSC - R&D project. And vide Business Standard dated February 2, 2018, these activities for the development of 800 MW advanced ultra-super critical thermal power plant project got Rs 100 crore for next year from the Department of Heavy Industry with a target to finalize the turbine design, as per 2018-19 budget papers. According the Union Budget, the project target for next fiscal includes finalization of turbine design, completion of detailed design for boiler and valves and commissioning of the turbine rotor test rig facility [12]; and the Ministry of Heavy Industries and Public Enterprises (MHI & PE) has brought forth this fund on board in its budget [13].

II. THE TECHNOLOGY

The basic understanding on the differences in the technologies and their pressure and temperature parameters of the technologies such as Sub-Critical, Super Critical, Ultra Super Critical, Advanced-Ultra Supercritical has been shown below as widely available in the literature. Different types of comparisons for different technologies are given below in the Table-1 and Table-2 respectively, where data are almost similar. Performance is compared for the coal based plant types, with the steam conditions shown in Table-1, representing Sub-Critical, Super Critical, Ultra Super Critical, and Advanced-Ultra Supercritical thermal cycles. These steam conditions are considered representative of current market offerings in the U.S., except for the A-USC plant which is in the advanced stage of Test program.

An excellent review on the subject has been published by *Chetal et.al.* referred at [14]. (*http://insa.nic.in/writereaddata/UpLoadedFiles/PINSA/Vol81_2015_4_Art06.pdf*). A lot work is being done for the development of such materials. In this light CSIR-National Metallurgical Laboratory (NML) Jamshedpur has presented the studies done on the 740 H Inconel materials procured presumably from outside India. They have studied the Strain rate effect on cyclic deformation behavior of advanced ultra-supercritical boiler grade wrought Ni-based super alloy IN 740H at 760 °C. It is understood that in India too as late as in 2016, the work on Ni-based super alloy IN 740H at 760°C has been initiated at National Metallurgical Laboratory but just at the evaluation stage only; as the alloy sample has been obtained presumably some other source. Strain rate effect on cyclic deformation behavior of advanced ultra-supercritical boiler grade wrought Ni-based super alloy IN 740H at 760°C by *R.K. Singh, J.K. Sahu; Materials Science and Engineering, Pages 272-279,Volume 658, 21 March 2016,* [15].

Table I: Cycle conditions used for Performance and Efficiency of Technology

Sl. No.	Plant Type	Main Steam Pressure (Bar/ kg per cm^2)	Main Steam Temperature (°C)	Thermal efficiency (Indicative) on Gross Calorific Value basis (%)	Change in Overall plant efficiency (% relative)	CO_2 Emission Reduction (%)
1.	Sub-Critical	170/173.3	540	33-35	Base case	Base Case
2.	Super Critical	240/244.7	565	36-40	2.9	12
3.	Ultra Super Critical	250/297.7	602-610	42-45	5.8	28
4.	Ultra Super Critical	292/297.7	603-621	42-45	6.6	28
5.	Advanced Ultra Super Critical* (A-USC-650°C)	345/351.8	650	46-50	9.5	41
6.	Advanced Ultra Super Critical* (A-USC-710°C)	345/351.8	700	46-50	12.7	41
7.	Advanced Ultra Super Critical (A-USC-760°C)	345/351.8	760	46-50	15.8	41

*Under Developmental stage

Table II: A comparison of different technologies vis-à-vis various parameters of steam temperature, pressure etc.

Quantity	Sub-critical	Super-critical	600°C USC	700°C A-USC	760°C A-USC
Coal Cost, $/GJ	3.42	3.42	3.42	3.42	3.42
Main Steam Temperature, °C	541	582	604	680	732
Main Steam Pressure, bar	179	262	276	352	352
Net heat rate, Btu/kWh (HHV)	9,430	8,860	8,700	7,990	7,633
Efficiency, % HHV	35.5	38.5	39.2	42.7	44.7
LCOE, $/MWh (1)	71.0	69.2	69.4	69.7	69.7
CO_2, kg/MWh from plant	900	851	836	763	729
Relative CO_2 emissions *vs* Subcritical	100	94.5	92.9	84.8	81.0
Technology	Sub-critical	Super-critical	700°C USC	700°C A-USC	760°C A-USC
Coal Cost, $/GJ	3.42	3.42	3.42	3.42	3.42
Main Steam Temperature, °C	541	582	604	680	732

Source: Ref: [35] Engineering and Economic Evaluation of 1300F Series Ultra-Supercritical Pulverized Coal Power Plants, *EPRI Study: on SC, USC, and A-USC Plant Study EPRI Report 1015699, September 30, 2008, EPRI Project Manager J. M. Wheeldon*

Present International scene on A-USC Technology Development: The USC technology for steam parameters up to 280 kg/cm2 and 600°C super-heater/re-heater temperatures is a in a stage of adoption in the world. To further improve the power generation efficiency and carbon dioxide emissions, work is in progress currently being conducted in the USA, European Union, and Japan for use of steam parameters of 300-350 kg/cm^2 pressure and 700°C-760°C and more steam temperatures (Table 3). In this context, for India, A-USC plants with moderate steam parameters of 310 kg/cm^2 and moderate steam temperatures of 710°C/720°C are being considered.

Table III: A-USC work is in progress in different countries

Sl. No.	Year	Country	Temperature of SH/RH (°C)	Pressure (kg/cm^2)
1.	1990	USA	760	350
2.	1998	Europe	700	350
3.	2007	China	700	300
4.	2008	Japan	700	350
5.	2010	India	710/720	310

Source: Ref (14): *Chetal et.al., Proc. Indian National Science Academy, 81 No. 4 September 2015 pp. 739-754*

At this moment it could be seen that EU countries are still paddling at lower temperature 700°C and 300 kg/cm^2 pressures which would give them lower efficiencies, lower reduction in CO_2 generation, lower cost reduction, lower reduction in operating costs and lower space reduction in Plant layouts as compared to the technologies performing at 760°C and pressure of 350 kg/cm^2 in USA since 1990 as already developed and is in advanced stage of performance tests.

As per the International Energy agency (IEA) Report the work on highest steam temperature is being done at 760°C in USA. The IEA report says that "The program on 'Advanced Ultra-supercritical Power Plant Materials' in the USA started in 2001. The research program is financially supported by the US Department of Energy and Ohio Office of Coal Development, and is split into two consortia, the major US boiler manufacturers (Alstom, Babcock & Wilcox, Foster Wheeler, Riley Power, GE Energy) and US steam turbine manufacturers (Alstom, GE energy, Siemens). The national laboratories, Oak Ridge National Laboratory and the National Energy Technology Laboratory support both consortia. The research program is managed by the Energy Industries of Ohio with the Electrical Power Research Institute serving as the program technical lead. The National Energy Technology Laboratory are aiming for 760°C (1400°F) maximum temperature and 35 M*Pa* (5000 psi) maximum pressure, with efficiencies of 45–47% (net, HHV) and a corresponding drop in carbon dioxide emissions of 15–22%. Alstom have estimated an increase of efficiency of 7% points when going from USC to AUSC steam parameters. Alstom argue that 760°C maximum temperatures should be reached as opposed to 700°C for three reasons. Firstly, nickel alloys can reach this temperature. Secondly, the cost of precipitation strengthened nickel alloy needed for 760°C is the same as solution strengthened alloy for 700°C. Finally, conventional PCC plant configuration can exploit temperatures of

760°C". Thus the experience of Alstom is pointing on AUSC technology operating at 760°C. In view of above, it is prudent to review the status of technology performing at 760°C and pressure of 350 kg/cm^2.

As per the Report entitled "Advanced Ultra-Supercritical Pulverized Coal Power Plant with and without Post-Combustion Carbon Capture. EPRI, Palo Alto, CA: 2015" released as Task-7 and authored by Goeorge Booras by U.S. Department of Energy (DOE) under Instrument Number DE-FE000234 and the Ohio Coal Development Office/Ohio Department of Development (OCDO) under Grant Agreement Number D-05-02B, [16]. The Report covers the progress of the work from October 1, 2009 to September 30, 2015. Such work has also referred the work earlier done on the same subject. (17-31).

The salient features of the work are enumerated below.
As explained in **Figure 1** that their team member Alston is working on this technology since 1995 [32]. (John L Marion). Their slides are reproduced for ready reference and better understanding.

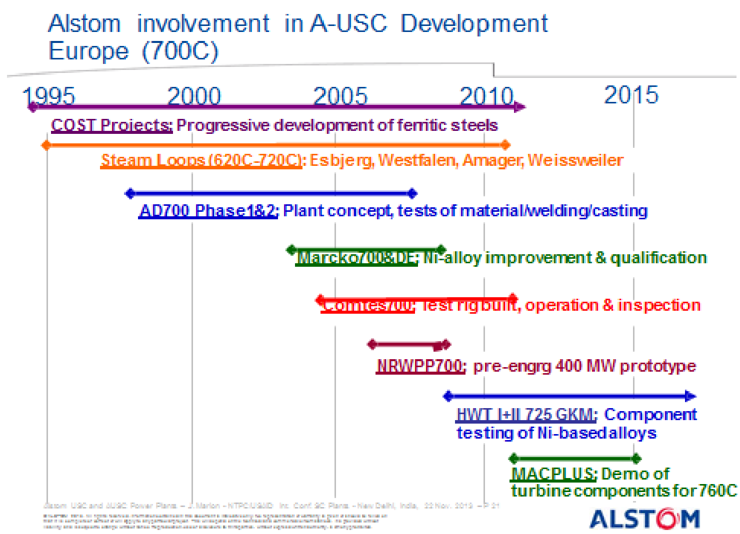


Figure 1: Western Countries working on A-USC since as early as 1995

Source: Reproduced from Ref [32] *with Approval of Author*

It is well known that achieving 700°C/760°C steam temperatures require, new advanced materials, New fabrication techniques and New materials include Ni-based alloys for SH/RH tubing/piping and turbine forgings/castings such as 617, 263, Sanicro 25, 740, 625. The new fabrication techniques include, Membrane wall tube panels from high-Cr ferritic alloy (T91/92), dissimilar welds in turbine rotor [32] (John L Marion).

As the amount of Ni is increased the material becomes more and more difficult to work with and if one is able to handle the material then one is able to achieve higher performance as explained In **Figure 2** [32] (John L Marion).

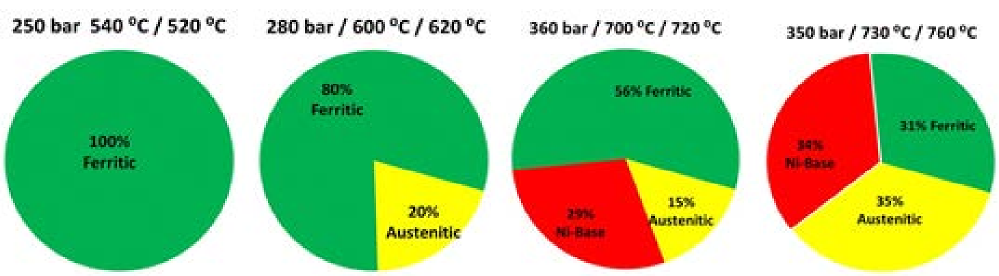


Figure 2: Variation in composition of material changes the scope of technology Application from Sub-Critical, Critical, Ultra-Super Critical and Advanced Ultra-Supercritical technology

Source: Reproduced from Ref [32] *with Approval of Author*

It is true that for the development of technology following activities are to be attended to or to be performed and at every component selective material is to be used.

i. The Conceptual Design
ii. Material Properties
iii. Steam side Oxidation
iv. Fireside Corrosion
v. Welding
vi. Fabricability
vii. Conceptual Design
viii. Material Properties
ix. Steam side Oxidation
x. Fireside Corrosion
xi. Welding
xii. Design Data & Rules (including Code interface)

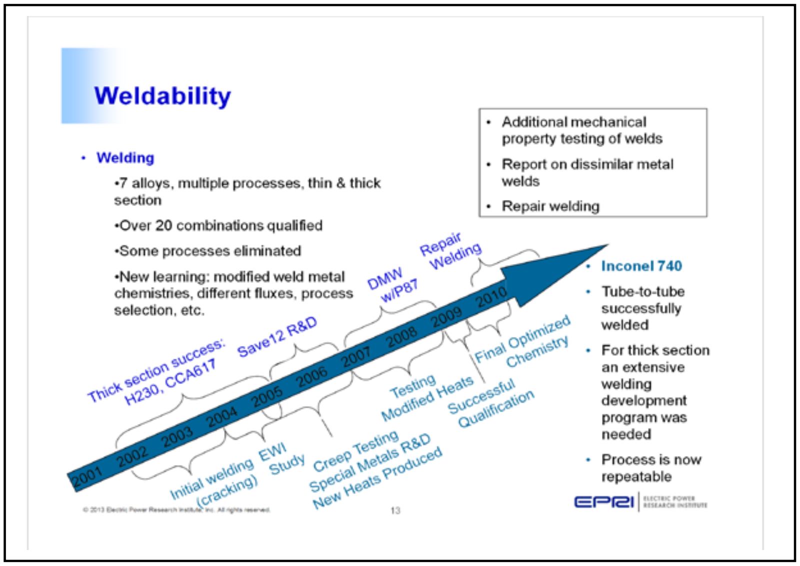
In the process developing the A-USC technology, Following have been achieved [32]

- Multiple potential host sites evaluated
- Primary and alternate host sites identified
- Pre-FEED (feed front end engineering design) and FEED tasks completed
- Preliminary capital cost estimate prepared
- PFD and P&ID documents developed. (Process flow diagram (PFD) and A Process and Instrument Drawing (P&ID) developed
- Interface conditions defined for scope boundaries
- Equipment arrangement defined for host site
- US-based supply chain development ongoing
- NEPA (National Environmental Policy Act) for primary host site proceeding

The proposed Next Steps are [32]

- Proceed with Detailed Engineering effort
- Complete NEPA procedure in support of environmental assessment for host site
- Finalize testing operating plans
- Develop procurement specifications for equipment
- Construct Component Test facility
- Operate for two years (ending in 2020)
- For example they have completed the World's First Inconel®740H Pipe Extrusion having following features Special Metals (Huntington, WV) & Wyman-Gordon (Houston, TX) Project § 15-inch (381mm) O.D. X 8- inch (203mm) I.D. X 34-1/2 feet (10.4m) long § Larger forging window for Inconel 740H compared to CCA617 (same size pipe extrusion was shorter, 8.9m)
- Major Step: Code Case 2702 (Inconel 740H) now Approved (2011) for Use in Section I and B 31.1; Maximum Use Temperature: 800°C (1472°F); and Rules approved for: Chemistry, Heat-treatment, Welding, Post-weld heat- treatment, Cold-forming, Weld strength reduction factors; Haynes 282 (Triple Melt) has been successfully forged into a disc for detailed evaluations, Disc meets criteria for largest A-USC forging needed (IP turbine); Characterization Plan: Tensile, Creep, LCF, HCF, FCGR and Toughness + fatigue in steam (ORNL)

Further research on this subject brought out that it is also worth mentioning that the studies are complete on such materials for a period of 1,00,000 hours i.e. their components have already completed the tests run for 11. 4 years or 1,00,000 hours as they are on the job this since 2001. This is demonstrated in **Figure 3:** where the developments of various stages are shown from 2001 to 2010 in their report.



*Source***:** *Reproduced from Ref [32] with the Approval of Author*

Figure 3: Boiler materials selection based on strength and stability

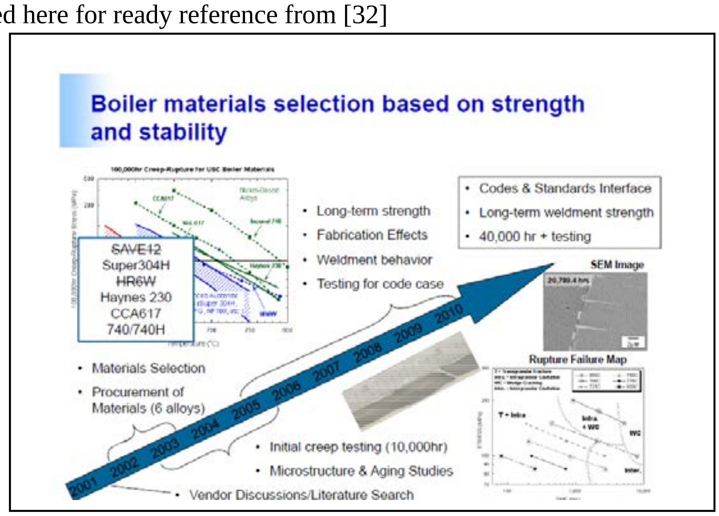
A. A case of A-USC Economics

It is well known fact that the Higher-strength alloys provide an avenue for cost savings; A-USC plant design study showed using 740H compared to alloy 617 for a main steam and hot-reheat piping system by way of reduced piping material cost (less material) by a factor of ~2. This reduced welding cost (less welds) and also provided a buffer for nickel-based alloy price fluctuations 732/760°C. A-USC is expected to cost 5-10% more than USC. In that case what is the business case that drives development in each of the continent?

This is understood nicely by looking at the following points where different situations are prevailing:

- In US - Low fuel cost, higher labor and construction costs.
- In Asia – High fuel cost, lower labor and construction costs.
- In Europe – High fuel cost, higher labor and construction costs.

Thus higher efficiency of A-USC is important in for achieving lower costs in any erection, operation. This is explained in **Figure 4,** which has been reproduced here for ready reference from [32]



Source: Reproduced from Ref [32] *with the Approval of Author*

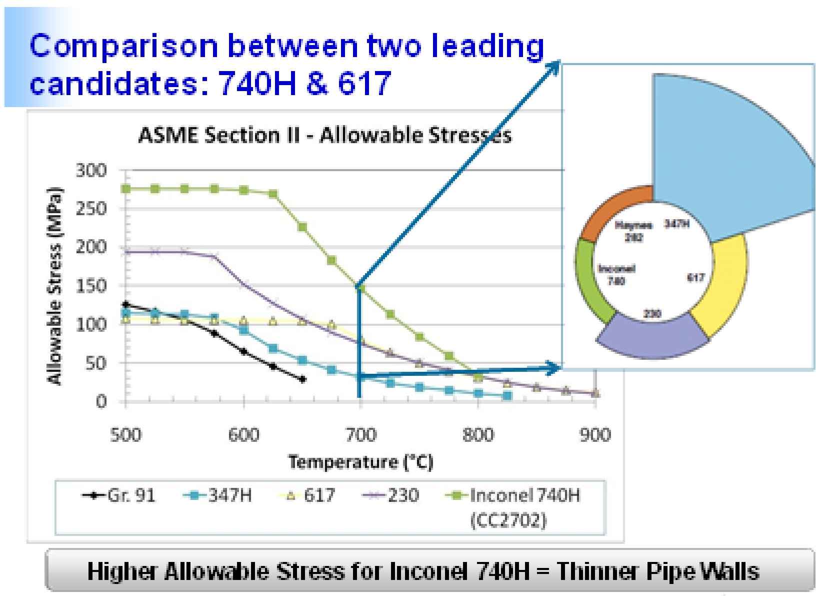
Figure 4: Time horizon from 2001 to 2010 for establishing weldability for A-USC materials

Saving on the part of material, thickness and size:

Now the following figure also explains very well that if one uses 617 material then the thickness of the tube would be reduced as shown in the blue colour and if the material Inconel 740 H is used then the thickness would be of the thickness shown in the green color. Similarly the material Inconel 740H takes much more stress as compared to the material 617 as explained in the graph.

It is fact that since the Europeans could develop the ~710˚C materials (USC), so the USA is aiming higher level of temperatures, the 760°C (A-USC), which gives an additional few more percent efficiency and more CO_2 reduction. Also even if India stays at 710˚C – USC technology, the materials like Inconel 740 H to be used for A-USC-760°C are more robust, and if used by India then that India would economize on that and would need less material; because of thinner wall thicknesses would be sufficient on account of the stronger material Inconel 740 H (A-USC-760°C) developed.

Hence, the most efficient and most green technology is A-USC-760°C technology performing at 760˚C
The following figure has been reproduced here for ready reference from [33] and shown in **Figure 5.**



Source: Reproduced from Ref [33] with the Approval of Author

Figure 5: A Comparison between two leading candidates for A-USC I-740H and 617

Achievement: This achievement is worth mentioning here and that is "Inconel® Alloy 740 Code Case 2702 Approval": A major step is achieved and Inconel® Alloy 740 Code Case Approval for Advanced Ultra-supercritical Power Plants and this important issue needs little explanation on Development of Code Case 2702 from the point of view of permissions to use the newly developed material.

Further research on this subject brought out that a consortium funded by the U.S. Department of Energy (DOE) Office of Fossil Energy and the Ohio Coal Development Office (OCDO) has successfully gained American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (B&PVC) approval for use of Inconel® Alloy 740 in Fossil Steam Boilers. This is a major step by the U.S. Department of Energy in the development of high-temperature materials needed for Advanced Ultra-supercritical (A-USC) steam cycles. **ASME Boiler and Pressure Vessel Code is issued by ASME**. The **ASME** Boiler & Pressure Vessel **Code** (BPVC) is an American Society of Mechanical Engineers (**ASME**) standard that regulates the design and construction of boilers and pressure vessels. These materials enable steam temperatures up to 760°C (1400°F), which can dramatically improve efficiency and reduce emission of all effluents (including carbon dioxide (CO_2) by about 30% over the current U.S. coal-fired power generating fleet.

The document [15] says that it is the requirement that the Materials used in the construction of fired pressure vessels must be approved for use by the **ASME B&PV Code**. While some materials are allowed for Section I construction at 760°C (1400°F), they did not have the requisite strength (allowable stresses) needed to design and build an A-USC boiler. The program developed a comprehensive data package which included test data on multiple material heats and product forms containing long-term data beyond 20,000 hours (more than two years of testing). Babcock & Wilcox championed the case with supporting data from the other project members. ORNL conducted the long-term testing and EPRI conducted the stress analysis. The robust data package was accepted on the first ballot and did not result in any negative votes. The approved Section I, Code Case 2702, contains fabrication rules, welding specifications (including weld strength reduction factors), allowable stresses, and other key requirements. Users now can design and specify the alloy for use in Section I construction to a maximum use temperature of 800°C (1472°F). Worldwide interest in the use of Inconel®

Alloy 740 is high, and as early as in 2011, Wyman-Gordon (using its internal resources), hot-extruded the world's largest Alloy 740 pipe, 381mm (15") outer diameter by 10.4 m (34.5 ft) long with a 89 mm (3.5-inch) wall thickness. A-USC-710°C programs in Europe, India and China are evaluating and planning use of the U.S.-produced material [15].

The countries like USA, Korea have developed the technology, to the advanced stages. Korea already put first Ultra Super Critical Power Plants in 2002 [34].

Today, remaining restricted in lower segment of technology India is still working on "A-USC" technology for power generation for development of Advanced-Ultra Super Critical (A-USC) which was started around 2010 as 710°C-720°C Grade Material and on related handling procedures involving the development of 700°C Grade Materials (304 H SS and 617 M).

The information available in public domain says that, in-fact currently the technology is in the development stage for components of boiler, turbine, valves, pressure parts, etc. and after their development that they have to be time-tested for 1,00,000 hours (11.42 years) *vide* Ministry of Commerce and Industry, Department of Industrial Policy & Promotion (DIPP) Notification dated 15-04-2015 for safety and performance as per as per generally accepted norms. It is understood that India has planned the performance test for a limited components developed and India has yet plan and perform the 'Performance test" for 1,00,000 hours (11.42 years) for the full range of components required in the construction of 800 MW Unit.

It is learned that the technology development for second stage i.e. is taking place on the higher side of the curve for materials such as Inconel 740 H (Ni-Cr-Fe), which operate at higher temperature of 760°C instead of 710°C-720°C. Also the aspects of running and testing the machine for about 1,00,000 hours is already complete [35] as shown below in **Figure 1.** The matching metallurgical skills such as forging, cutting welding, fabrication, scale up, coatings etc. After running their material for 1,00,000 hours, the work of Component Test (CompTest) regime for this material and is in progress to be completed by year 2020. [39,40,41]

It is true that The National Energy Technology Laboratory are aiming for 760°C (1400°F) maximum temperature and 35 MPa (5000 psi) maximum pressure, with efficiencies of 45–47% (net, HHV) and a corresponding drop in carbon dioxide emissions of 15–22% as mentioned by Romanosky in 2012 [36,37]. Alstom have estimated an increase of efficiency of 7 percentage points when going from USC to AUSC steam parameters as suggested by Marion in 2012 *[38]*. Alstom argue that 760°C maximum temperatures should be reached as opposed to 700°C for three reasons. Firstly, nickel alloys can reach this temperature. Secondly, the cost of precipitation strengthened nickel alloy needed for 760°C is the same as solution strengthened alloy for 700°C. Finally, conventional PCC plant configuration can exploit temperatures of 760°C as suggested by Marion in 2012 *[32,38,39]* and by David Hassler Gorge Booras in EPRI U.S. DOE work [40,41].

III. Summary and Conclusion

India is going in big way for the Renewable Energy resources for the supply of power. At present the coal route has taken a back seat. In-spite of that Coal inevitably will be on the scene for the power generation. And for the it si natural choice that the best technologies are to be used. In today's time the best coal based technology for power generation is Advanced-Ultra Super Critical technology. Western countries have developed the technology which operates at 760°C and 46-50% efficient and has 41% less CO_2 Emission.
The developed countries are working on this since last 20 years, and A-USC development over the past 20 years has significantly advanced in the technology to the point where it is on the cusp of commercial deployment. The increased efficiency of the technology has two significant businesses "drivers". One is reduced cost and another is lesser GHG emissions.

As per EPRI studies when compared to USC, the cost of A-USC is approximately 10% higher in capital cost. For this study, the estimated capital cost was $2,933/kW, and the levelized cost of electricity (LCOE) was $84.70. Similarly it appears that when A-USC-740 is used in place of A-USC-617, the one-time capital cost may be higher, but 20-25 years' operating cost likely to be lower. A significant contributor to the higher cost has been the main and re-heat steam piping lines, which would be fabricated from Inconel 740 H. This impact on capital cost has led the power industry to respond with several innovative boiler concepts, as discussed in the EPRI report. Capital cost estimates on some of these concepts indicate that they may result in reductions that would bring the cost of an A-USC plant into parity with an equivalently sized USC plant. As these concepts are further developed, A-USC technology will likely become more cost competitive. The A-USC programs in countries such as China and India have announced plans to build plants within the next decade. As experience is gained with the technology, the risks and cost associated with a new technology will diminish.

i. The material Inconel 740H to perform at 760˚C, the Advanced-Ultra Super Critical Technology has been developed along with matching metallurgical skills such as forging, cutting welding, fabrication, scale up, coatings etc..
ii. In contrast, as per plan, India is working on the proposal since 2010 and developing materials capable to function at 710°C-720°C; and to develop the material and to deploy the material at 760˚C (A-USC) technology is still far away for India team that too with matching metallurgical skills as mentioned above. In to-days' time of competition of cutting edge technology, it is felt that if possible, it would be prudent to work ahead of "What has already been Developed" by western countries. Although India may not need 760˚C (A-USC) today, but it would prepare India very well to be self-reliant in such

technologies for the times to come. India is developing the technology of its own – it's excellent – but others have already invented the advanced technologies. So, if India continues with the present pace of development then such approach would slow down the India's progress on the path of self-reliance in developing of cutting edge technology. Obviously self-learning is the best though, but always it is time consuming. It is felt that the most effective route for faster progress is to go for the best, which is already present.

iii. The materials like Inconel 740H (A-USC-760°C) is the need of time. Since this material (Advanced-Ultra Supercritical material) is already invented, it would be prudent to concentrate more on developing 760˚C materials and associated technologies.

iv. It is felt that India need to plan with full care and guard so that India is not at a loss in aspects such as (i) cost, (ii) data sharing, (iii) technology sharing and *vis-à-vis* Proprietary terms, so that India do not lag behind in the "Make in India" Mission successful in the advanced power generation technology.

v. India would be able to build up the capacity to remain leader in such frontier technologies and may emerge as a technology provider in future, when self-sufficiency in A-USC-760°C is achieved.

vi. Today a power generation philosophy is tilting on full throttle for solar and it is excellent. But it is worthwhile to give **equal thrust** on **Solar and Coal** based Advanced-USC (760°C) technology. If possible, the required Agreements for such tasks need to be developed.

vii. Huge time and money may be saved by probably shifting from A-USC-710°C to A-USC-760°C and "Re-Research" could be is avoided. It is felt that by the time the plans are made and materials are ready for A-USC-710°C, and technology is matured in India and implemented on large scale, India would be running in the year 2030-2035 or likewise.

viii. Power generation would be more efficient, say at 46%-50% level. Power produced would be greener, as CO_2 emissions are reduced to 41% level. Power generation would be more efficient, say at 46%-50% level. Power produced would be greener, as CO_2 emissions are reduced to 41% level. There would be 3% more efficiency in A-USC-760°C technology as compared to A-USC-710°C technology.

ix. In todays' fast changing scene, A-USC (710°C-720°C**)** technology, like sub-critical technology is not going to stay for long time and most likely soon it would be to be taken over by A-USC-760°C technology. It is most likely that by year 2030 the A-USC-710°C might be out dated; the way today sub-critical technology has become out dated today.

x. As per the Press Information Bureau (PIB), Government of India referred earlier [3,4,5,6,7,8 and 9] at present India is restricting to A-USC-710°C-720°C technology level only. This may be because its O&M supplies are likely to be available from many of the European counter parts and such O&M supplies are not ensured right now for A-USC-760°C technology.

xi. It is also true that if Indian power sector goes for A-USC-760°C technology then, they would be using lesser materials and thus thinner tubes would be sufficient to build boiler and turbines and related components leading to large cost saving on O&M costs in long run. This increased efficiency is likely to result in reduced fuel consumption, lesser material resources consumption, decreased solid waste generation, water use and operating costs. This means a clear cut saving for putting up and running an A-USC power plant with lesser GHG emissions.

xii. In one of the possibilities, the huge Solar Power generation capacity planned in India may make Coal power plants less important. In such a situation, only most efficient (46-50%) and least polluting (41% less CO_2 emitting) power plants are likely to be preferred such as A-USC by the year 2030-35 or so. If situation is favorable, then Sub-critical and USC power plants may be withdrawn in such scenarios.

xiii. Baring few tests presumably done in India, India have to start the actual work *ab-initio* and which would last for about 10 years for covering the technology trials and full safety aspects. The PIB release saying that by the year 2022, an 800 MW unit of A-USC 710°C technology would be ready; appears to be unrealistic under the present mode of handling the works for the mandate given by the government. If examined carefully, this way, it would be the year 2030, by which the functional units of 800 MW size may come for manufacturing, erection and commissioning. If manufacturing is on the scale of 1-2, then it is alright, but if manufacturing is on commercial scale, then other issues come into play as BHEL or other companies may not have matching infrastructure for such large scale production.

xiv. It is felt that there is a need of utilizing the knowledge and technology already developed internationally, but this needs to be done with full care and guard so that India is not at a loss on different aspects such as (i) cost, (ii) data sharing, (iii) technology lead sharing and (iv) the Proprietary terms etc. This is expected to avoid duplicating of work which is already accomplished, and save in terms of years. However, parallel indigenous development may continue to progress. There is always need for getting better technology to keep with latest trends and swings in technology arena. This has shown again and again that Victory is for them who have the most modern technology.

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