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ENGINEERING-ECONOMIC EVALUATION OF SCR NO_X CONTROL SYSTEMS FOR COAL-FIRED POWER PLANTS

H. Christopher Frey, Ph.D.
Assistant Professor
Department of Civil Engineering
North Carolina State University
Raleigh, NC 27695-7908

INTRODUCTION

Selective catalytic reduction (SCR) is a process for the post-combustion removal of NO_X from the flue gas of fossil-fuel-fired power plants. SCR is capable of NO_X reduction efficiencies of up to 80 or 90 percent. SCR technology has been applied for treatment of flue gases from a variety of emission sources, including natural gas- and oil-fired gas turbines, process steam boilers in refineries, and coal-fired power plants.[1] SCR applications to coal-fired power plants have occurred in Japan and Germany.[2,3] Full-scale SCR systems have not been applied to coal-fired power plants in the U.S., although there have been small-scale demonstration projects. SCR has become increasingly widely applied in the U.S. to natural-gas fired gas turbine combined cycle systems.

Increasingly stringent environmental regulations for coal-fired power plants, coupled with the emergence of advanced coal-based technologies which offer the promise of low NO_X emissions, will lead to requirements for lower NO_X emissions. The top-down approach to determining best available control technology (BACT) is one motivating factor for more stringent emission permitting. Furthermore, implicit in Title IV of the 1990 Clean Air Act Amendment is a national NO_X emission reduction of 4 million pounds per year. This represents approximately a 25 percent reduction in total NO_X emissions, of which coal-based power generation contributes approximately one-third.

The Role of SCR

The combination of regulatory and technological factors discussed here may lead to U.S. SCR applications for conventional coal-fired power plants, as well as to coal gasification systems which do not remove fuel-bound nitrogen as part of coal gas cleanup. In the near-term, SCR is likely to be applicable to plants burning low sulfur coals whose coal characteristics are most nearly similar to that of coals used at plants with successful SCR experience in Germany and Japan.[4] Due to changing regulations, there may be a strong incentive to adapt SCR technology more generally to U.S. coal-fired power plants with varying coal sulfur contents. However, concern remains over the applicability of SCR technology to U.S. plants burning high sulfur coals or coals with significantly different fly ash characteristics than those burned in Germany and Japan. There is also concern regarding the application of SCR to peaking units due to potential startup and shutdown problems.[5]

SCR may serve as a near-term or bridging technology for use with advanced power generation systems such as integrated gasification combined cycle (IGCC), pressurized fluidized bed combustion (PFBC), and externally-fired combined cycle (EFCC). For these technologies, research is underway to develop combustion systems that minimize fuel-NO_X formation. However, if such technologies are not available in time for commercial deployment, SCR may be considered as backup. It is also possible that the stringency of future regulations may motivate the use of SCR, even if the development of advanced combustors is successful.

A Brief History of SCR

SCR was invented and patented in the U.S. in 1959. It was used originally in industrial applications. In the 1970's, SCR was first applied in Japan for control of NO_X emissions from power plants. Japan was the first country to make widespread use of this technology in response to national emission standards for NO_X. In Japan, SCR has been applied to gas, oil, and coal-fired power plants. There were over 200 commercial SCR systems operating on all types of sources in Japan in 1985. The Japanese SCR systems tend to run at moderate NO_X removal efficiencies of 40 to 60 percent.[6] By 1990, a total of 40 systems had been installed on 10,852 MW of coal-fired power plants.[5] Coal-based experience has occurred primarily in Japan and Germany. SCR applications to gas turbine-based systems are increasingly prevalent in the U.S.

SCR EXPERIENCE IN COAL-BASED APPLICATIONS

The Federal Republic of Germany currently imposes more stringent NO_X emission standards than Japan. To meet the emission requirements, SCR has been adopted and applied to many coal-fired power plants. SCR will be required as a retrofit technology on a total of 37,500 MW of existing capacity. As of 1989, SCR had been applied in 70 pilot plants and 28 full scale retrofit installations, with the latter totaling 7,470 MW of hard coal-fired capacity.[7] By 1990, more than 23,000 MW of capacity were fitted with SCR systems.[6] These plants typically burn low sulfur coals (0.8 to 1.5 percent sulfur) with 0.1 to 0.3 percent chlorine. SCR has been retrofitted to power plants with both wet and dry bottom boilers, with variations on the location of the SCR system. As of 1989, 18 installations involve "high dust" placement of the SCR system between the economizer and air preheater, while the remaining involve "low dust" or "tail-end"

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placement of the SCR downstream of the flue gas desulfurization (FGD) system. Two of the high-dust retrofits involve wet bottom boilers.[7] In 1991, 129 systems were reported to have been installed on a total of 30,625 MW of coal-fired capacity.[5]

The process environment for SCR in Germany is typically more demanding than that in Japan, with the requirement for higher NO_X removal efficiencies in the presence of higher flue gas sulfur and ash loadings.[6] In both Japan and Germany, the SCR systems are not operated during startup or shutdown.[5]

Recently, a number of U.S. projects for coal-fired applications of SCR technology have been initiated. These include, for example, a U.S. Department of Energy Clean Coal Program funded demonstration of SCR at Gulf Power Company's Plant Crist. SCR systems have also been permitted for two coal-fired cogeneration plants to be built in New Jersey.[8]

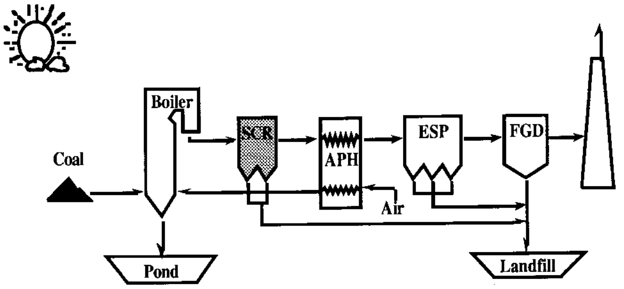
SCR Economics

Since the 1970's, the cost of SCR has dropped substantially. For example, the levelized cost of SCR dropped by a factor of 3 in Japan within a 6 year period, while in recent years costs in Germany have dropped by an additional factor of 2. These improvements are due in part to the international competition among catalyst suppliers. SCR catalysts are available from manufacturers in Japan, Germany, and the U.S. U.S. manufacturers, such as Grace, expect improvements in catalysts to continue, resulting in potential further drops in capital and operating costs. For example, Grace is testing a new catalyst design which is expected to lead to a 50 percent increase in catalyst activity while also increasing catalyst life.[6]

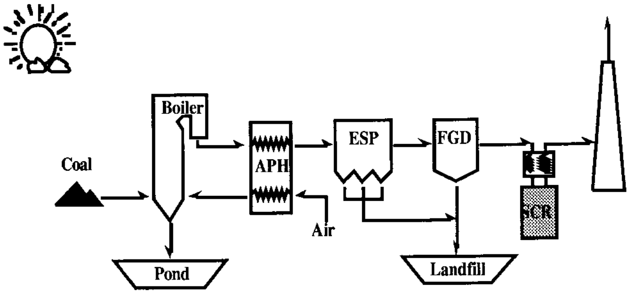
SCR Applicability to U.S. Coal Power Plants

SCR has not yet been used commercially on conventional coal-fired power plants in the U.S. The experience in Germany, which includes boiler types similar to those in the U.S., provides useful data for predicting SCR performance and cost in the U.S. However, U.S. coals, such as eastern bituminous coals, typically have a higher sulfur content than that of German coals. In addition, fly ash compositions may vary significantly. These differences lead to concerns about maintenance of catalyst activity and potential difficulties downstream of SCR reactors, such as deposition of ammonia salts.

The German experience is particularly useful for U.S. planners because German SCR systems are subject to a more relevant range of flue gas conditions than typical Japanese systems. For example, slagging wet bottom boilers produce different flue gas and flyash characteristics that can significantly affect catalyst performance.[9]



(a) Hot-side, high dust configuration



b) Tail-end configuration

Figure 1. Hot-Side and Tail-End SCR Systems.

SCR INTEGRATION INTO THE POWER PLANT

The SCR system can be located in several places in the coal-fired power plant flue gas stream.[2,7] A key limitation of SCR systems is the operating temperature requirement. The operating temperature window for SCR systems is typically from approximately 550 to 750 °F. Two possible locations are illustrated in Figure 1. These are:

a) "Hot-side" and "high-dust" SCR, with the reactor located between the economizer and the air preheater. In this configuration, shown in Figure 1(a), the SCR is located upstream of a cold-side electrostatic precipitator (ESP) and, hence, is subject to a high fly ash or "dust" loading. At full-load, the economizer outlet temperature is typically around 700 °F. An economizer bypass is required to supply hot gas to the SCR during part-load operating conditions, in order to maintain the proper reaction temperatures.[5]

b) "Cold-side" or "Tail-end" placement of the SCR system downstream of the air preheater, particulate collector, and FGD system. This system minimizes the effects that flue gas contaminants have on SCR catalyst design and operation, but requires a gas-gas heat exchanger and duct burners to bring the flue gas up to reaction temperature.[5]

The most common configurations envisioned for U.S. power plants are the hot-side high-dust and post-FGD tail-end systems, with high-dust systems predominating. These are the two most common configurations employed in German coal-fired power plants retrofitted with SCR.[4]

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SCR SYSTEM DESIGN

Ammonia is injected into the flue gas upstream of the SCR reactor vessel. The ammonia/flue gas mixture enters a reactor vessel, containing SCR catalyst. The catalyst promotes the reaction of ammonia and NO_x to form nitrogen and water vapor. Products of the SCR reactions may form ammonium sulfate or bisulfate, which can deposit on downstream equipment. In the case of a conventional coal-fired power plant, additional air preheater water washing is expected to be required to remove such deposits.

The SCR system consists primarily of a reactor housing containing catalyst material, an ammonia storage and handling system, an ammonia injection system, and a control system. In additional, air preheater wash water pretreatment may be required to remove ammonia from the wastewater.

SCR catalysts typically consist of a ceramic honeycomb substrate, a metal "carrier" and active components dispersed by the carrier on the honeycomb surfaces. A typical carrier is titanium dioxide (TiO_2). Vanadium pentoxide (V_2O_5) and tungsten trioxide (WO_3) are commonly used as active components for hot-side SCR applications.[7] WO_3 provides thermal and mechanical stability to the catalyst.[2] Catalysts based on titanium dioxide are best suited for operating temperatures of 280 to 400 ^oC (536 to 752 ^oF).[7] At lower temperatures, catalyst activity drops substantially. At higher temperatures, catalyst material phase transition occurs, which causes irreversible activity loss.[10] Catalysts using activated carbon may be employed for lower temperature applications near 100 ^oC (212 ^oF).[7] The actual catalyst formulations which are offered commercially are closely held propriety information.

A key innovation from Japanese development of SCR technology has been the switch from noble metal oxides to base metal oxides for use as catalyst carrier materials, which has reduced many of the major problems associated with oil- and gas-fired flue gas applications. For coal applications, Japanese catalyst development also focused on improving catalyst geometry. To avoid plugging and erosion, parallel flow honeycomb and plate catalysts were developed. By the early 1980's, ceramic honeycomb and plate configurations have been developed that provide high surface areas while reducing the tendency for flyash plugging. In recent years, research has focused on understanding the deactivation mechanisms of SCR catalyst, particularly due to alkalis and trace metals such as arsenic.[6]

V_2O_5 is the typical component which controls the reactivity of the catalyst for base metal catalyst formulations. However, it also catalyzes the conversion of SO_2 to SO_3, which may lead to opacity, ammonium salt deposition, or acid condensation problems downstream.[2,11] For high-sulfur coal applications, the amount of V_2O_5 is minimized by homogeneous distribution throughout the catalyst. To obtain NO_x reduction, properly mixed ammonia and NO_x must enter micropores in the catalyst, which are the active sites for the reactions which consume NO_x.

Other types of catalyst formulations include precious metals and zeolites. Precious metal catalysts are often based on platinum. They are effective at a slightly lower temperature range than base metal catalysts, ranging from 425 to 525 ^oF. Precious metal catalysts offer advantages of recyclability compared to base metal catalysts. However, precious metal catalysts have a high sulfur dioxide oxidation potential and, when operated above their temperature range, catalyze the formation of NO_x from ammonia. Base metal catalysts are effective over a wider temperature range, and thus may be somewhat less sensitive to temperature fluctuations than the precious metal catalysts.[11,12]

Zeolite catalysts are also known as molecular sieve catalysts. They operate at a much higher temperature than either precious metal or base metal catalysts. They are reported to operate at temperatures of approximately 950 ^oF. This temperature is a reasonable match to the exhaust gas temperature of some simple cycle gas turbines. For this reason, zeolite catalysts may be practical for use with gas turbines that do not have heat recovery systems. There are currently four gas turbines operating with zeolite catalysts.[11]

Base metal catalysts are the most widely used of the three major types described here. Therefore, most of the discussions of catalyst performance in this report will be based on base metal catalysts, unless otherwise indicated.

The catalyst is typically installed in a reactor housing in three layers, with provision for a dummy layer for flow straightening and distribution. In some designs, provision is also made for a fourth active catalyst layer. In these cases, the initial catalyst charge consists of three active layers. When catalyst activity drops to the design value, a fourth active layer is added. Then the four layers are changed out periodically to maintain overall catalyst activity. Catalyst modules may be loaded and unloaded from the reactor housing using a fork-lift track assembly and/or rollers.[2]

Ceramic, homogeneous, honeycombed catalyst elements approximately 6 inches square can be extruded to a length of about 39 inches.[2] SCR systems subject to high-dust loadings often include a dummy honeycomb or leading edge to control catalyst erosion.[5] Catalyst honeycomb design depends on the location of the SCR system in the power plant. For high-dust systems, catalysts with a large pitch (spacing within honeycomb cells) are employed, to allow passage of fly ash. For low dust systems, smaller pitch catalysts can be used.[7]

MODELING SCR SYSTEMS

Analytical performance and cost models of SCR systems have been developed by the author. These are documented elsewhere.[13] These include performance and cost models for high-dust, hot-side and tail-end, low-dust SCR systems. For the hot-side system, downstream effects on the power plant air preheater are modeled. For the tail-end system, a gas-gas heat exchanger and duct burner used for flue gas reheat are modeled.

Performance Model

The modeling approach adopted here is to assume a reference catalyst and to apply a series of multiplicative correction factors to adjust space velocity for different design conditions. The general formulation is:

$$SV = SV_{ref} \prod_{i=1}^{4} f_i \qquad (1)$$

Each correction factor, f_i, is a ratio that reflects the difference in space velocity from the reference to design conditions due to differences in certain design parameters. If the reference and design conditions are the same, these correction factors have a value of unity. A total of four correction factors have been developed, based on: (1) NO_x removal efficiency; (2) end-mole ratio; (3) catalyst activity; and (4) reaction temperature. These correction factors are detailed by Frey.[13]

The performance model includes: (1) SCR catalyst requirement; (2) SCR reactor housing cost; (3) ammonia injection cost; (4) SO2 oxidation rate; (5) downstream affects due to ammonia salt deposition; (6) pressure drops; and (7) other energy penalties.

Cost Model

Analytical models of direct, indirect, and total capital costs have been developed for SCR systems applied to both coal-fired power plants and gas turbine-based systems. The major components of these systems include: (1) reactor housing; (2) catalyst; and (3) ammonia storage and injection. Other components include: (1) ductwork; (2) air preheater modifications or gas-gas heat exchanger; (3) ID fan or booster fan; (4) structural supports; and (5) miscellaneous other direct costs.

The annual costs for SCR systems include fixed and variable operating costs. Fixed operating costs include operating labor, maintenance labor and materials, and overhead costs associated with administrative and support labor. Variable operating costs include consumables, such as ammonia and catalyst replacement. Costs for steam and electricity consumed from within the plant may also be estimated.

MODELING APPLICATIONS: HOT-SIDE VS. TAIL-END SYSTEMS

Here, we choose to focus on evaluation and comparison of "hot-side" and "tail-end" SCR systems for a conventional coal-fired power plant. In the "hot-side" configuration, a base metal SCR catalyst is located between the power plant economizer and air preheater and is therefore subject to high fly ash and SO_2 concentrations. In the "tail-end" configuration, the SCR system is located downstream of the air preheater and flue gas desulfurization system. Therefore, the fly ash and sulfur concentrations are substantially reduced. However, flue gas reheat is necessary to meet the temperature requirements of conventional base metal catalysts. Some advantages of the tail end system are that catalyst volume requirements may be lower and catalyst life higher than for the high-dust system. Downstream impacts related to SO_2 oxidation, acid condensation, ammonia slip, and formation of ammonia salts differ for the two configurations.

Engineering-economic models of the SCR systems have been developed and implemented as part of the Integrated Environmental Control Model (IECM), which includes performance, emissions, and cost models for major components of fossil-fuel-fired power plants. The IECM can be configured to represent a variety of power plant configurations. A unique feature of the IECM is a capability to quantitatively deal with uncertainty in technology assessments. The performance and cost models of SCR systems are applied to a number of detailed case studies to: (1) evaluate the performance and cost of high-dust and tail-end systems; (2) enable comparisons of these two systems; and (3) identify the key sources of uncertainty affecting total costs.

Uncertainty Analysis

A unique feature of this work is a probabilistic approach to dealing with uncertainties. Uncertainties in key performance and cost parameters of the SCR systems were characterized using probability distributions. These distributions were based on data obtained from literature reviews or discussions with process engineers. The uncertainties represent both technological and economic risks. For example, the change in catalyst activity with time is not well known for U.S. coal-fired power plant applications. Therefore, model parameters representing the decay in catalyst activity were assigned probability distributions. Another important uncertainty is that regarding the cost of new catalyst. This too was assigned a probability distribution.

The uncertainties are propagated through the performance and cost model using a variant of Monte Carlo simulation. The modeling results allow the consequences of the simultaneous uncertainties to be displayed and evaluated. This enables decision makers to understand the risks of high costs as well as the pay-offs of low costs, particularly compared to alternative technologies.

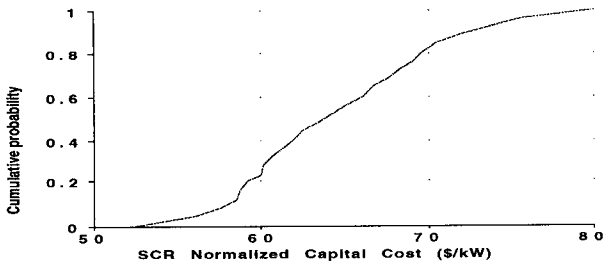

Figure 2. Hot-Side SCR Capital Cost.

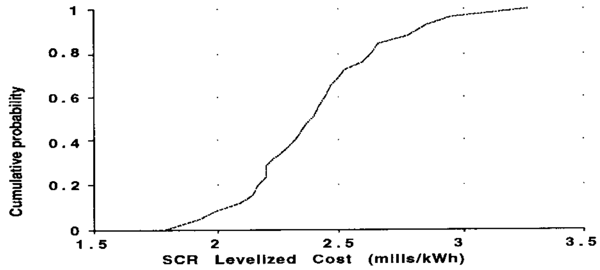

Figure 3. Hot-Side SCR Levelized Cost.

Model Results: Hot-Side System

The hot-side SCR system has been evaluated for a nominal 480 MW_{net} power plant burning a 4.4 percent Illinois No. 6 coal with a heat rate of 10,060 BTU/kWh. The plant is assumed to operate with a capacity factor of 75 percent. Based on a point-estimate (deterministic) analysis, the nominal SCR catalyst space velocity is estimated to be 2,100 hr^{-1}. The NO_x removal efficiency is 80 percent, and the inlet NO_x concentration is 470 ppm_v. The total catalyst charge is approximately 26,000 ft^3, and the annual replacement volume is approximately 5,700 ft^3. The equivalent catalyst life is thus 4.5 years. The nominal total capital cost is $60/kW, and the annual revenue requirement is 2.1 mills/kWh. All costs are in 1993 dollars.

Results for probabilistic modeling of the capital cost of a hot-side SCR system is shown in Figure 2. The probability that the capital cost will be $60/kW or lower is approximately 30 percent. Thus, there is a 70 percent probability of cost overrun, due to uncertainties affecting catalyst requirements and catalyst cost. The uncertainty in SCR capital cost spans a range of approximately $25/kW.

The uncertainty in the levelized cost is shown in Figure 3. There is only about a 10 percent probability that levelized costs will be below the nominal estimate from the deterministic analysis. Hence, uncertainties in catalyst price and catalyst replacement requirements that were not addressed by the deterministic analysis are shown to significantly influence levelized costs. There is a 30 percent probability that costs could exceed 2.5 mills/kW, or that they would be 20 percent higher than the budgetary estimate from the deterministic analysis.

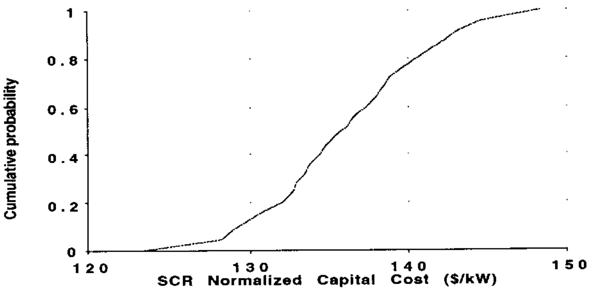

Figure 4. Tail-End SCR Levelized Cost.

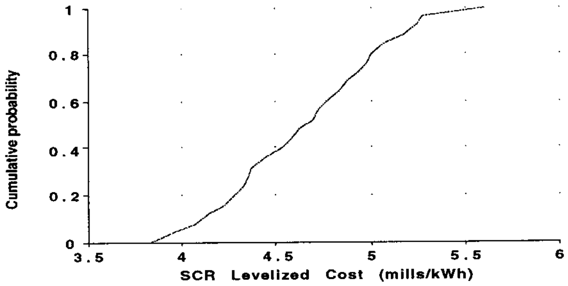

Figure 5. Tail-End SCR Levelized Cost.

Model Results: Tail-End System

The tail-end SCR system has been evaluated for the same basic power plant design as for the hot-side system. Based on a point-estimate (deterministic) analysis, the nominal SCR catalyst space velocity is estimated to be 5,900 hr^{-1}. The NO_x removal efficiency is 79 percent, and the inlet NO_x concentration is 375 ppm_v. The total catalyst charge is approximately 11,200 ft^3, and the annual replacement volume is approximately 1,200 ft^3. The equivalent catalyst life is thus nine years. Thus, in contrast to the hot-side system, less catalyst is required and it has a significantly longer life. In this regard, the technical risks of the process appear to be lower. The nominal total capital cost is $130/kW, and the annual revenue requirement is 4.5 mills/kWh. Thus, in return for lower technical risk, the costs of the tail-end system appear to be approximately twice that of the hot-side system.

Results for probabilistic modeling of the capital cost of a tail-end SCR system is shown in Figure 4. The probability that the capital cost will be $130/kW or lower is approximately 15 percent. Thus, there is an 85 percent probability of cost overrun, due to uncertainties affecting catalyst requirements and catalyst cost. The uncertainty in SCR capital cost spans a range of less than $25/kW.

The uncertainty in the levelized cost is shown in Figure 5. There is a 40 percent probability that levelized costs will be below the nominal estimate from the deterministic analysis. There is little risk that the levelized cost will exceed the nominal estimate by more than 20 percent. Thus, although the costs of the tail-end system are higher than for the hot-side system, the *risks* associated with cost growth and performance shortfall appear to be less.

FUTURE WORK

In future work, the case studies developed here will be further investigated, with focus on more detailed characterization of input assumptions and modeling results. Comparisons to other types of systems, such as advanced combined SO_2/NO_x controls, will be made. Coal-fired power plants with high efficiency SO_2 and NO_x control will also be compared to other advanced coal-based power generation concepts, such as coal gasification systems.

CONCLUSIONS

SCR systems based upon the "hot-side" configuration offer the promise of lower cost than tail-end systems. Tail-end systems offer advantages in terms of less technological risk as reflected in lower catalyst volume requirements and higher catalyst "life" than for hot-side systems. However, this analysis indicates that such advantages are not sufficiently reflected in the process economics to justify the use of tail-end systems for the application evaluated here. Of course, any conclusions are strictly limited to the assumptions made regarding key model inputs, such as catalyst price and catalyst activity curves. The power of a detailed process engineering model, however, is that alternative assumptions can be evaluated in a systematic manner. This is especially true for probabilistic analyses, which enable both the range and likelihood of alternative outcomes to be considered in the context of a single case study.

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