

# ***EXERGEN***

---

C O R P O R A T I O N

---

## **Specializing in Thermal Management via IR Sensing**

**Increasing Production Speeds via IR -Controlled Heat Balance**



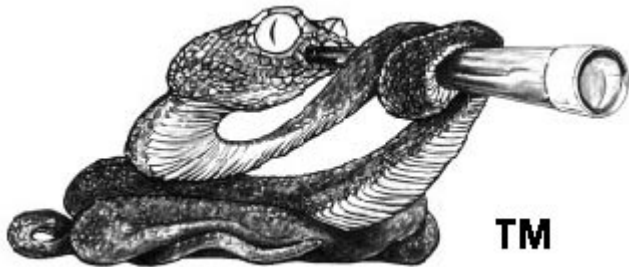
***EXERGEN***  
CORPORATION

# ***EXERGEN***

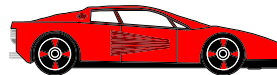
C O R P O R A T I O N

**Industrial  
Division**

***EXERGENIR***  
***Sensors***



Increasing Production Speeds via IR -Controlled Heat Balance



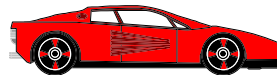
***EXERGEN***  
CORPORATION

# *Increasing Production Speeds via Heat Balance Control With IR Sensing*

**From  
Fundamentals  
to Frontiers**

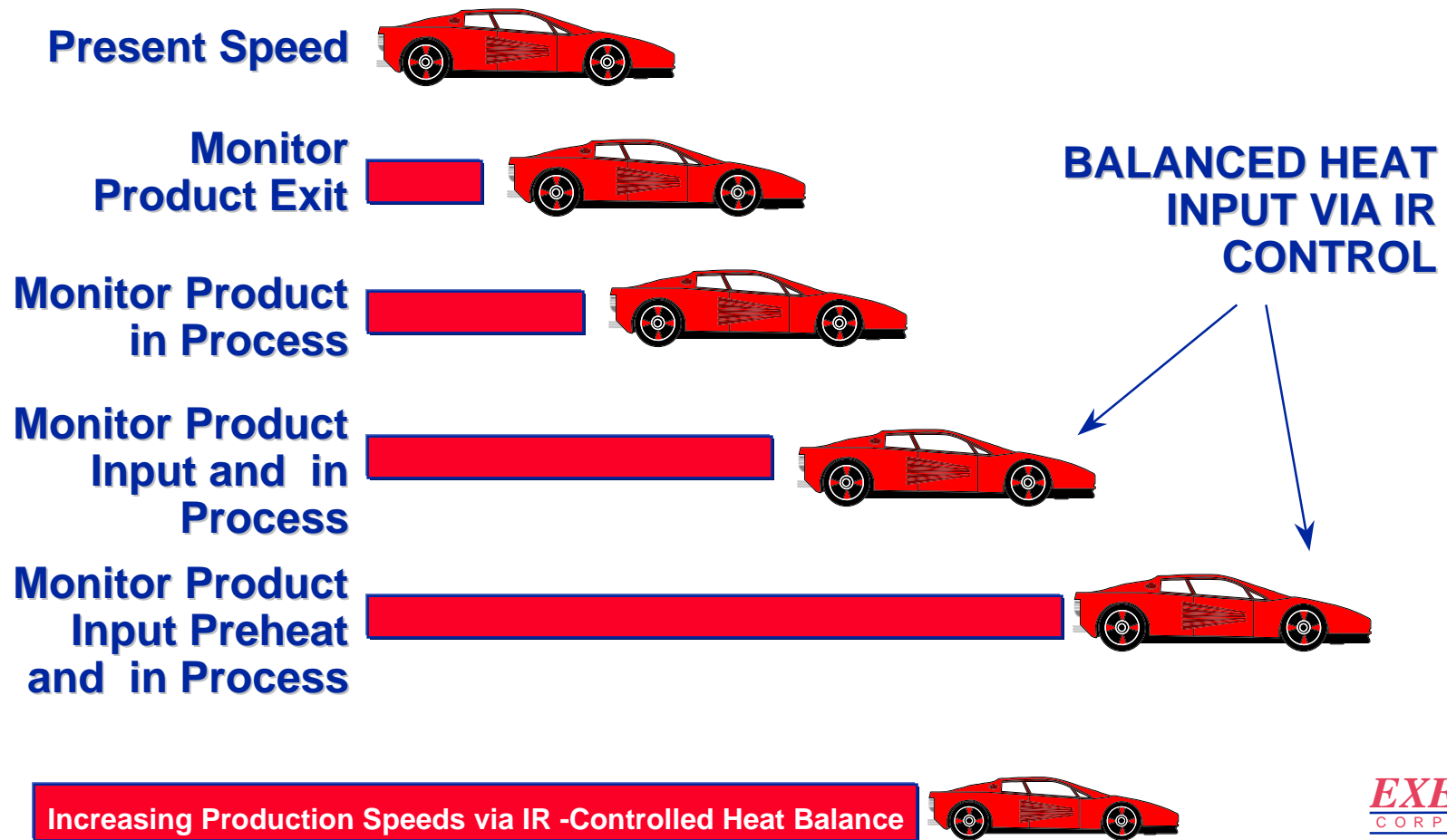


Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

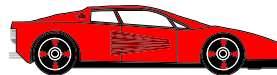
# Speed Increase Stages



# ***Fundamentals***

- **Infrared Physics and Math (Briefly)**
- **Emissivity High and Low**
- **Principles of the IRt/c in Non-Contact Temperature Measurement**
- **Heat Transfer Physics and Math (Briefly)**

**Increasing Production Speeds via IR -Controlled Heat Balance**

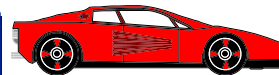


***EXERGEN***  
CORPORATION

# *Frontiers*

- **Principles of the Heat Balance in Time and Space**
- **The Speed Boost Equation**
- **Balanced Heat Input via IR Control**
- **Applications**
  - Laminating, Drying, Printing, Heat Sealing, Color Copying
- **High Speed Event Detection**

Increasing Production Speeds via IR -Controlled Heat Balance

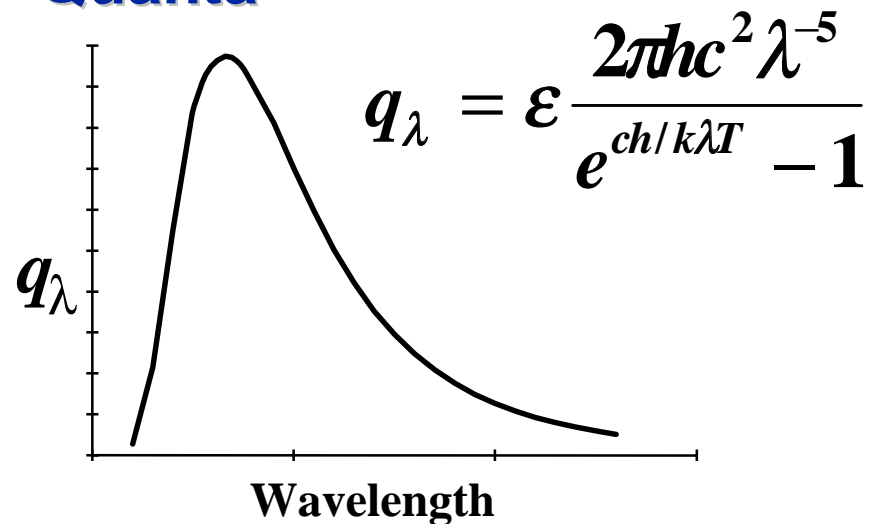


**EXERGEN**  
CORPORATION

# Max Planck ~ 1900



- Desperation Move to Explain Black Body Radiation
- Mathematical Equation for Thermal Radiation Using Quanta



Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

# *Albert Einstein ~ 1905*



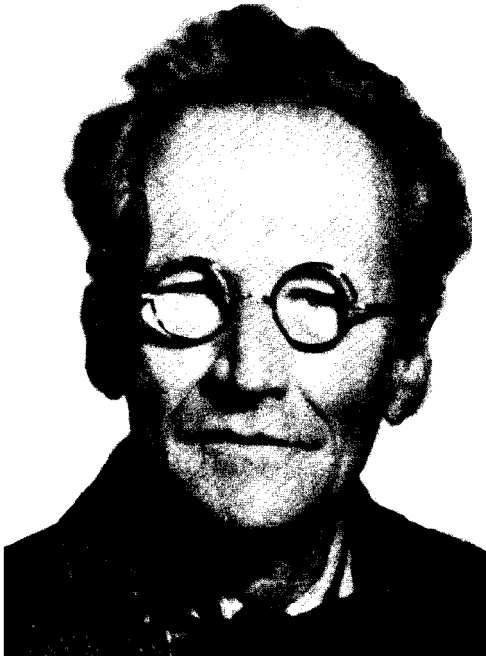
- **Confirmed Planck's Quanta by Explanation of **Photoelectric Effect****
- **But Never Really Liked the Eventual Result**

Increasing Production Speeds via IR -Controlled Heat Balance

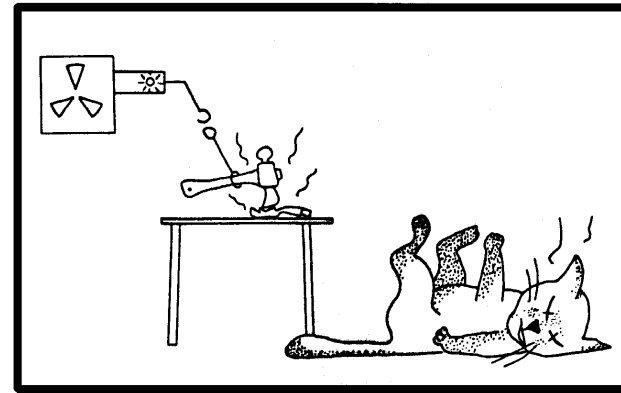
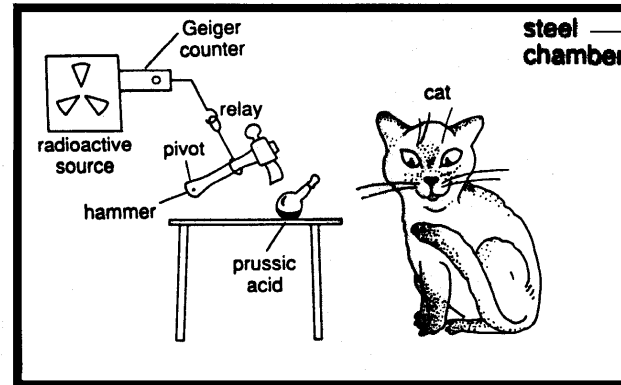


**EXERGEN**  
CORPORATION

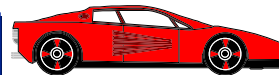
# Erwin Schrodinger ~ 1935



- The Cat Paradox



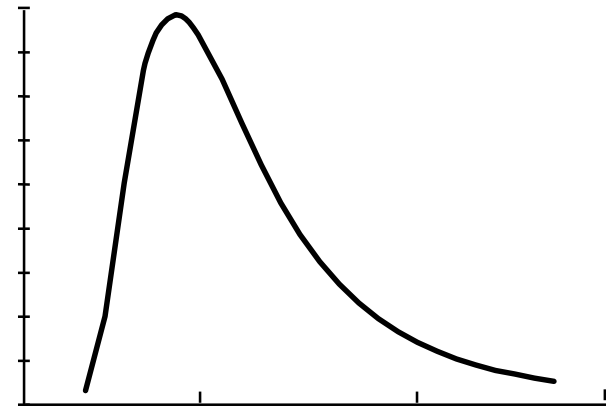
Increasing Production Speeds via IR -Controlled Heat Balance



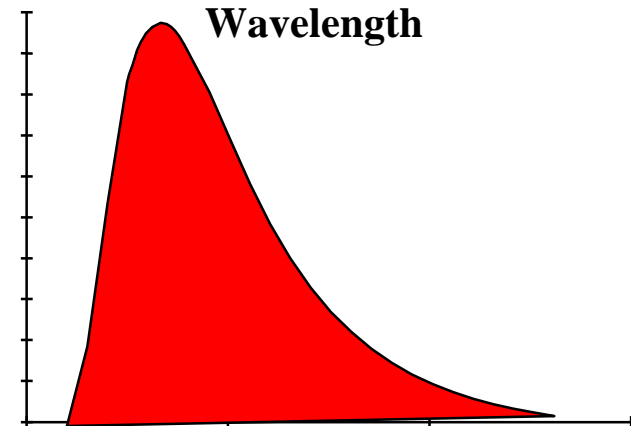
**EXERGEN**  
CORPORATION

# Basic Infrared Equations

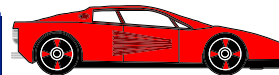
$$q_{\lambda} = \frac{2\pi hc^2 \lambda^{-5}}{e^{ch/k\lambda T} - 1} \quad \longrightarrow \quad q_{\lambda}$$



$$q = \int_0^{\infty} q_{\lambda} d\lambda \quad \longrightarrow \quad q_{\lambda}$$
$$= \sigma T^4$$



Increasing Production Speeds via IR -Controlled Heat Balance



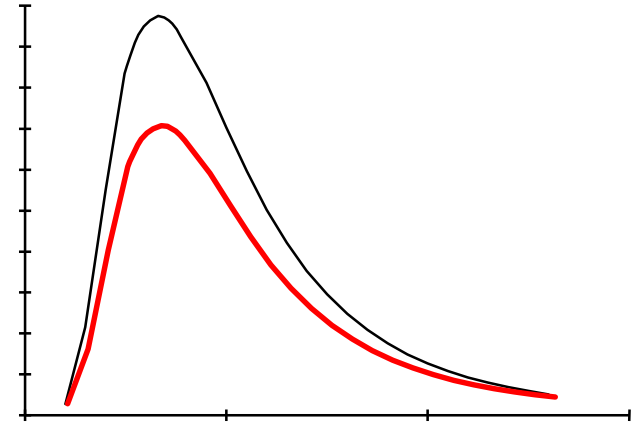
**EXERGEN**  
CORPORATION

# Emissivity

$$q_{\lambda} = \epsilon \frac{2\pi hc^2 \lambda^{-5}}{e^{ch/k\lambda T} - 1}$$



$q_{\lambda}$

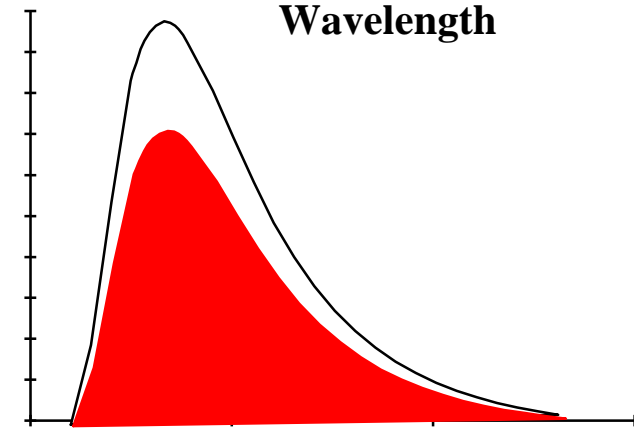


Wavelength

$$q = \int_0^{\infty} q_{\lambda} d\lambda$$
$$= \epsilon \sigma T^4$$

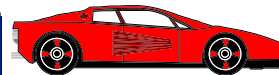


$q_{\lambda}$



Wavelength

Increasing Production Speeds via IR -Controlled Heat Balance



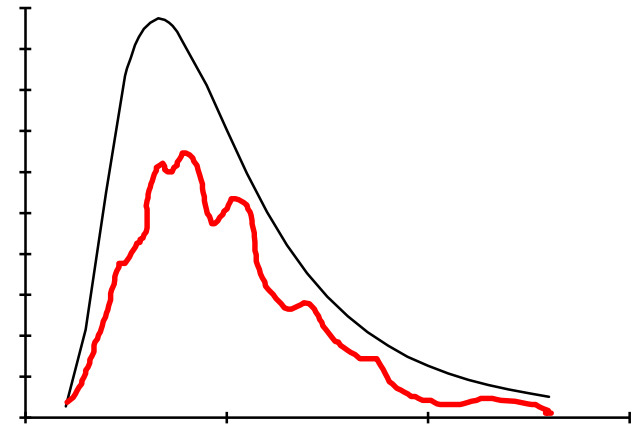
**EXERGEN**  
CORPORATION

# Wavelength Dependent Emissivity

$$q_{\lambda} = \epsilon_{\lambda} \frac{2\pi hc^2 \lambda^{-5}}{e^{ch/k\lambda T} - 1}$$



$q_{\lambda}$

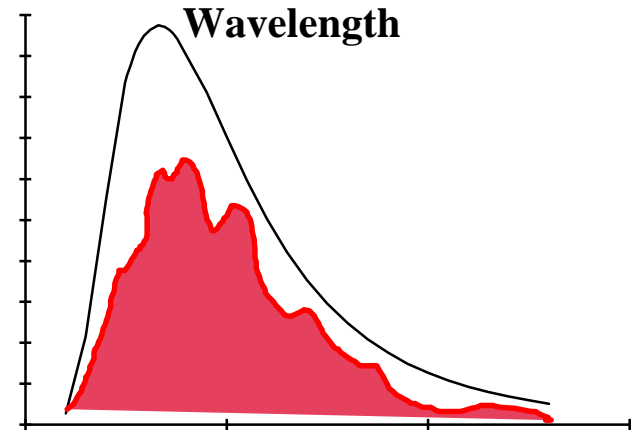


$$q = \int_0^{\infty} q_{\lambda} d\lambda$$

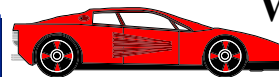
$$\neq \epsilon \sigma T^4$$



$q_{\lambda}$



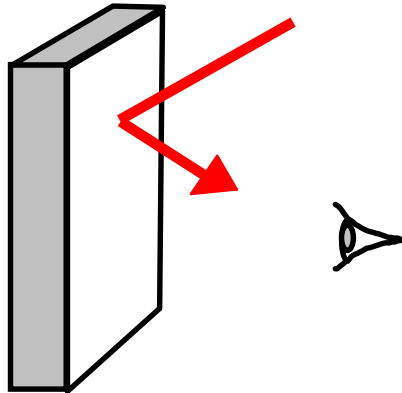
Increasing Production Speeds via IR -Controlled Heat Balance



Wavelength

**EXERGEN**  
CORPORATION

# Low Emissivity Surfaces

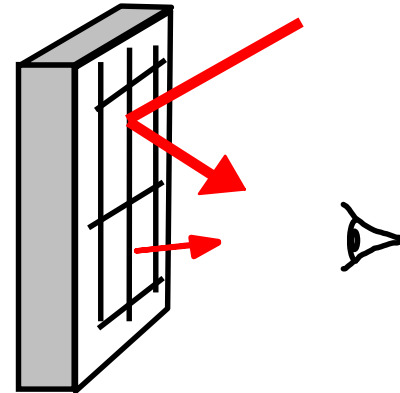


**Perfect Mirror**

Emissivity = 0.0

Reflectivity =  $\frac{1.0}{1.0}$

1.0



**Poor Emitter**

Emissivity = 0.1

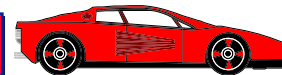
Reflectivity =  $\frac{0.9}{1.0}$

1.0

**Theoretical**

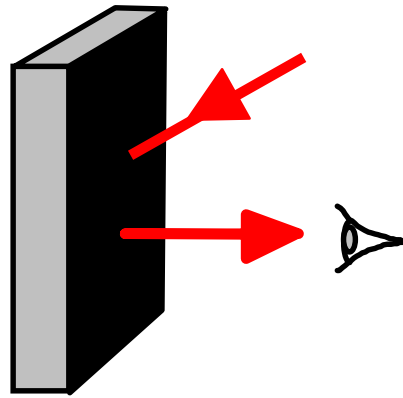
**Real: Uncoated  
Metals**

Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

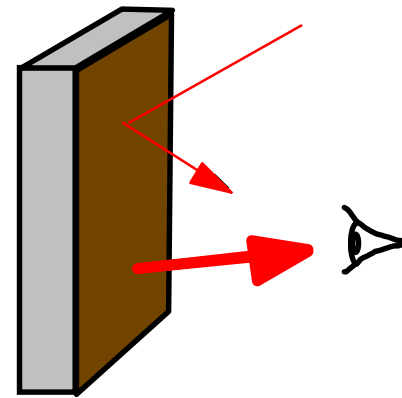
# High Emissivity Surfaces



**Perfect Blackbody**

Emissivity = 1.0  
Reflectivity = 0.0  
1.0

**Theoretical**

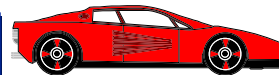


**Good Emitter**

Emissivity = 0.9  
Reflectivity = 0.1  
1.0

**Real:  
Non-Metals**

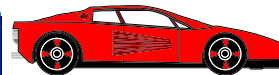
Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

# *Measuring High Emissivity Surfaces*

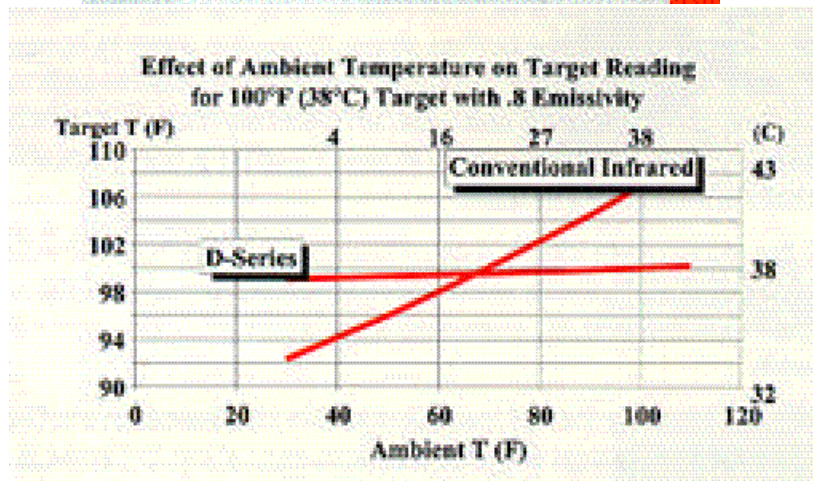
- **Use Sensors Designed For High Emissivity**
- **Calibrate Sensors to Actual Material in Production Process for High Accuracy**
- **Use D-Series to Determine Accurate Temperature for Calibration**



# *D-Series: Measure True Temperature for Calibration*

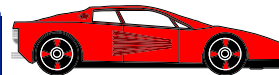


*D501 and D501-RS*



- Reflective cup provides true emissivity-free, and reflection-free temperature measurement
- Primary standard for calibration of IR sensor installations

Increasing Production Speeds via IR -Controlled Heat Balance



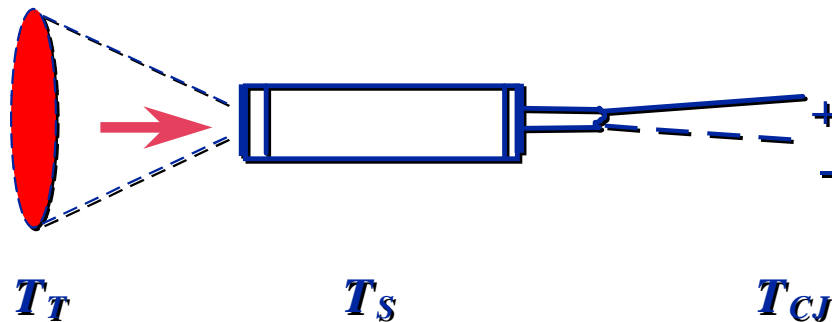
**EXERGEN**  
CORPORATION

# ***Measuring Low Emissivity Surfaces***

- **Coat the Surface, Then Use High Emissivity**  
**If Not, Then**
- **Use Sensors Designed For Low Emissivity**
- **Calibrate Sensors to Actual Material in Production Process for High Accuracy**
- **Use D-Series to Determine Accurate Temperature for Calibration**
- **Use Cavities if Available on the Part**

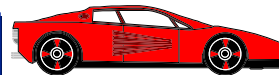


# Principles of the IRt/c

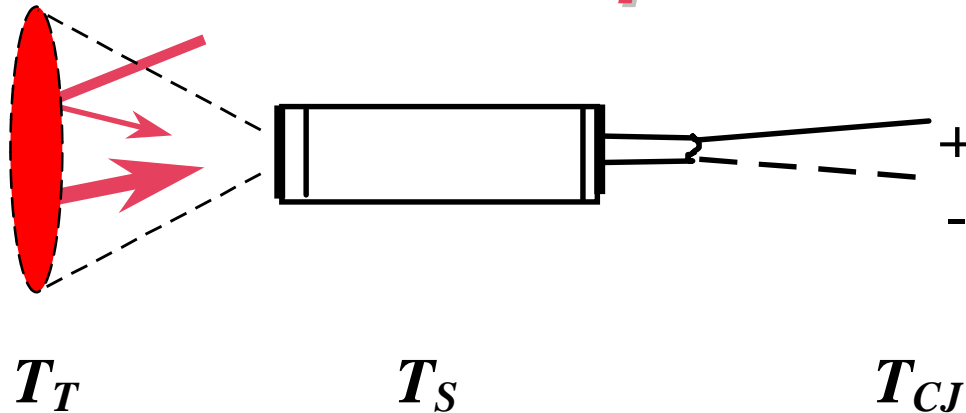


$$\begin{aligned} mV_{out} &= c ( T_T - T_S ) + \alpha ( T_S - T_{CJ} ) \\ &= \alpha ( T_T - T_{CJ} ) \text{ when } c = \alpha \\ \alpha &= \text{Seebeck coefficient} \end{aligned}$$

- No Power Required
- T/C Compatible
- 0.0001°C Resolution
- 0.01°C Repeatability
- Intrinsically Safe
- Simple, Rugged, Inexpensive



# Principles of the IRt/c



- Calibrated to Real World Surfaces to Reduce Errors Caused by Emissivity < 1
- Optimum Temperature Range Selection for Highest Possible Accuracy in Real World Applications

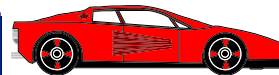
$$mV_{out} = c(\epsilon T_T + (1-\epsilon)T_S - T_S) + \alpha(T_S - T_{CJ})$$

$$= \alpha(T_T - T_{CJ}) \text{ when } (c \epsilon) = \alpha$$

$\alpha = \text{Seebeck coefficient}$

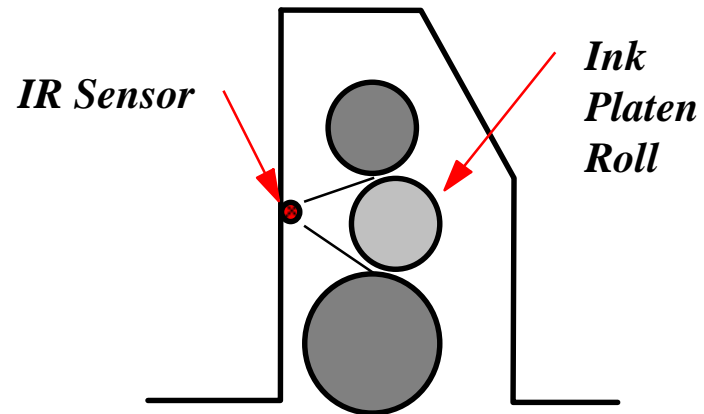
Compensates for the Ambient Reflections on Real Surfaces

Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

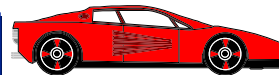
# Example of Improved Accuracy: Printing



*IR Temperature Control Accuracy:*

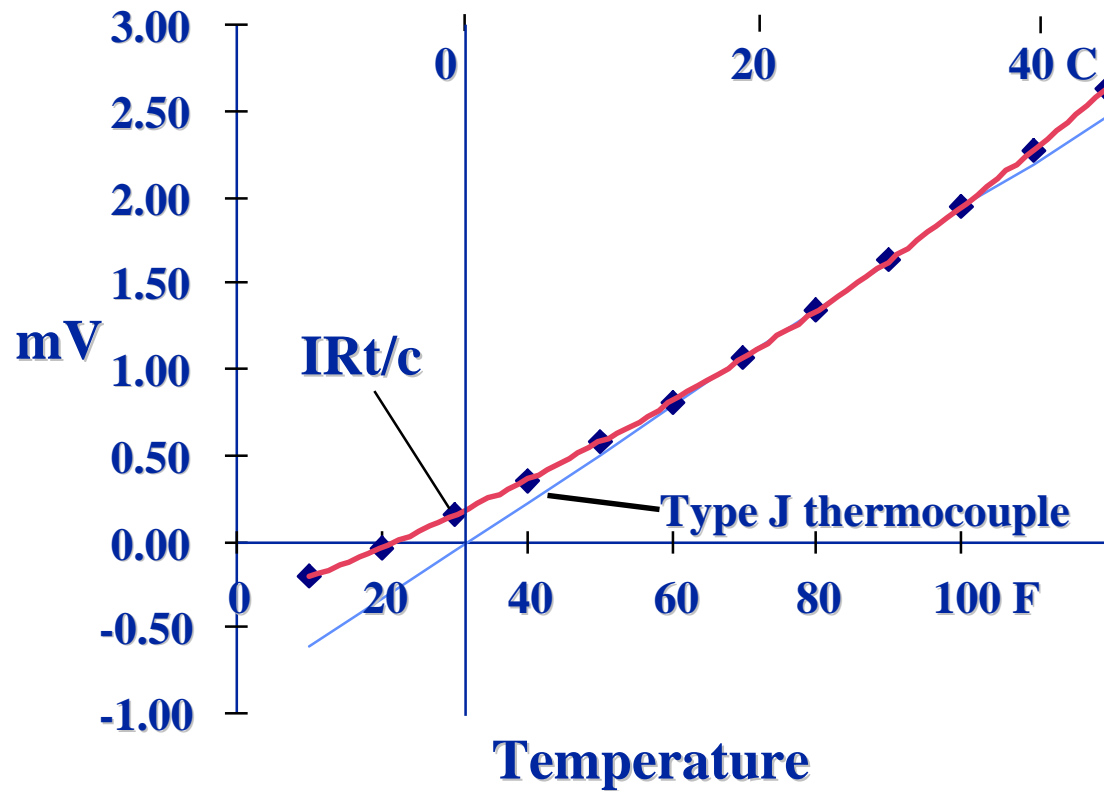
<i>Conventional IR</i>	<i>3°F (1.7°C)</i>
<i>IRt/c</i>	<i>0.2°F (0.1°C)</i>

Increasing Production Speeds via IR -Controlled Heat Balance

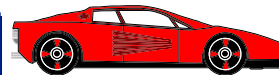


**EXERGEN**  
CORPORATION

# *IRt/c Signal Output*



Increasing Production Speeds via IR -Controlled Heat Balance

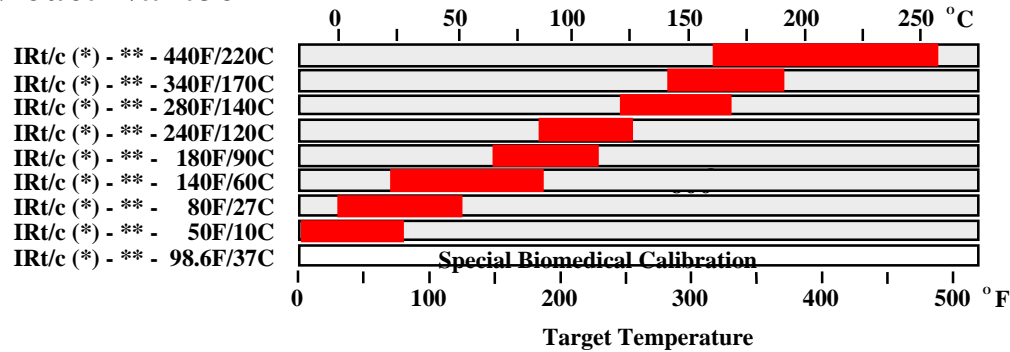


**EXERGEN**  
CORPORATION

# Optimum Temperature Range Selection for Highest Possible Accuracy in Real World Applications

Select  
Model Number

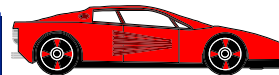
Optimum Sensor Chart



Optimum Range

320 - 500F (160 - 260C)  
 280 - 370F (140 - 190C)  
 240 - 330F (115 - 165C)  
 180 - 250F (80 - 120C)  
 140 - 220F (60 - 105C)  
 70 - 190F (20 - 90C)  
 32 - 120F (0 - 50C)  
 0 - 85F (-18 - 30C)  
 Human Body Range

Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

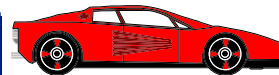
# Signal Output Polynomials For User Programming

## Master Polynomial Table for IRt/c Signal Output

$$(TT - CJT) = A*(mV)^6 + B*(mV)^5 + C*(mV)^4 + D*(mV)^3 + E*(mV)^2 + F*(mV) + G$$

	A	B	C	D	E	F	G
IRt/c.xxx - J - 50F/10C	-6.14473E-09	2.08199E-06	-2.72953E-04	1.75317E-02	-5.84883E-01	1.53005E+01	0
IRt/c.xxx - J - 80F/27C	-2.83996E-08	7.41635E-06	-7.54046E-04	3.79224E-02	-1.00406E+00	2.06592E+010	
IRt/c.xxx - J - 140F/60C	-4.31591E-08	1.06077E-05	-1.01002E-03	4.72155E-02	-1.14872E+00	2.20397E+010	
IRt/c.xxx - J - 180F/90C	-7.03138E-08	1.59317E-05	-1.39844E-03	6.02655E-02	-1.35167E+00	2.39075E+010	
IRt/c.xxx - J - 240F/120C	-1.05707E-07	2.23776E-05	-1.83521E-03	7.38926E-02	-1.54843E+00	2.55885E+010	
IRt/c.xxx - J - 280F/140C	-1.89514E-07	3.63996E-05	-2.70839E-03	9.89395E-02	-1.88106E+00	2.82034E+010	
IRt/c.xxx - J - 340F/170C	-2.99852E-07	5.33519E-05	-3.67751E-03	1.24452E-01	-2.19192E+00	3.04447E+010	
IRt/c.xxx - J - 440F/220C	-5.20472E-07	8.44263E-05	-5.30444E-03	1.63572E-01	-2.62438E+00	3.31770E+010	

Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

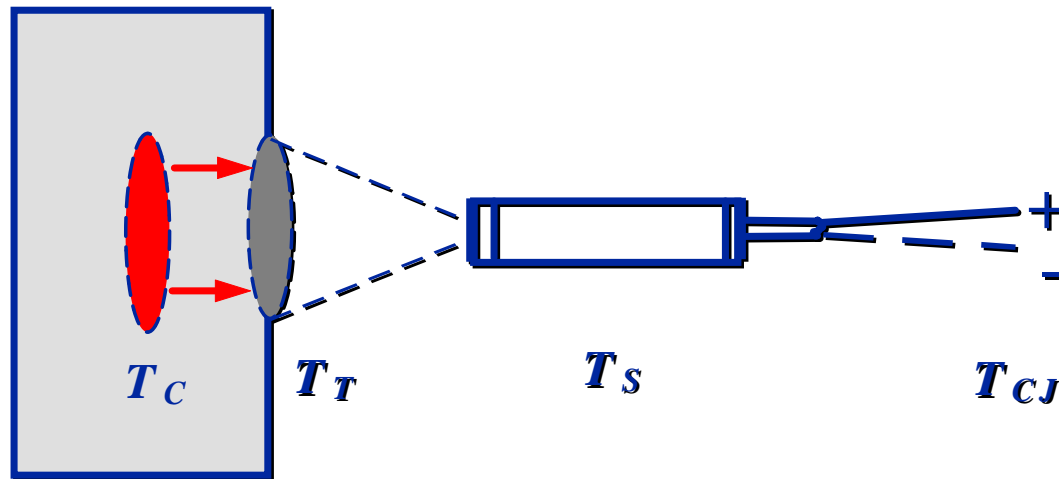
***Thermal Energy  
Balance in Space  
and Time:  
The Space Domain***

Increasing Production Speeds via IR -Controlled Heat Balance



***EXERGEN***  
CORPORATION

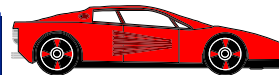
# Principles of the IRt/c: With Heat Balance



- Automatically Computes Heat Balance, Using Material Properties Alone
- Can be Configured for Unpowered or Powered Configurations

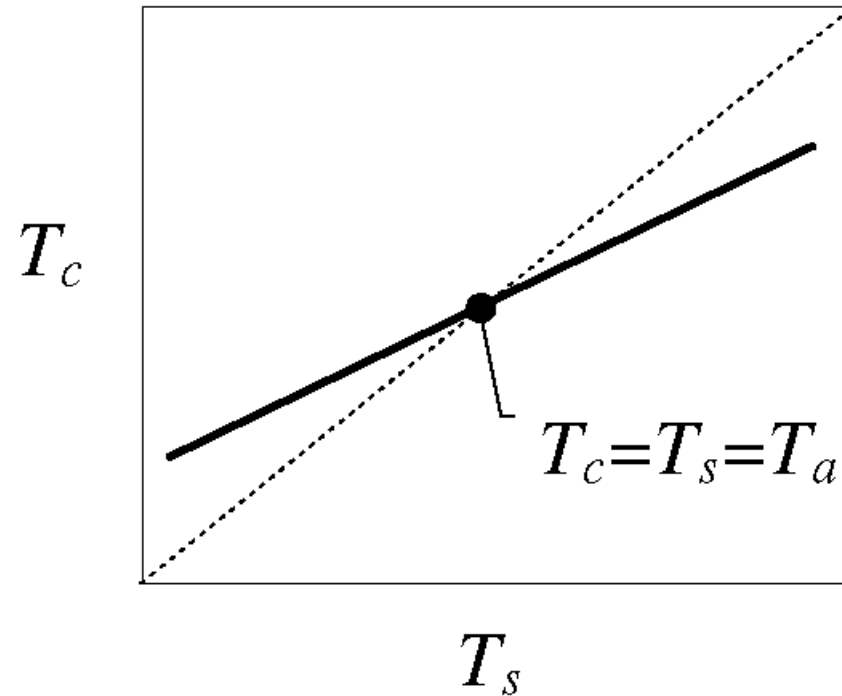
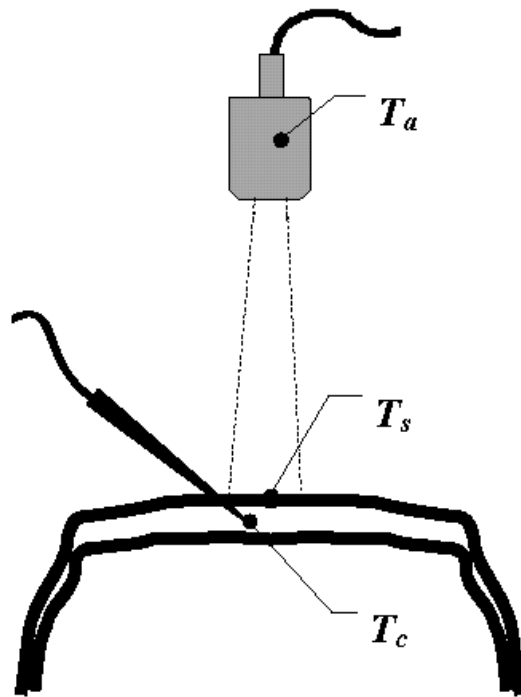
$$\begin{aligned} mV_{out} &= c((T_C - T_S)(1/k) + T_S - T_S) + \alpha(T_S - T_{CJ}) \\ &= \alpha(T_C - T_{CJ}) \quad \text{when } c = (\alpha k) \\ \alpha &= \text{Seebeck coefficient} \end{aligned}$$

Increasing Production Speeds via IR -Controlled Heat Balance

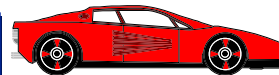


**EXERGEN**  
CORPORATION

# Heat Balance Example: Internal Tire Temperatures

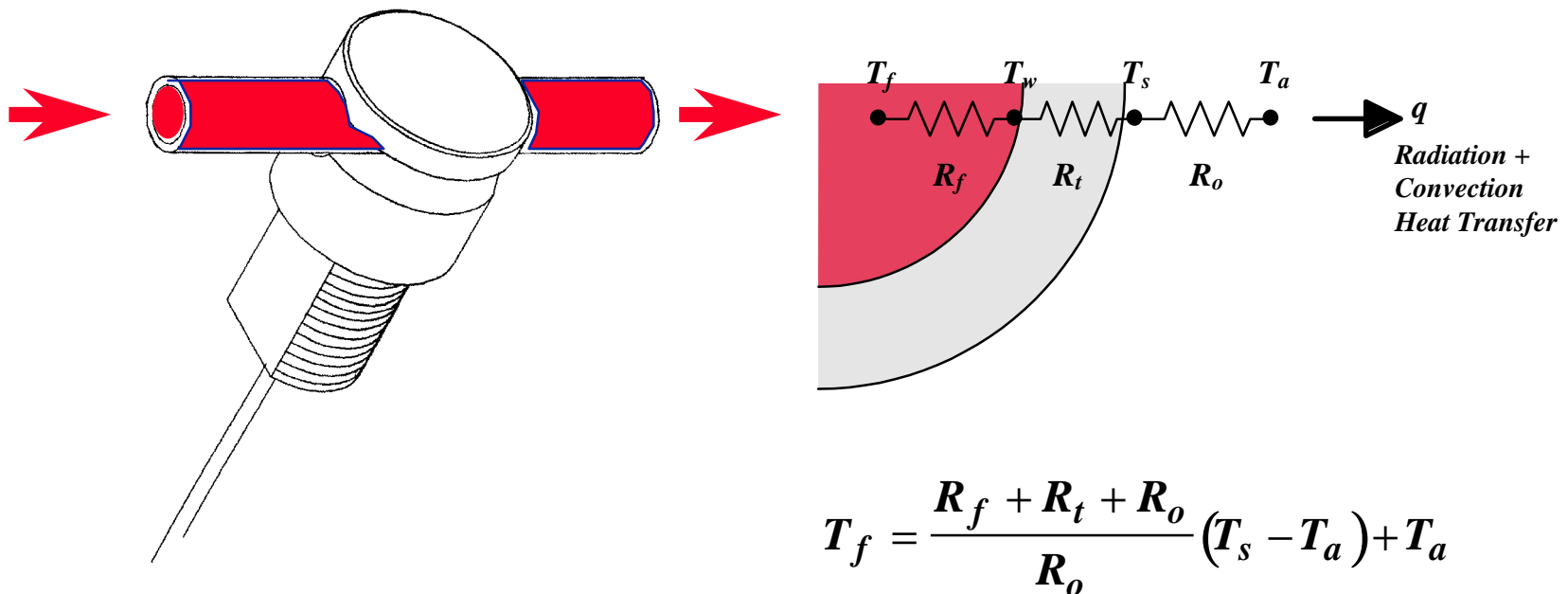


Increasing Production Speeds via IR -Controlled Heat Balance



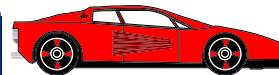
**EXERGEN**  
CORPORATION

# Non-Invasive Fluid Temperature in Tubing via IRt/c Heat Balance



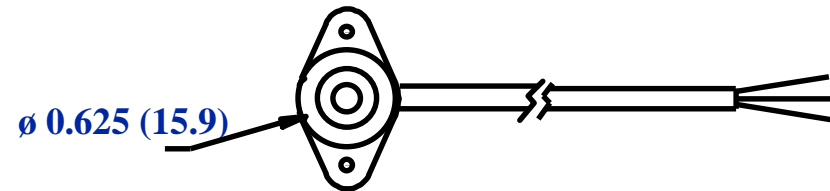
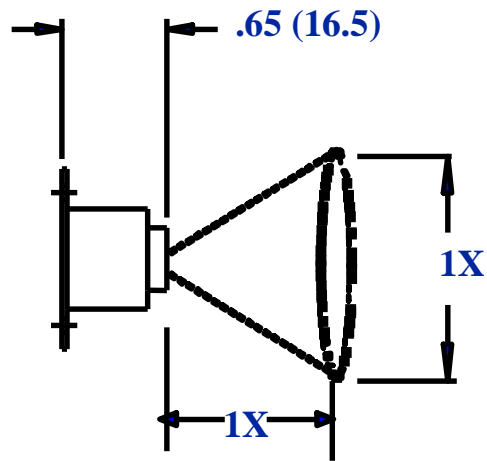
$$T_f = \frac{R_f + R_t + R_o}{R_o} (T_s - T_a) + T_a$$

Increasing Production Speeds via IR -Controlled Heat Balance

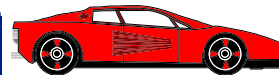


**EXERGEN**  
CORPORATION

# *Ultra-Miniature Infrared Thermocouple With Heat Balance*



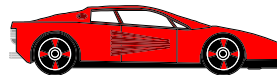
Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

***Thermal Energy  
Balance in Space  
and Time:  
The Time Domain***

Increasing Production Speeds via IR -Controlled Heat Balance



***EXERGEN***  
CORPORATION

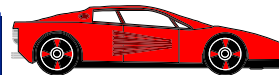
# ***Jean Baptiste Joseph Fourier*** ***1768-1830***

- **Fourier's Equation of Heat Conduction**

$$\left(\frac{q}{A}\right)_x = -k \frac{\partial T}{\partial x}$$

- **Unsteady State Heat Conduction for Moving Materials**

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\kappa} \frac{\partial T}{\partial t}$$



# ***Pierre Simon Marquis de LaPlace***

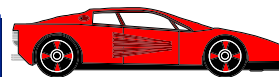
***1749 -1827***

- **Laplace Transform Method of Solution**

$$\bar{T}(x, s) = \int_0^{\infty} e^{-st} T(x, t) dt$$

- **Converts Partial Differential Equation to Ordinary Differential Equation**

$$\frac{d^2 \bar{T}}{dx^2} - \frac{s}{\kappa} \bar{T} = \frac{T_o}{\kappa}$$

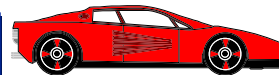


# *Francesco Pompei*

1948 -

- **New Method of Solution Leads to a General Equation for Non-Contact Temperature Monitoring of Internal Temperatures of Moving Materials**

$$T_c = \frac{h\sqrt{\tau K}}{k} \sinh\left(\frac{a}{\sqrt{\tau K}}\right) (T_s - T_\infty) + T_s + \left[ \cosh\left(\frac{a}{\sqrt{\tau K}}\right) - 1 \right] (T_s - T_0)$$



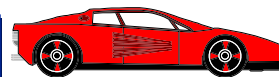
- Which simplifies to

$$T_c = K_1(T_s - T_\infty) + T_s + K_2(T_s - T_o)$$

where

$$K_1 = \frac{1}{a} \sqrt{\tau\kappa} \frac{ha}{k} \sinh\left(a \sqrt{\frac{1}{\tau\kappa}}\right), \quad K_2 = (\cosh\left(a \sqrt{\frac{1}{\tau\kappa}}\right) - 1)$$

$$\frac{1}{a} \sqrt{\tau\kappa} = (Fo)^{1/2}, \quad \text{and} \quad \frac{ha}{k} = Bi$$



# ***Deriving The Speed Boost Equation***

$$T_c = K_1(T_s - T_\infty) + T_s + K_2(T_s - T_o)$$

- **Set the surface temperature equal to the center temperature, then the equation reduces to**

$$T_c = T_s$$
$$\frac{(T_\infty - T_s)}{(T_s - T_o)} = \frac{K_2}{K_1}$$

- **Since  $K_2/K_1$  is a function only of material properties and speed:**

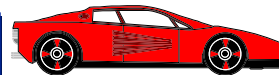


The ratio can be formed, which then becomes:

## *The Speed Boost Equation*

$$\frac{V_{new}}{V_{old}} = \frac{(\overline{\Delta T})_{new}}{(\overline{\Delta T})_{old}}, \quad \text{where } \overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

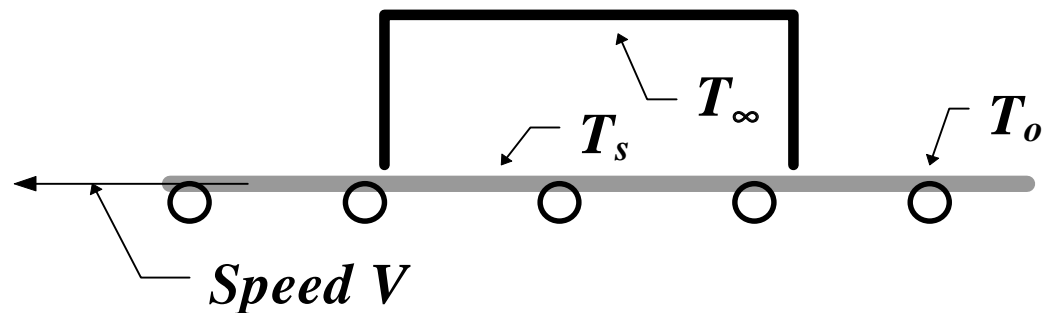
- **General Equation for Non-Contact IR Temperature Monitoring of Internal Temperatures of Moving Materials is Combined with Surface Temperature**
- **Leads to Uniform Material Temperature When Controlled via the *Speed Boost Equation***
- **Which Forces the Control System to Apply Heat at an Optimally *Balanced* Rate**



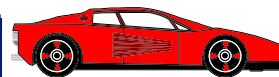
# Applying The Speed Boost Equation

$$\frac{V_{new}}{V_{old}} = \frac{(\overline{\Delta T})_{new}}{(\overline{\Delta T})_{old}}, \quad \text{where } \overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

Thermal Input (oven,  
dryer, rolls, etc.)



Increasing Production Speeds via IR -Controlled Heat Balance

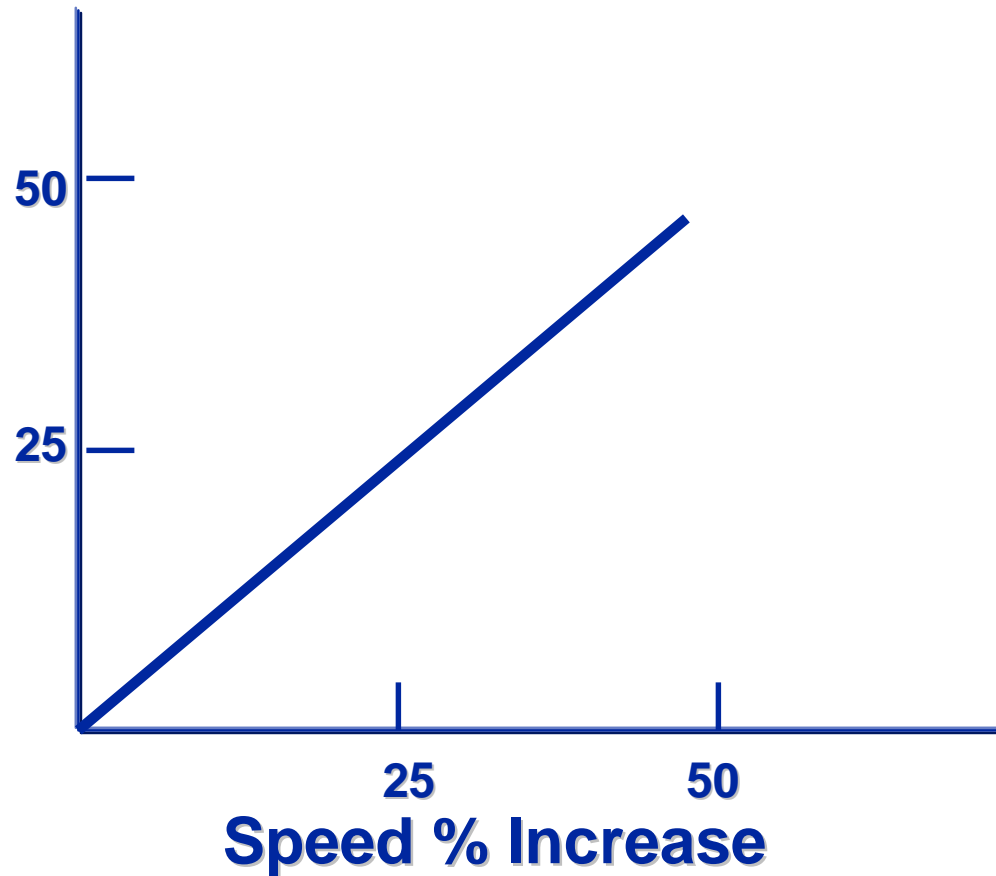


**EXERGEN**  
CORPORATION

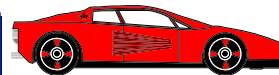
# *Speed Boost Equation is Generally Linear for Most Applications*

$$\overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

**% Increase**



**Increasing Production Speeds via IR -Controlled Heat Balance**

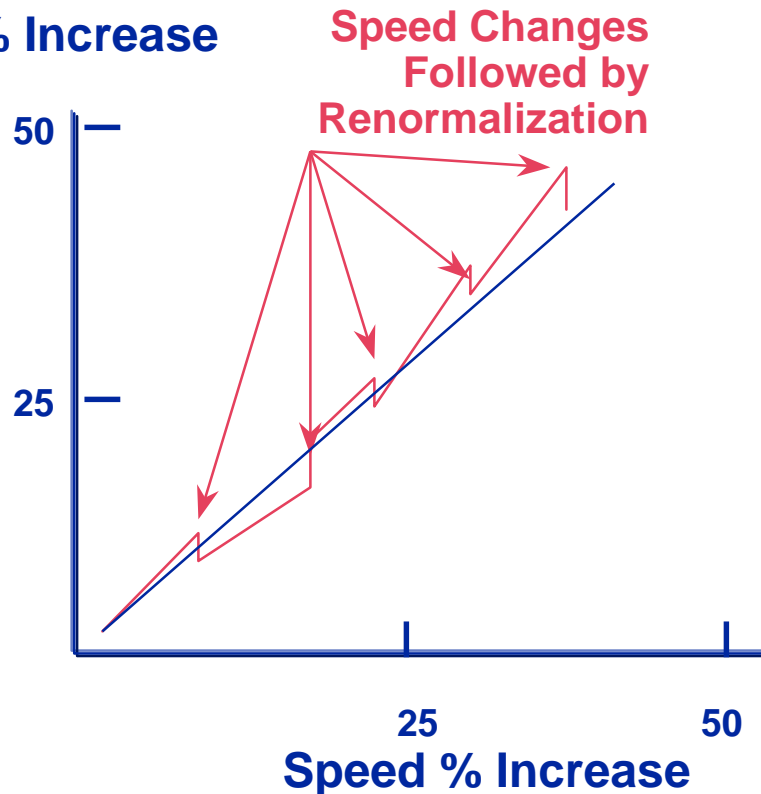


**EXERGEN**  
CORPORATION

# Implementing Speed Boost to Include Non-Linearities

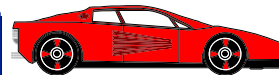
$$\overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

% Increase



- Apply step-wise speed increases in accordance with speed boost equation, and renormalize at new operating condition to account for property changes.
- For variable speed systems, program to follow the characteristic curve.

Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

## Example Speed Boost: Laminating

- Existing Set-up:

$$T_{\infty} = 105 \text{ C}$$

$$T_s = 85 \text{ C}$$

$$T_o = 25 \text{ C}$$

- New Set-up:

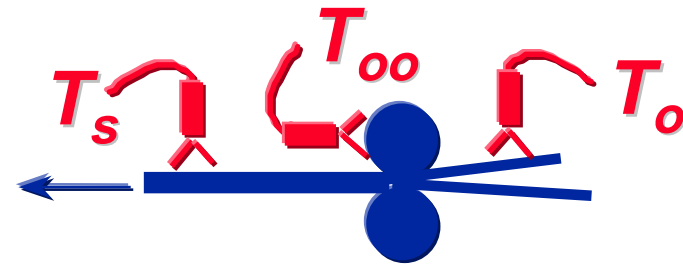
$$T_{\infty} = 120 \text{ C}$$

$$T_s = 85 \text{ C}$$

$$T_o = 25 \text{ C}$$

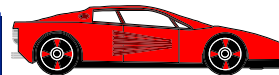
- Potential Speed Increase\*:

⇒ 25%



$$\overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

\*Assuming all other factors are permitting



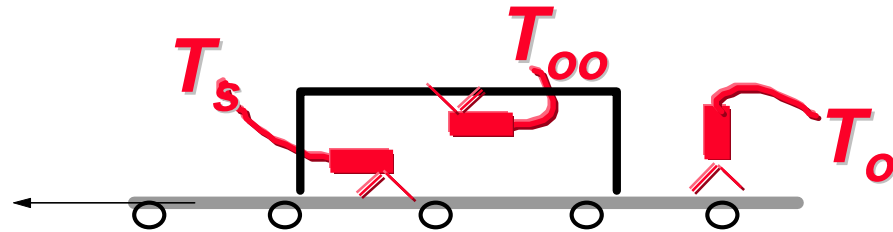
## Example Speed Boost: Drying

- Existing Set-up:

$$T_{\infty} = 260 \text{ C}$$

$$T_s = 85 \text{ C}$$

$$T_o = 25 \text{ C}$$



- New Set-up:

$$T_{\infty} = 260 \text{ C}$$

$$T_s = 85 \text{ C}$$

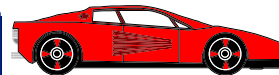
$$T_o = 40 \text{ C (with preheat)}$$

$$\overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

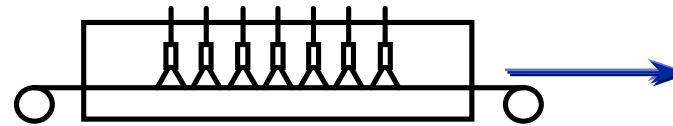
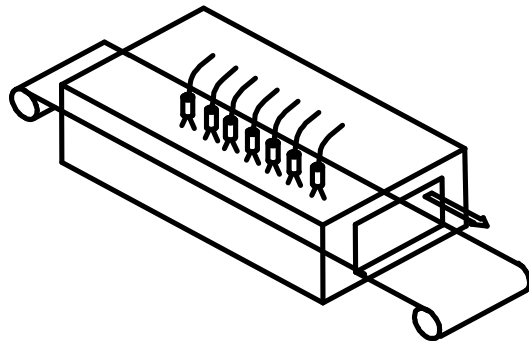
- Potential Speed Increase\*:

⇒ 33%

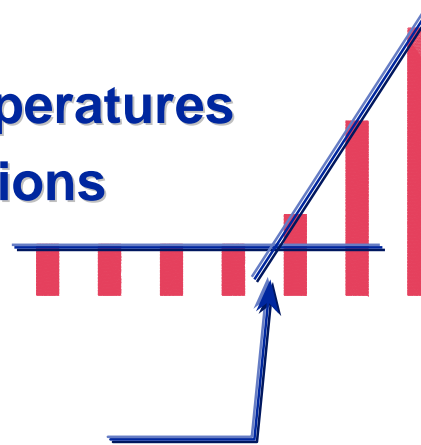
\*Assuming all other factors are permitting



# *Precision Drying Control for Maximum Production Speed*

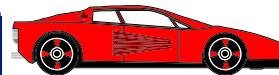


**Relative Temperatures  
at IRt/c Locations**



**Dry-Out Point (Phase Change)**

**Increasing Production Speeds via IR -Controlled Heat Balance**



**EXERGEN**  
CORPORATION

# Example Speed Boost: Heat Sealing

- Existing Set-up:

$$T_{\infty} = 150 \text{ C}$$

$$T_s = 120 \text{ C}$$

$$T_o = 25 \text{ C}$$

- New Set-up:

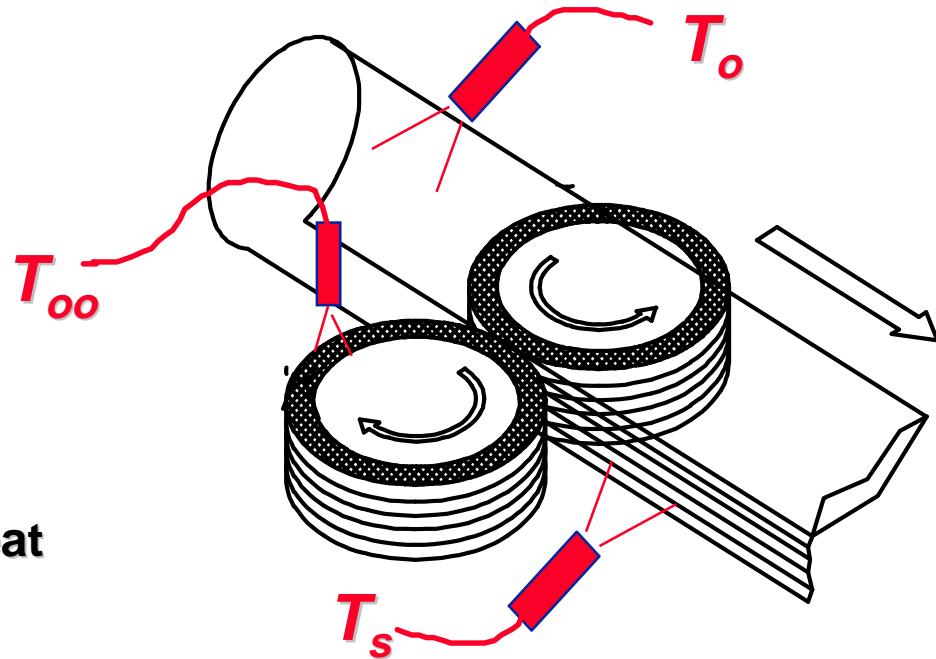
$$T_{\infty} = 150 \text{ C}$$

$$T_s = 120 \text{ C}$$

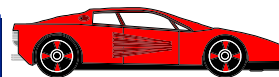
$$T_o = 45 \text{ C (with preheat added)}$$

- Potential Speed Increase:

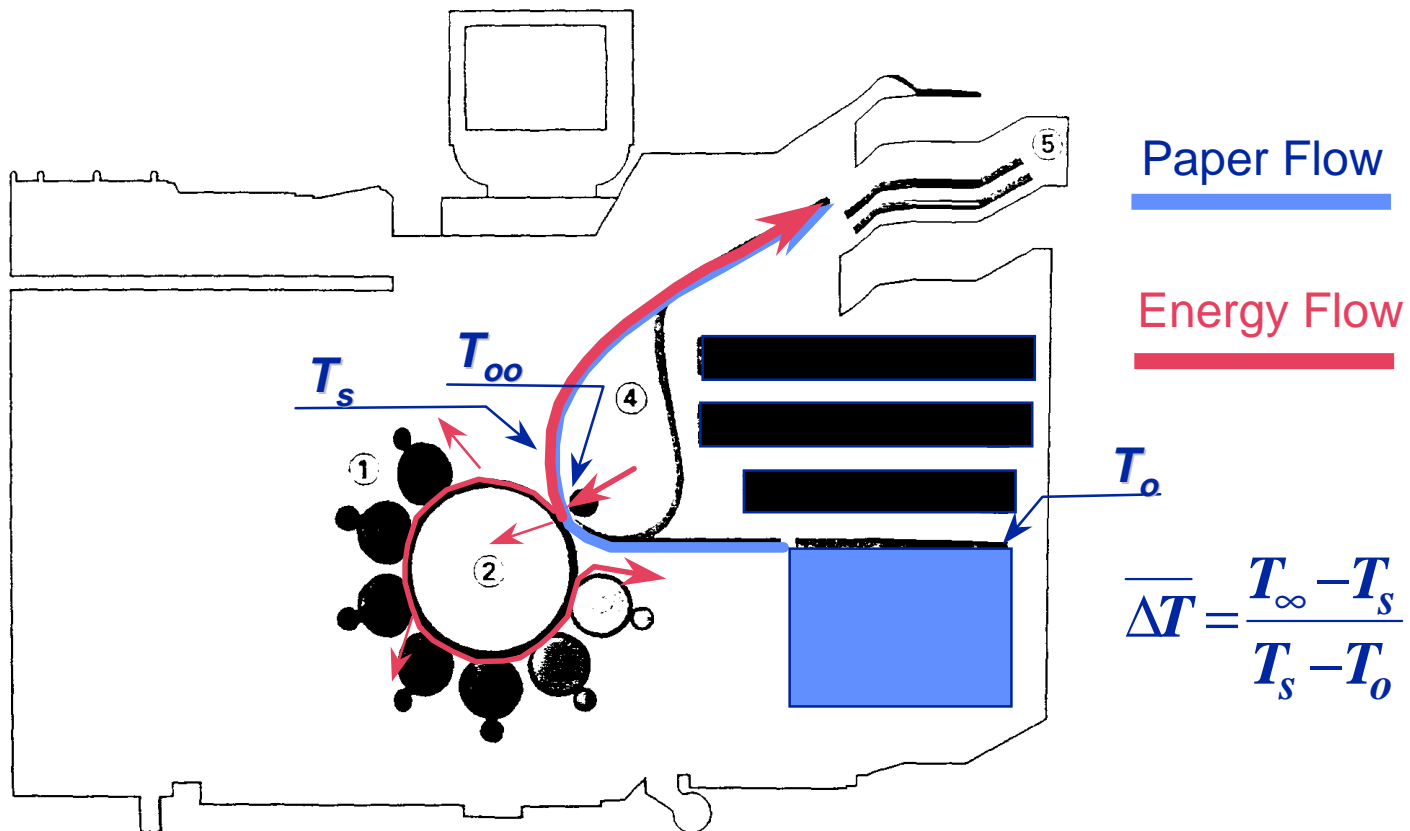
$$\Rightarrow 27\%$$



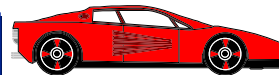
$$\overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$



# Example: High Speed Color Copy Process



Increasing Production Speeds via IR -Controlled Heat Balance



**EXERGEN**  
CORPORATION

# Speed Boost Equation

$$\frac{V_{new}}{V_{old}} = \frac{(\overline{\Delta T})_{new}}{(\overline{\Delta T})_{old}}, \quad \text{where } \overline{\Delta T} = \frac{T_{\infty} - T_s}{T_s - T_o}$$

- Above Can Be a Simplified Control Algorithm

$$T_{\infty} = (\overline{\Delta T} + 1)(T_s) - (\overline{\Delta T})(T_o)$$

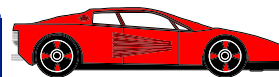
Heat Source Temperature

Control Loop Gain

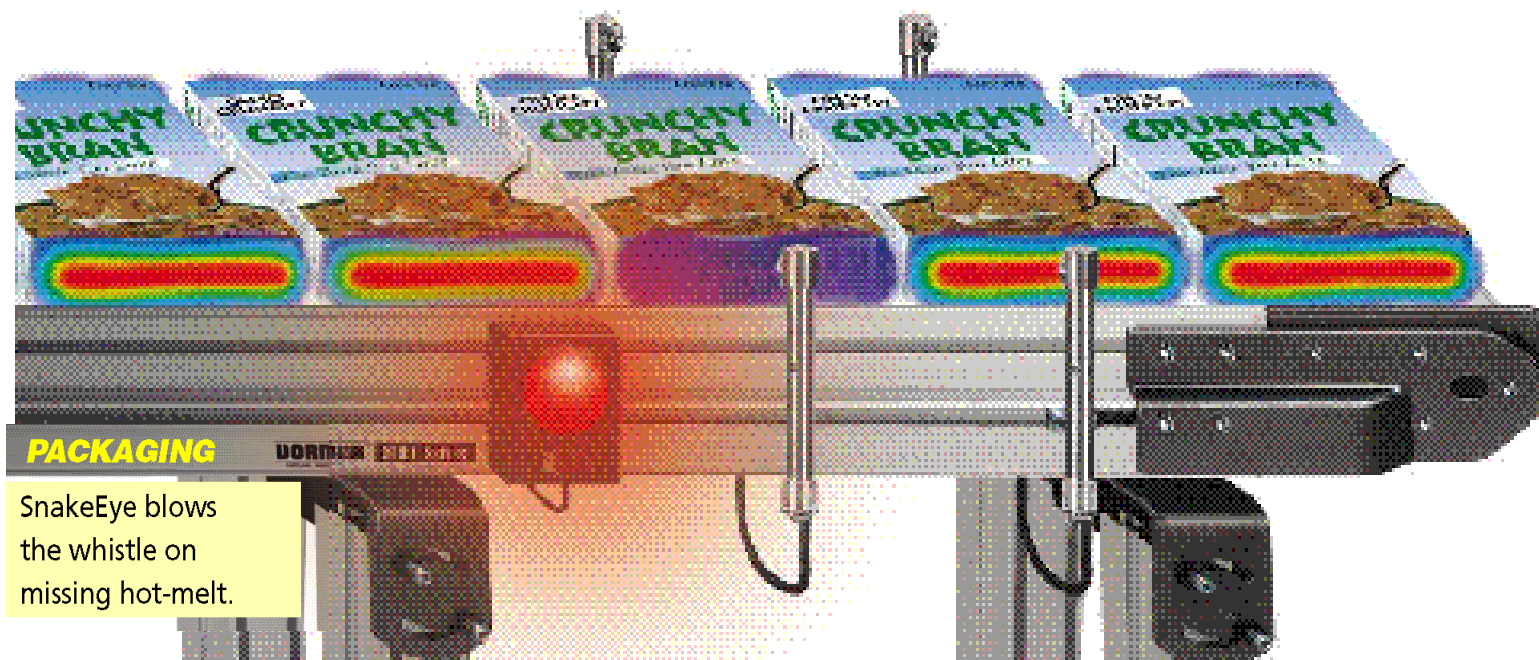
Product Input

Product Surface - setpoint

- Keep Equation Balanced to Within a Few % to Avoid Non-Uniformity in Material Temperature



# SnakeEye Photocell-Like Non-Contact Thermal Inspection



## PACKAGING

SnakeEye blows the whistle on missing hot-melt.

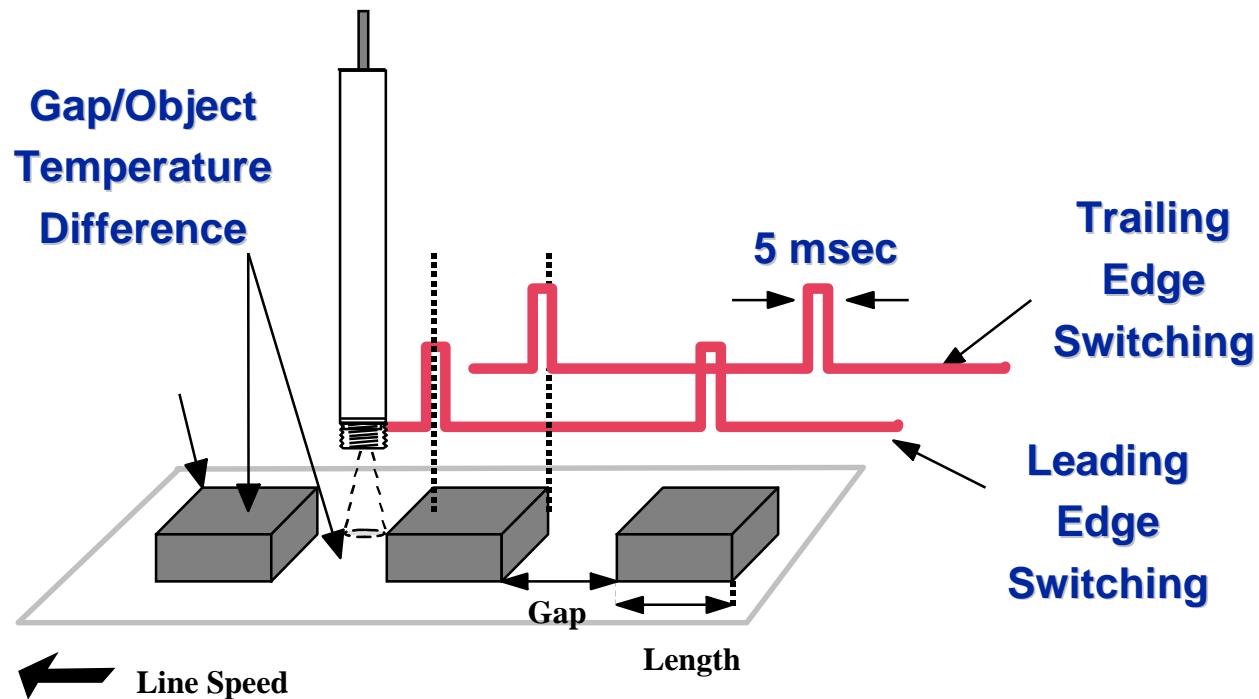
Increasing Production Speeds via IR -Controlled Heat Balance



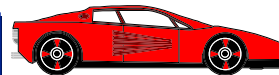
**EXERGEN**  
CORPORATION

# *SnakeEye* Photocell-Like Non-Contact Thermal Switches

## Thermal Switching of Objects With Less Than 1°C Differential

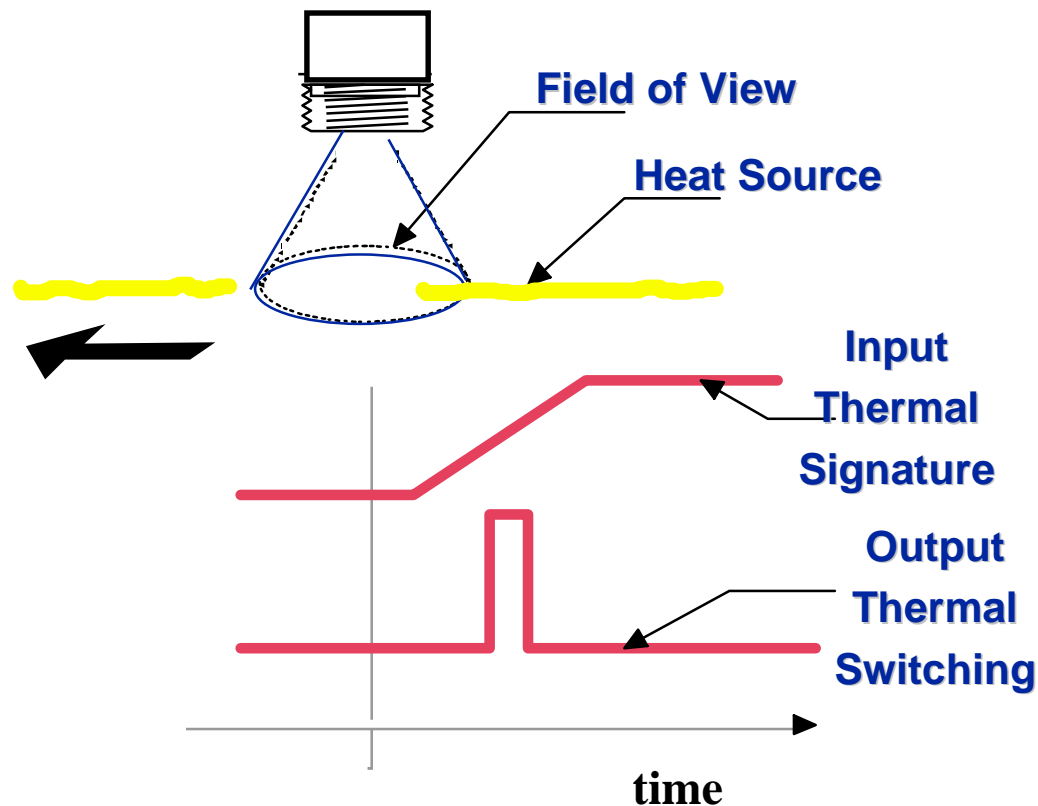


Increasing Production Speeds via IR -Controlled Heat Balance



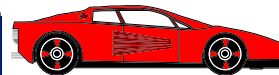
**EXERGEN**  
CORPORATION

# Principles of the SnakeEye



- The heat source enters the field-of-view of the SnakeEye and is detected by the sensing system.
- If the rate of change is of sufficient magnitude the SnakeEye causes the output to switch.

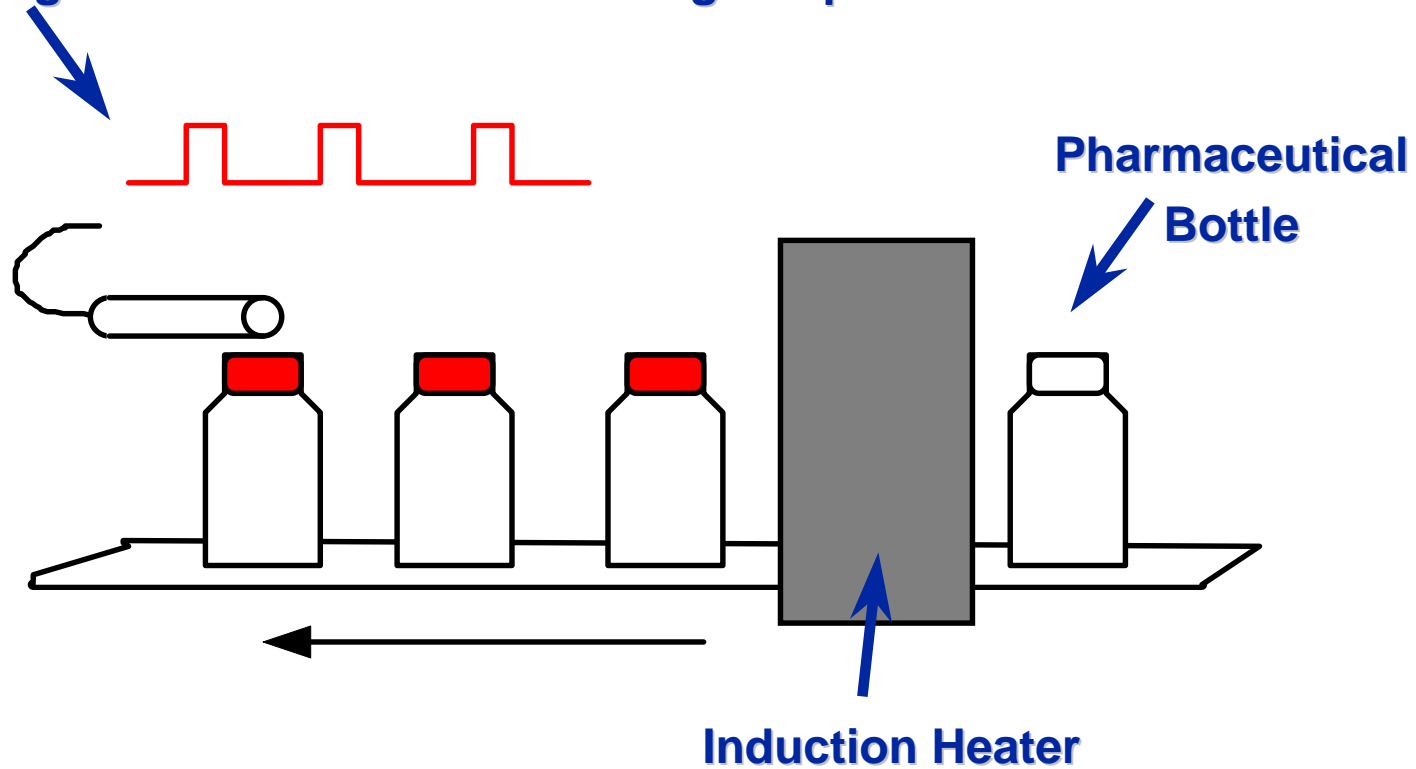
Increasing Production Speeds via IR -Controlled Heat Balance



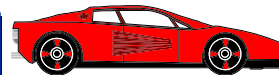
**EXERGEN**  
CORPORATION

# Detecting Presence/Absence Hidden Foil Safety Seal

Heat Signature of Heated Foil Through Cap

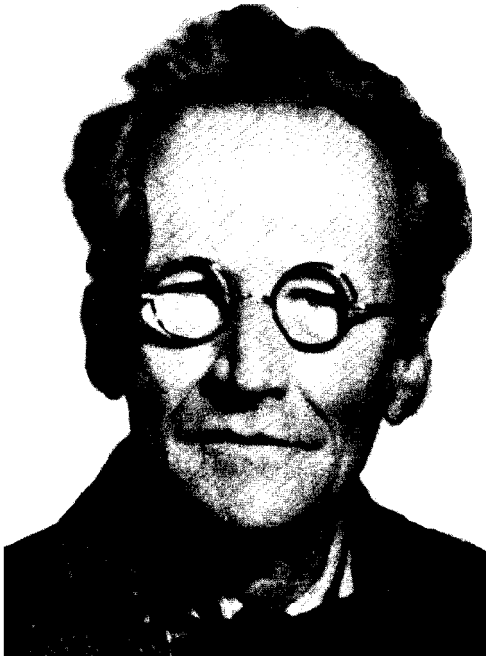


Increasing Production Speeds via IR -Controlled Heat Balance

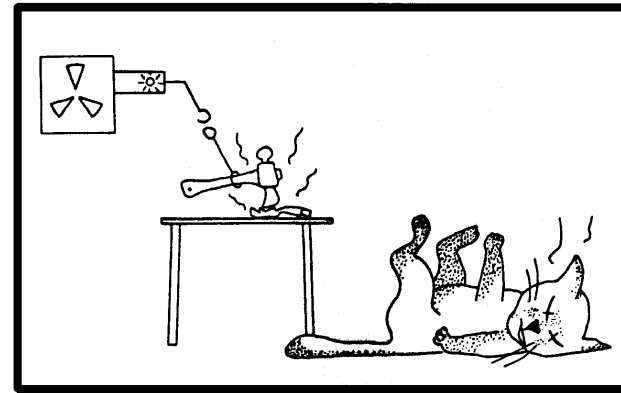
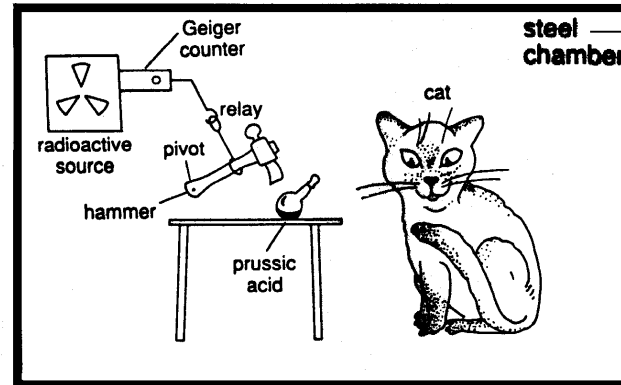


**EXERGEN**  
CORPORATION

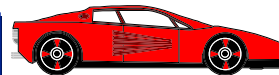
# Erwin Schrodinger ~ 1935



- The Cat Paradox



Increasing Production Speeds via IR -Controlled Heat Balance

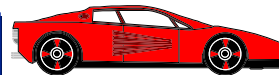


**EXERGEN**  
CORPORATION

***You Cannot Know For Sure That  
the Product is Right Unless You  
Look...***

***With  
EXERGENIR  
Sensors***

**Increasing Production Speeds via IR -Controlled Heat Balance**



**EXERGEN**  
CORPORATION

# *The Exergen Creed*

*We are the best in the world at  
what we do,*

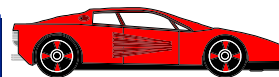
*And our products and services must  
be commensurate with our mission  
of supplying our customers with the  
best,*

*To help them be the best in the  
world at what they do.*

*F. Pompei  
President and Founder*

© Exergen Corporation 1996

**Increasing Production Speeds via IR -Controlled Heat Balance**



**EXERGEN**  
CORPORATION